

P-ISSN: 2706-7483
E-ISSN: 2706-7491
NAAS Rating [2026]: 4.5
IJGGE 2026; 8(9): 13-25
www.geojournal.net
Received: 25-06-2026
Accepted: 27-07-2026

Prakarsh Srivastava
Research Scholar, Department
of Geography, University of
Rajasthan, Jaipur, Rajasthan,
India

Naresh Kumar
Research Scholar, Department
of Geography, University of
Rajasthan, Jaipur, Rajasthan,
India

Sarina Kalia
Professor, Department of
Geography, University of
Rajasthan, Jaipur, Rajasthan,
India

Corresponding Author:
Prakarsh Srivastava
Research Scholar, Department
of Geography, University of
Rajasthan, Jaipur, Rajasthan,
India

Assessing Built-up Land Disparities in the Uttar Pradesh State Capital Region: A Sentinel-2 NDBI-Based Analysis

Prakarsh Srivastava, Naresh Kumar and Sarina Kalia

DOI: <https://doi.org/10.22271/27067483.2026.v8.i9a.861>

Abstract

The Uttar Pradesh State Capital Region, notified in July 2024, brings six districts around Lucknow under one planning framework, yet its built environment has not been described at the regional scale. This study maps built-up land using Sentinel-2 imagery. Nine near-cloud-free Level-2A scenes acquired in October 2025 were mosaicked, masked by district and processed using the Normalized Difference Built-up Index, with classified extents checked against high-resolution reference imagery. Built-up intensity ranges from 10.11 per cent of district area in Unnao to 26.89 per cent in Lucknow, with a coefficient of variation of 36.8 per cent. The regional Gini coefficient of 0.159 indicates relatively low inequality in the distribution of built-up land. Only Lucknow shows a clearly agglomerated built-up form; elsewhere built-up land remains dispersed. Disparity within the UPSCR is thus expressed more through intensity and spatial form than through distribution, providing a baseline for understanding regional development patterns.

Keywords: Uttar Pradesh State Capital Region, Built-up land, NDBI, Sentinel-2, Urban spatial disparity, Built-up intensity

1. Introduction

Built-up land is the physical record of urbanisation. Buildings, roads and paved surfaces mark where a society has settled and invested. Their extent decides how much cultivated land has been lost, how much rainfall runs off instead of soaking in, and how far service networks have to reach. *Angel et al.*¹ found that cities expand at roughly twice the rate of their populations, so the physical footprint of a settlement and its demographic size drift apart over time. For India, *Seto et al.*² showed that urban land conversion has been driven mainly by population growth rather than by rising per capita output, which is not the pattern they report for China. Where development has actually taken place therefore has to be measured spatially. It cannot be read off a census table.

Satellites make that measurement possible at a frequency no statistical system can match, and what they record does not depend on administrative definitions or reporting cycles. That independence matters most when institutions change faster than the statistical record does. A planning body created between two censuses governs a territory for which no contemporaneous enumeration exists, yet an image-derived account of its built environment can be produced within weeks and refreshed whenever the sky is clear.

1.1 Spectral indices and the remote sensing of built-up land

Normalised spectral indices remain the standard tool for delineating built-up surfaces over large areas. They trade a little accuracy for transparency, speed and very modest data requirements. *Zha, Gao and Ni*³ proposed the Normalized Difference Built-up Index (NDBI), which exploits a consistent contrast between the shortwave infrared and near-infrared response of constructed and vegetated surfaces. Two bands and one arithmetic operation are enough to separate the two covers, and Section 2.4 sets out the physical basis in detail.

The index has a known weakness. Dry bare soil, harvested fields and exposed sediment share part of the spectral signature of construction, and NDBI cannot reliably tell them apart. *Xu*⁴ combined several normalised indices into an index-based built-up index to address this, and *As-syakur et al.*⁵ added a thermal term in the enhanced built-up and bareness index for the

same purpose. Reviewing the field, *Kaur and Pandey*⁶ count a large family of such variants and conclude that none of them resolves every category of urban surface equally well. Choosing an index is therefore a matter of trade-offs rather than a settled question. NDBI stays in wide use for regional baselines because it is cheap to compute and easy for a reader to audit.

Sensor capability has improved alongside. *Drusch et al.*⁷ describe the Sentinel-2 mission of the European Space Agency, which provides thirteen spectral bands at 10, 20 and 60 m with a five-day revisit from its two-satellite constellation, distributed free of charge. Band 8 (near-infrared, 10 m) and Band 11 (shortwave infrared, 20 m) supply the terms NDBI requires. The finer grid matters in India, where 10 m resolution picks out individual building blocks, ribbon development along roads and the small nucleated villages in which much of the rural population lives. At the 30 m resolution of Landsat, on which most earlier built-up work was based, all of these are heavily generalised.

1.2 Built-up assessment in India

Two findings from the Indian remote-sensing literature frame this study. *Taubenböck et al.*⁸ tracked the twelve largest agglomerations from the 1970s onward and showed that Indian cities grow in distinctive spatial patterns, with cores and edges following different trajectories. *Pandey and Seto*⁹ compared satellite-derived urban extent with census figures and found the two diverge, because much physical urbanisation takes place in settlements the census still classes as rural. The physical and administrative pictures of urbanisation are not interchangeable, a point Section 4.3 returns to.

Case studies at city scale document rapid expansion. *Naikoo et al.*¹⁰ measured a 328 per cent increase in built-up area across the Delhi National Capital Region between 1990 and 2018. *Chettry*¹¹ reported that built-up land in the Lucknow urban agglomeration rose from 60.25 km² in 1991 to 235.47 km² in 2021, a growth of 291 per cent, with edge expansion accounting for most of the increase and entropy values indicating pronounced sprawl. For Lucknow city, *Khan and Khan*¹² modelled land-cover change with a combined cellular automata and artificial neural network approach, recording built-up cover rising from 10.93 per cent (127.82 km²) in 2001 to 25.47 per cent (297.74 km²) in 2021 and projecting 29.99 per cent by 2031. Work on Varanasi has added a regulatory dimension. *Jha et al.*¹³ quantified sprawl through combined spatial and statistical analysis, and *Rai et al.*¹⁴ assessed how far the city master plan has contained the growth it was drawn to contain.

Together these studies show that built-up expansion in northern India is rapid, that edge growth dominates it, and that formal planning has controlled it only in part. What they describe, though, is almost always a single city or a single agglomeration.

1.3 Research gap and objectives

For a newly constituted planning region this literature has two limits. It works overwhelmingly at the scale of individual cities, whereas Indian regional planning increasingly operates on groups of districts. It also reports built-up extent almost invariably as one percentage of the areal unit studied.

The second limit deserves emphasis, because the convention

looks harmless. A percentage tells us how thoroughly a unit's own territory has been built over and nothing else. It is silent on how much land that percentage represents, on whether built-up land is spread across a region in proportion to the land available, and on which units hold the bulk of a region's built environment. Where units differ in size by a factor of two or more, as Indian districts routinely do, those are separate questions and they can have separate answers.

The Uttar Pradesh State Capital Region (UPSCR) allows both of these gaps to be addressed at once. Notified in July 2024 and administered by a statutory authority headquartered in Lucknow, it follows the model of the National Capital Region around Delhi and brings six districts of central Uttar Pradesh (Lucknow, Barabanki, Unnao, Sitapur, Hardoi and Raebareli) under one planning framework, with the declared aim of promoting balanced regional development and easing pressure on the state capital.¹⁵ The region was created after the most recent census, so no contemporaneous statistical description of its territory exists. Its built environment has, to our knowledge, not yet been described at regional scale, and the new planning framework creates a clear need for a baseline against which later development can be judged.

The study sets out to do three things:

- To map built-up land in the six UPSCR districts from Sentinel-2 imagery using NDBI.
- To compare the districts on two measures, built-up intensity as a share of district area and absolute built-up stock in km².
- To measure how concentrated the region's built-up land is and describe its spatial form.

2. Materials and Methods

2.1 Study Area

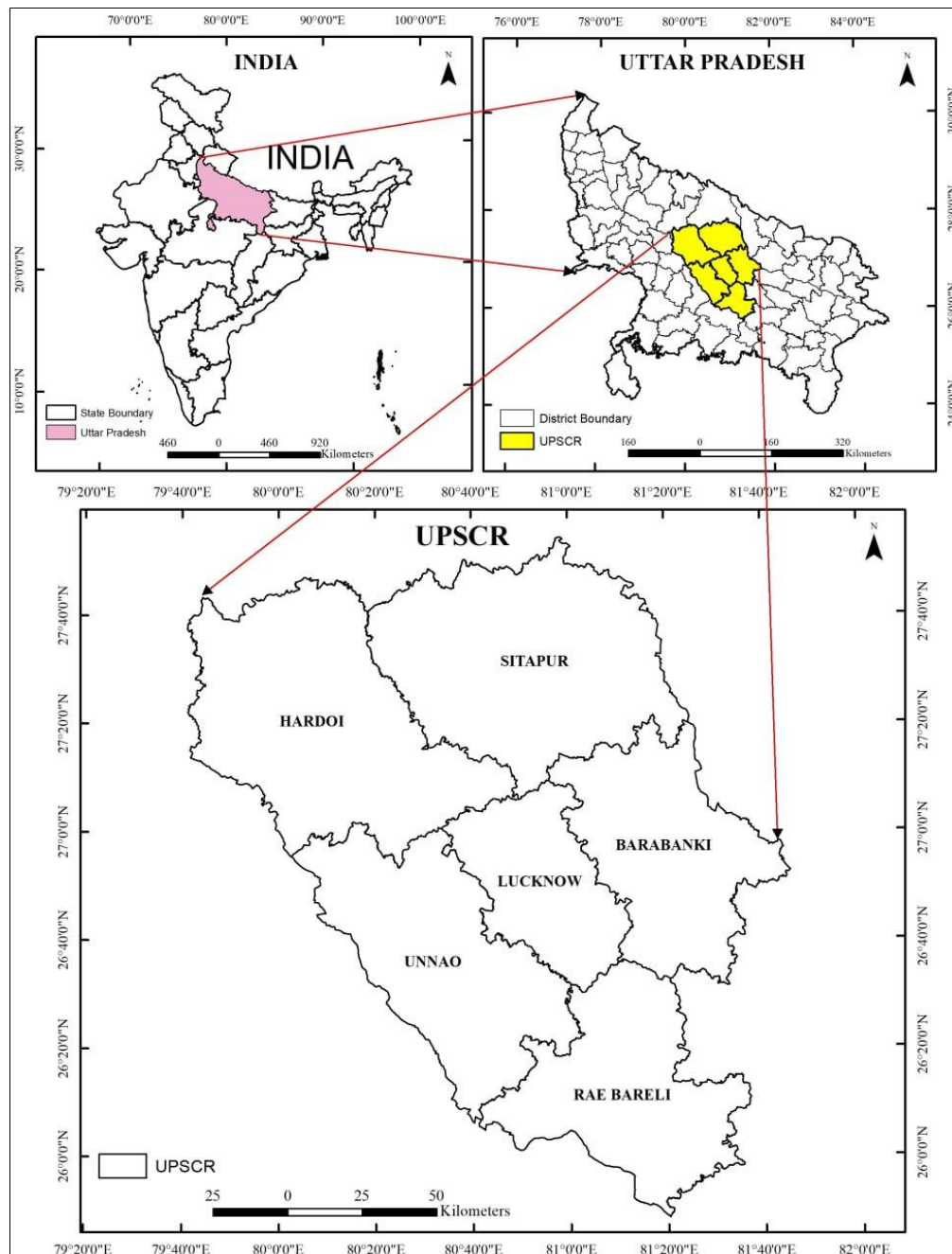
The UPSCR lies in central Uttar Pradesh, within the middle Ganga plain, and covers 27,826 km², the combined geographical area of its six districts. As delimited by the district boundary layer used here, it extends approximately from 25°50' N to 27°55' N and from 79°40' E to 81°55' E (Fig. 1). Lucknow, the state capital, forms the administrative and functional core. Barabanki adjoins it on the east, Unnao lies to the south-west towards the Kanpur industrial belt, Sitapur to the north, Hardoi to the north-west and Raebareli to the south.

The region lies entirely within the alluvial plain of the Ganga and its tributaries. Relief is subdued, the surface slopes gently to the south-east, and soils are alluvial throughout. The Gomti crosses the region through Lucknow, the Ghaghra bounds the northern and eastern margins of Sitapur and Barabanki, and the Ganga bounds the south-western margin of Unnao and the southern margin of Raebareli.¹⁶ The climate is humid subtropical, with most rainfall delivered by the south-west monsoon between June and September. That uniformity helps the analysis. Terrain, soil and climate vary so little across the six districts that differences in built-up extent are unlikely to reflect differences in land capability. The large braided river courses along several district margins matter for a different reason, taken up in Sections 3.1 and 4.6.

The districts differ considerably in size and settlement character (Table 1). Lucknow is the smallest at 2,528 km², yet holds the largest population, the highest density at 1,816 persons km⁻² and much the highest urban share at 66.21 per cent. The other five range from 4,402 to 5,986 km², with

densities between 682 and 781 persons km^{-2} and urban shares between 9.69 and 17.10 per cent. Outside Lucknow the economy is predominantly agrarian, with a limited number of industrial and institutional nodes. A single large

metropolitan centre set among five substantially rural districts is precisely the sort of arrangement in which the internal distribution of built-up land is worth examining.



Source: Prepared by the authors.

Fig 1: Location of the Uttar Pradesh State Capital Region within India and Uttar Pradesh, showing the six constituent districts.

Table 1: Area, population and settlement characteristics of the six districts of the Uttar Pradesh State Capital Region.

District	Area (km^2)	Population ^[2011]	Density (persons km^{-2})	Urban population (%)
Lucknow	2,528	4,589,838	1,816	66.21
Barabanki	4,402	3,260,699	741	10.15
Unnao	4,558	3,108,367	682	17.10
Sitapur	5,743	4,483,992	781	11.84
Hardoi	5,986	4,092,845	684	13.24
Raebareli	4,609	3,405,559	739	9.69
Region	27,826	22,941,300	824	N.A.

Note: District areas are the Census 2011 figures, which reproduce the reported densities. Regional density is total population divided by total area; a regional urban share is not applicable.

Source: Census of India, 2011.¹⁶

2.2 Data Sources

Built-up mapping used Sentinel-2 MultiSpectral Instrument Level-2A products, distributed by the Copernicus programme of the European Space Agency as bottom-of-atmosphere surface reflectance. Nine tiles were needed to cover the six districts: six acquired on 14 October 2025 and three on 17 October 2025 (Table 2). Cloud cover and acquisition date governed the choice of scenes. Cloud cover across the nine tiles ranges from 0.001 to 0.284 per cent, indicating very limited cloud contamination; no additional cloud or shadow masking was applied. Keeping acquisition inside a four-day window means the mosaic represents a near-simultaneous view, and that differences between districts do not simply reflect differences in season, crop

stage or soil moisture at the moment of imaging. Band 8 (near-infrared, 10 m) and Band 11 (shortwave infrared, 20 m) were extracted from each product.

District boundaries in vector form delimited the analysis and partitioned the imagery. High-resolution imagery available through Google Earth served as the reference source for the visual checking described in Section 2.5. The length of pucca roads maintained by the Public Works Department, as reported for 2023-24 in the Economics and Statistics Division's district-wise indicators, was also assembled as a reference variable measured independently of the imagery; Section 3.6 uses it to check the classified built-up ranking.¹⁷ Figure 2 summarises the processing chain set out below.

Table 2: Sentinel-2 Level-2A scenes used for built-up mapping.

Sentinel-2 Level-2A scene identifier	Acquisition date	Cloud cover (%)
L2A T44RNQ A044947 20251014T051602	14 October 2025	0.018
L2A T44RMQ A044947 20251014T051602	14 October 2025	0.094
L2A T44RMR A044947 20251014T051602	14 October 2025	0.284
L2A T44RNR A044947 20251014T051602	14 October 2025	0.043
L2A T44RMP A044947 20251014T051602	14 October 2025	0.008
L2A T44RNP A044947 20251014T051602	14 October 2025	0.014
L2A T44RMR A044990 20251017T052549	17 October 2025	0.003
L2A T44RLR A044990 20251017T052549	17 October 2025	0.001
L2A T44RLQ A044990 20251017T052549	17 October 2025	0.002

Source: Copernicus Open Access Hub, European Space Agency.

2.3 Sentinel-2 Data Pre-processing

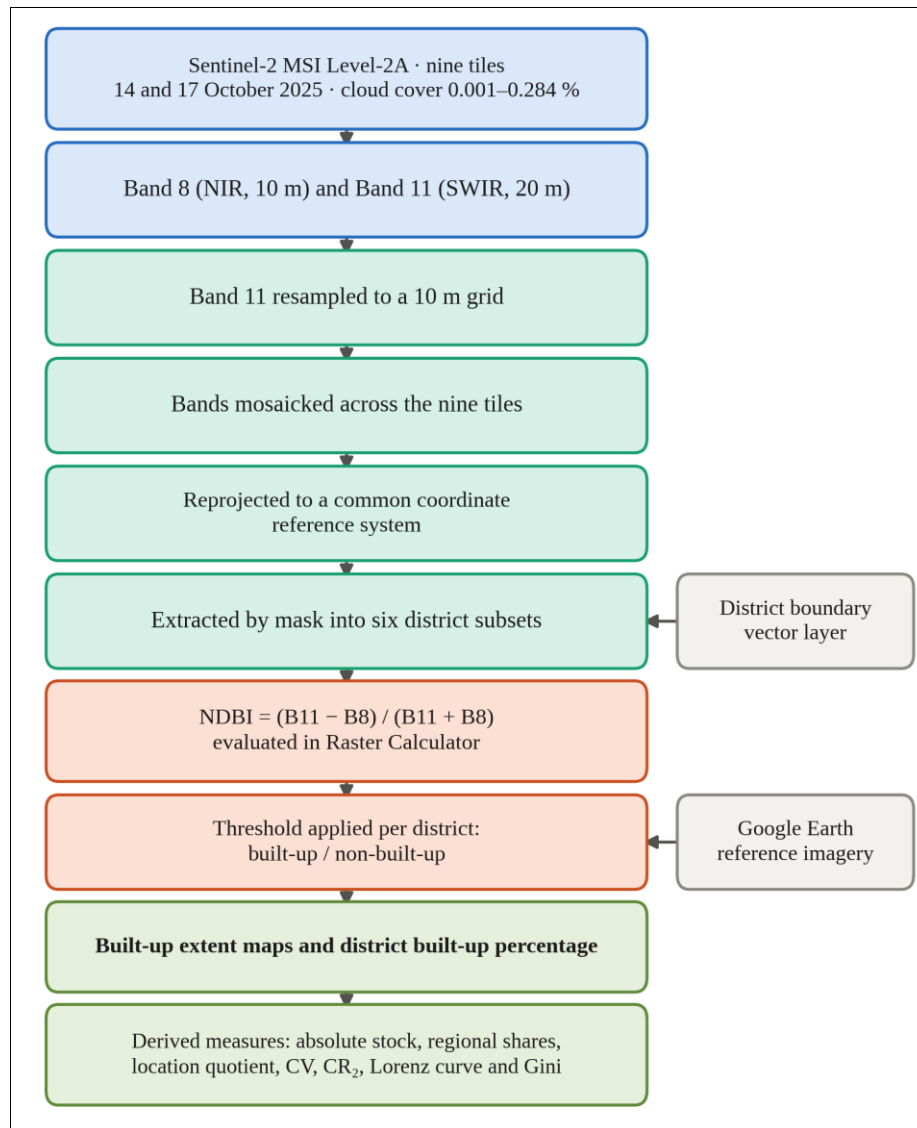
Level-2A products arrive as atmospherically corrected surface reflectance, so no further atmospheric correction was applied. Working from Level-2A rather than Level-1C keeps the reflectance values, and with them the index values, comparable between the two acquisition dates and across all nine tiles.

Band 11 was resampled from 20 m to a 10 m grid. NDBI is computed pixel by pixel from two bands, and an arithmetic operation between rasters needs both of them on the same grid. Working at 10 m, rather than degrading Band 8 to 20 m, keeps the detail of the near-infrared band. Resampling of course creates no shortwave-infrared information that the sensor did not record, and the effective detail of the shortwave-infrared contribution stays that of a 20 m

observation.

The resampled Band 11 and the native Band 8 layers were then mosaicked across the nine tiles. District boundaries do not coincide with the Sentinel-2 tiling grid, and several districts fall across two or more tiles, so computing the index tile by tile would have left discontinuities inside single districts. Building a seamless regional layer for each band before computing the index avoids that.

The mosaicked layers were reprojected to a common coordinate reference system and extracted by mask with the district boundary polygons, which gave a pair of band subsets for each district. Masking confines each calculation to the reporting unit of the study, and it allows the classification threshold to be examined district by district.



Source: Prepared by the authors.

Fig 2: Processing chain followed in this study, from Sentinel-2 Level-2A acquisition through NDBI computation and thresholding to the derived measures of built-up disparity.

2.4 NDBI-Based Built-up Extraction

NDBI was computed in its original formulation³ as

$$NDBI = (SWIR - NIR) / (SWIR + NIR)$$

which, for the Sentinel-2 band designation, becomes

$$NDBI = (B11 - B8) / (B11 + B8)$$

The index works because constructed and vegetated surfaces behave in opposite ways across these two wavelength regions. Healthy vegetation reflects strongly in the near-infrared, where leaf mesophyll scatters radiation efficiently, and absorbs in the shortwave infrared, where liquid water in leaf tissue is a strong absorber. Concrete, asphalt, brick, tile and metal roofing hold very little water, so their reflectance rises from the near-infrared into the shortwave infrared. The numerator is positive over built-up surfaces and negative over vegetation. Dividing by the sum normalises the result to the range -1 to $+1$ and removes much of the variation caused by differences in illumination and viewing geometry. The expression was evaluated in a raster calculator on the masked band pairs, giving a continuous NDBI surface for

each district. A continuous index surface is not a land-cover classification, and converting one to the other requires a decision rule. A district-specific threshold was determined empirically for each district. The NDBI value distribution of each district was first examined to identify a range in which built-up surfaces could be distinguished from vegetated and agricultural cover. A candidate cut-off was then applied and inspected against high-resolution imagery available through Google Earth. The cut-off was adjusted and re-inspected until the delineated extent corresponded as closely as possible to the observed settlement pattern while avoiding obvious commission over non-built-up surfaces. Thresholds were therefore curated manually for each district rather than adopted from a published constant, with the aim of obtaining the most defensible built-up delineation supported by the index under local conditions. The proportion of each district's geographical area above the selected threshold was then computed as its built-up percentage, and the classified layers were mapped at a common scale and legend (Fig. 3). The same classification procedure was followed across all six districts, and the resulting percentages are interpreted as district-level estimates within a common analytical framework.

2.5 Validation

The classified output was checked visually against high-resolution imagery available through Google Earth. For each district, the delineated extent was compared with the settlement pattern visible in the reference imagery, with particular attention to the principal urban centres, smaller nucleated settlements, major transport corridors and obvious commission over agricultural land, exposed surfaces and river margins. Because Google Earth imagery is compiled from acquisitions of varying dates, it served as a spatial reference for settlement patterns rather than as a same-date comparison. The assessment therefore provides a spatial consistency check rather than a formal pixel-level accuracy assessment¹⁸; no independently sampled reference dataset was available. The results are consequently interpreted as comparable district-level estimates, with emphasis on relative spatial differences rather than treating the mapped areas as exact measurements.

2.6 Derived Measures of Built-up Disparity

Four quantities were derived from the NDBI output to capture properties that a built-up percentage cannot express. All of them use the district areas given in Table 1. Absolute built-up stock converts intensity into a quantity of land:

$$B_i = A_i \times BU_i / 100$$

where B_i is the built-up area of district i in km^2 , A_i its geographical area and BU_i its built-up percentage. Each district's share of the regional built-up stock is B_i as a percentage of the regional total ΣB , compared with its share of the regional land area ΣA . A location quotient expresses district intensity relative to the region:

$$LQ_i = BU_i / (100 \times \Sigma B / \Sigma A)$$

Values above unity identify districts built over more intensively than the region as a whole.

Dispersion is summarised by the coefficient of variation, computed separately for intensity and for absolute stock so that the two can be set against each other. Concentration is measured in two ways. A two-district concentration ratio (CR_2) gives the combined share of regional built-up land held by the two districts with the largest absolute stock, which can be read against the 33.33 per cent that an equal division among six districts would produce. A Gini coefficient is then derived from a Lorenz curve, in which districts are ordered by ascending built-up intensity and cumulative shares of regional built-up land are plotted against cumulative shares of regional land area. A Gini coefficient of zero would mean built-up land spread exactly in proportion to the land available, and higher values mean greater concentration.

All of these measures are descriptive, and with six units no inferential claim is made. The correlation coefficients in Section 4.3 are exploratory. They relate an October 2025 built-up measure to 2011 Census characteristics, and both Pearson and Spearman statistics are given so that the influence of a single extreme observation can be judged.

3. Results

3.1 Spatial Distribution of Built-up Area

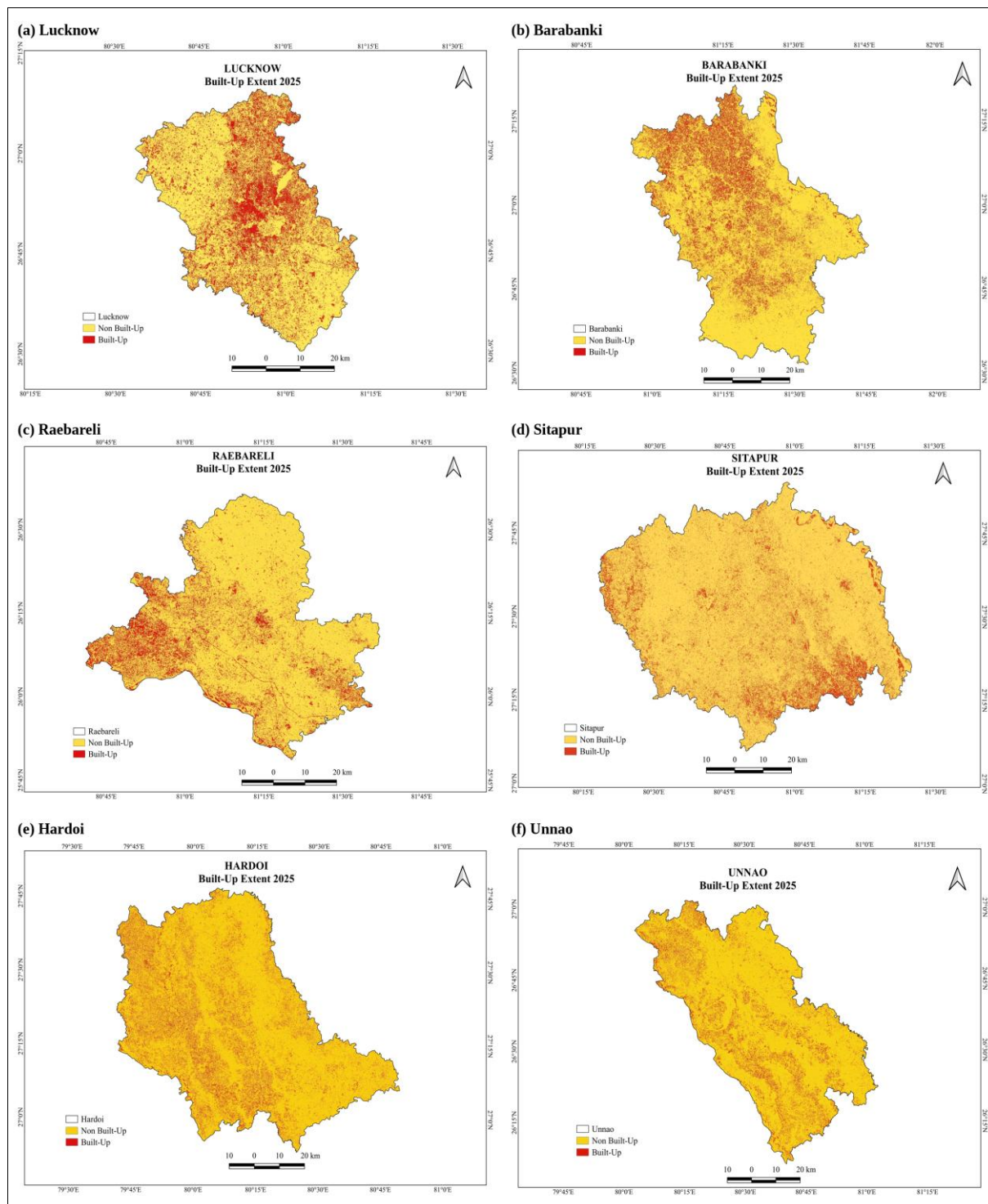
Figure 3 shows the NDBI-derived built-up extent of the six districts at a common scale and legend. Three distinct built-up forms can be made out.

Lucknow (Fig. 3a) is the only district in which built-up land is agglomerated. A large, near-continuous mass occupies the centre of the district, corresponding to the metropolitan area, with well-defined arms extending north-east, east, south-east, south and west along the principal routes out of the city. Unclassified enclaves within the mass correspond to the Gomti and to large institutional and open tracts. The rest of the district is far from empty. Classified pixels form a dense but broken matrix over most of its area, thinning only towards the extreme west and the south-east, and a secondary concentration appears in the north. Lucknow therefore combines an agglomerated core with a densely settled rural surround, and both contribute to its regional maximum of 26.89 per cent.

Barabanki (Fig. 3b) has no comparable core. Built-up land forms a fine-grained scatter of small patches, much denser in the north and north-west along the boundary with Lucknow and thinning towards the south and south-east. Its high aggregate share comes from the density of dispersed settlement in the western half of the district, and the gradient runs towards the regional core.

Raebareli (Fig. 3c) shows a similar dispersed form with clearer internal structure. Density is greatest in the west and south-west and lowest in the north-east, a compact denser cluster near the centre corresponds to Raebareli town, and a narrow linear feature crosses the district from north-west to south-east. Sitapur (Fig. 3d) presents the most uniform surface in the region, an even speckle at moderate density across almost the whole district, with a denser tract in the south-east and elongated bands along the eastern margin. Hardoi (Fig. 3e) and Unnao (Fig. 3f) share the dispersed form at lower density. Classified pixels in Hardoi are more frequent along the western margin and in a south-central belt, while much of the north-east returns little cover. Unnao has the lowest built-up intensity and the most uniform distribution among the six districts.

Some elevated NDBI responses also occur over exposed river sediment and bare or recently harvested fields, particularly along river margins and in the more agrarian districts.



Note: Panels are arranged in descending order of built-up percentage. Red denotes classified built-up surface and yellow non-built-up surface. Each panel carries its own graticule, north arrow and scale bar.

Source: Prepared by the authors.

Fig 3: NDBI-derived built-up extent of the six districts of the Uttar Pradesh State Capital Region, from Sentinel-2 Level-2A imagery acquired in October 2025: (a) Lucknow, (b) Barabanki, (c) Raebareli, (d) Sitapur, (e) Hardoi, (f) Unnao.

3.2 Built-up Intensity and Relative District Position

Built-up intensity varies substantially across the region (Table 3). Lucknow records the highest value at 26.89 per cent of its area, followed by Barabanki at 18.59 per cent. Raebareli (15.93 per cent) and Sitapur (14.77 per cent) sit close to the regional figure, and Hardoi (11.62 per cent) and Unnao (10.11 per cent) record the lowest. The range is 16.78 percentage points, and the highest value is 2.66 times the lowest.

The area-weighted regional intensity is 15.23 per cent,

below the unweighted mean of the six district values, which is 16.32 per cent. Hardoi and Sitapur, the two largest districts by area, both fall below the regional figure, so weighting by area pulls the regional value down. Location quotients run from 1.77 in Lucknow to 0.66 in Unnao. Only Lucknow, Barabanki and, marginally, Raebareli exceed unity.

This ordering does not follow the degree of urbanisation, and Figure 3 shows why. Barabanki has no city approaching the size of Lucknow and its built-up land is dispersed rather

than agglomerated, yet it returns the second-highest intensity in the region, well above Unnao, which adjoins a major industrial centre. A high built-up percentage in this region can arise either from metropolitan agglomeration, as

in Lucknow, or from a dense fabric of small dispersed settlements, as in Barabanki. The percentage on its own cannot tell the two apart, which Section 4.3 takes further.

Table 3: District-wise built-up intensity and location quotient derived from NDBI, October 2025.

District	Built-up land (% of district area)	Rank	Location quotient
Lucknow	26.89	1	1.77
Barabanki	18.59	2	1.22
Raebareli	15.93	3	1.05
Sitapur	14.77	4	0.97
Hardoi	11.62	5	0.76
Unnao	10.11	6	0.66
Region (area-weighted)	15.23	n.a.	1.00

Note: The location quotient expresses district intensity relative to the area-weighted regional intensity.

Source: Computed by the authors.

3.3 Absolute Built-up Stock and Regional Shares

Converting intensity into absolute area produces a different hierarchy (Table 4, Fig. 4). Sitapur holds the largest quantity of built-up land at 848.2 km², followed by Barabanki (818.3 km²), Raebareli (734.2 km²) and Hardoi (695.6 km²). Lucknow, first on intensity, ranks fifth at 679.8 km², and Sitapur holds 1.25 times as much built-up land as the capital district. Only Unnao, at 460.8 km², stands clearly below the rest.

Figure 4 sets the two measures side by side. Barabanki, Raebareli and Unnao keep their positions, but Lucknow falls from first to fifth, Sitapur rises from fourth to first, and Hardoi from fifth to fourth. District size explains the reordering. Sitapur and Hardoi are the two largest districts, so each turns a below-average intensity into a large quantity of land, while the small territorial base of Lucknow turns the region's highest intensity into no more than a moderate stock. Four of the six districts hold between 695 and 850 km² of built-up land, a spread of about 22 per cent, even though their intensities range from 11.62 to 18.59 per cent. Setting each district's share of regional built-up land against its share of regional land area makes the same point in relative terms. Lucknow holds 16.04 per cent of the built-up

land on 9.09 per cent of the area, a positive divergence of nearly seven percentage points and by far the largest in the region. At the other end, Unnao holds 10.88 per cent on 16.38 per cent and Hardoi 16.42 per cent on 21.51 per cent, negative divergences of 5.5 and 5.1 points. Barabanki is over-represented by 3.5 points, while in Raebareli and Sitapur the two shares differ by less than one percentage point.

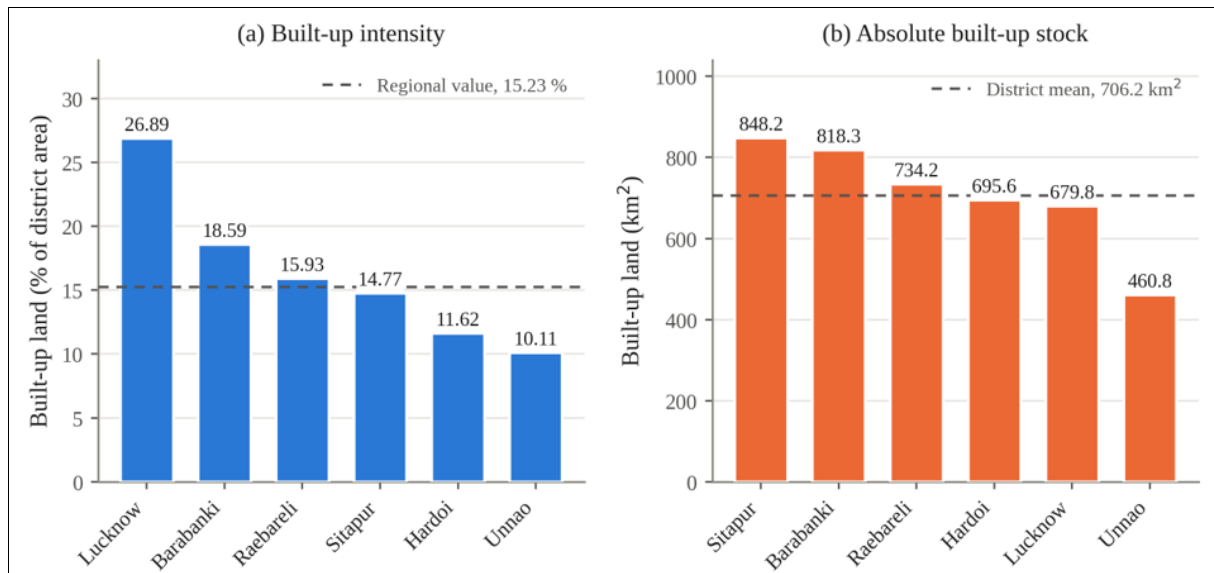
The classified extents include the riverine and bare-surface commission described in Section 3.1, and that commission probably falls more heavily on the agrarian districts than on Lucknow, so the robustness of this reordering was tested directly. On the least favourable assumption for the result, that Lucknow's estimate carries no commission error while the others do, Sitapur's stock would have to be overstated by 19.9 per cent and Barabanki's by 16.9 per cent before either fell below Lucknow. The finding that the capital district does not hold the largest quantity of built-up land is therefore not fragile. The margins over Raebareli and Hardoi are considerably smaller, at 7.4 per cent (54.4 km²) and 2.3 per cent (15.8 km²), respectively, so these adjacent rankings should be interpreted with greater caution.

Table 4: Absolute built-up stock and shares of regional built-up land and regional land area, by district.

District	Built-up land (km ²)	Rank	Share of regional built-up land (%)	Share of regional land area (%)
Sitapur	848.2	1	20.02	20.64
Barabanki	818.3	2	19.31	15.82
Raebareli	734.2	3	17.33	16.56
Hardoi	695.6	4	16.42	21.51
Lucknow	679.8	5	16.04	9.09
Unnao	460.8	6	10.88	16.38
Region	4,237.0	n.a.	100.00	100.00

Note: Built-up land in km² is computed as district area × built-up percentage.

Source: Computed by the authors.



Note: Districts are ordered by descending value within each panel; the two orderings differ.

Source: Prepared by the authors.

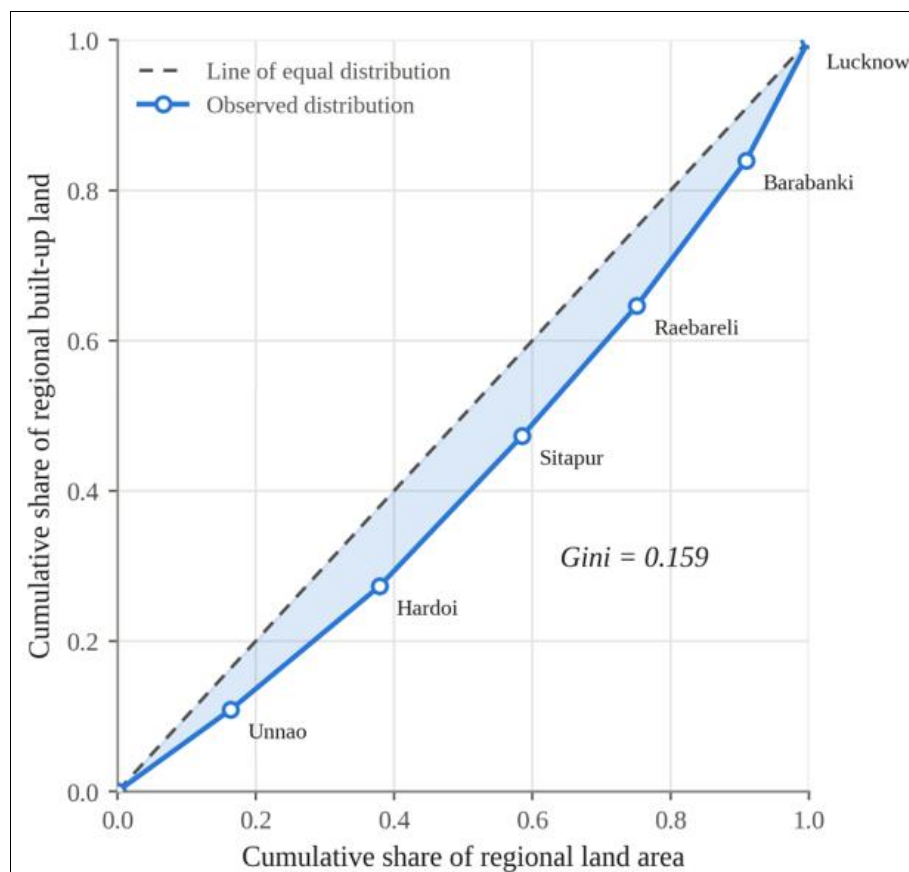
Fig 4: Built-up land in the Uttar Pradesh State Capital Region expressed as (a) intensity, the percentage of each district's own area, and (b) absolute stock in km².

3.4 Built-up Disparity and Spatial Concentration

The concentration measures put these results in a regional frame. Sitapur and Barabanki between them hold 39.33 per cent of the region's built-up land, only six percentage points above the 33.33 per cent that an equal division among six districts would give, and the three largest hold 56.66 per cent against a benchmark of 50 per cent. The Lorenz curve in Figure 5 departs correspondingly little from the line of

equal distribution, and the Gini coefficient is 0.159.

The two dispersion measures together give the central quantitative result of the study (Table 5). Built-up intensity has a coefficient of variation of 36.8 per cent across the six districts, whereas absolute stock has a coefficient of variation of 19.5 per cent. Variation in how intensively districts are built over is thus 1.89 times the variation in how much built-up land they actually contain.



Note: The shaded area between the observed distribution and the line of equal distribution corresponds to a Gini coefficient of 0.159.

Source: Prepared by the authors.

Fig 5: Lorenz curve of built-up land against land area across the six districts, ordered by ascending built-up intensity.

Table 5: Descriptive statistics for built-up intensity and absolute built-up stock across the six districts (n = 6).

Statistic	Built-up intensity (%)	Built-up land (km ²)
Mean	16.32	706.2
Standard deviation	6.00	137.5
Coefficient of variation (%)	36.8	19.5
Minimum	10.11 (Unnao)	460.8 (Unnao)
Maximum	26.89 (Lucknow)	848.2 (Sitapur)
Range	16.78	387.4

Note: Standard deviations are sample values. Means are unweighted district means and therefore differ from the area-weighted regional values reported in Tables 3 and 4.

Source: Computed by the authors.

3.5 Spatial Form of Built-up Development

Read together, the maps and the concentration measures describe a region whose built-up land is spread across the land base close to proportionally, with every district holding a substantial absolute quantity of it. The districts are separated by how far that land is compressed into a small territory and drawn together into continuous urban form. Lucknow holds a large stock within the smallest district in the region and is alone in agglomerating part of it into a single metropolitan mass with radial extensions. In the other five, including the two with the largest absolute stocks, built-up land remains a fine-grained scatter spread across two to two-and-a-half times as much territory.

3.6 External Consistency of the Built-up Ranking

The classification has no formally validated counterpart for this region, so an external check was sought in a variable measured independently of the imagery. Road length is recorded on the ground by the Public Works Department, and roads are themselves a built surface, so a district that is more thoroughly built over should carry more road per unit of territory. Table 6 sets the two measures against each other.

The agreement is close. Road length per 1,000 km² rises with built-up intensity across the six districts ($r = +0.861$, $p = 0.028$; Spearman $\rho = +0.943$, $p = 0.005$), and the two measures place four of the six districts in an identical rank. The only discrepancy is an adjacent swap between Raebareli, third on built-up intensity and fourth on road density, and Sitapur, fourth and third, whose built-up intensities differ by 1.16 percentage points. The correspondence does not rest on the capital district, since it survives the exclusion of Lucknow ($r = +0.832$, $p = 0.081$; Spearman $\rho = +0.900$, $p = 0.037$).

Normalising the same road data by population instead of by area destroys that correspondence. Road length per lakh population is unrelated to built-up intensity ($r = -0.200$, $p = 0.705$; $\rho = +0.257$, $p = 0.623$), and only one of the six districts keeps its rank. Lucknow records the highest road density per unit area in the region and the second-lowest road length per resident. One measurement therefore yields two different district hierarchies according to the denominator chosen, which is the point Section 4.1 makes about intensity and absolute stock, reached here from an independent dataset.

This comparison provides an independent consistency check on the district ranking. Because road surfaces are themselves part of the built environment detected by NDBI, the relationship should not be interpreted as a substitute for

pixel-level accuracy assessment. It nevertheless provides useful external support for the broad spatial pattern identified by the classification.

Table 6: Built-up intensity compared with road length per unit area and per unit population, by district.

District	Built-up land (%)	Rank	Road length per 1,000 km ² (km)	Rank	Road length per lakh population (km)	Rank
Lucknow	26.89	1	1,495.84	1	66.93	5
Barabanki	18.59	2	1,193.63	2	134.46	1
Raebareli	15.93	3	1,138.95	4	116.49	4
Sitapur	14.77	4	1,179.62	3	124.39	2
Hardoi	11.62	5	978.83	5	120.75	3
Unnao	10.11	6	492.84	6	63.37	6

Note: Ranks run from the highest value to the lowest on each measure. PWD pucca road length is for 2023-24, as reported in District wise development indicators¹⁷.

Source: built-up percentages computed by the authors; road length from the Economics and Statistics Division, Government of Uttar Pradesh.¹⁷

4. Discussion

4.1 Two Measures, Two Hierarchies

Built-up intensity and absolute stock rank the six districts differently, and the gap between the two rankings is wide. Lucknow leads decisively on the first measure and comes fifth on the second, while Sitapur, fourth on intensity, holds the largest quantity of built-up land in the region. Intensity is normalised by district area, and the districts differ in size by a factor of 2.4, so the two measures are answering different questions and there is no reason to expect them to agree.

Neither measure is the right one on its own. Intensity describes how thoroughly a district's territory has been built over, and it is the quantity that matters where the concern is pressure on land, whether that means cultivated area lost to construction, infiltration surface removed, or a district approaching a practical limit on further building. Absolute stock describes how much built environment a district actually contains, and it is the quantity that matters where the concern is the volume of settlement that must be supplied with roads, water, sanitation, schools and health facilities. An authority allocating infrastructure on intensity alone would systematically under provide for Sitapur and Barabanki, the two districts holding the largest built-up stocks in the region.

This is not peculiar to the UPSCR. Whenever administrative units of unequal size are compared through a normalised percentage, which is the usual convention in the literature reviewed above, the ranking obtained is partly an artefact of how those units happen to have been drawn. Section 3.6 shows the same effect in an unrelated dataset, where road length normalised by area and by population ranks the districts quite differently. Reporting both measures costs nothing, since one follows from the other by a single multiplication, and it heads off an inference that the percentage alone invites.

4.2 Concentration, Form and Endowment

The concentration measures show how far this configuration departs from an even one. A Gini coefficient of 0.159, and a two-district concentration ratio of 39.33 per cent against a benchmark of 33.33 per cent, describe a distribution close to

proportional to the land base. Set against that, intensity varies at 36.8 per cent, nearly twice the 19.5 per cent recorded for absolute stock.

Disparity within the region is therefore expressed mainly through differences in built-up intensity and spatial form rather than through strong concentration of built-up land in a small number of districts. Districts differ considerably in how tightly their built-up land is packed and organised, while differences in their absolute built-up stocks are comparatively modest.

What Figure 3 adds to the summary statistics is the question of form. A built environment that remains a fine-grained scatter works very differently from one of equivalent total area organised around several urban nodes, because dispersed settlement generates longer service networks per unit of built-up land and responds poorly to conventional master-planning instruments. On that reading Lucknow is not simply the most built-over district but the only one whose built environment is organised in a way that master-planning was designed to handle.

One reading fits the whole pattern, although six observations at a single date cannot demonstrate it. The absolute quantity of built-up land in a district of the middle Ganga plain may reflect a long-established rural settlement fabric of broadly similar density per unit area, on which metropolitan development in the capital district has been superimposed. On that reading Lucknow is distinguished not by having more built environment than its neighbours but by holding a comparable amount within a much smaller territory, and in agglomerated rather than dispersed form. We put this forward as a hypothesis for multi-temporal work at finer spatial units, not as a finding of the present study.

4.3 Physical Built-up Extent and Administrative Urbanisation

One result carries a caution beyond this region. Built-up intensity is strongly associated with 2011 population density (Pearson $r = +0.890$, $p = 0.017$; Spearman $\rho = +0.829$, $p = 0.042$), and the agreement between the two coefficients indicates an association carried by the whole sample. The association with the census urban share behaves quite differently. Pearson's r is $+0.802$ ($p = 0.055$) while Spearman's ρ is -0.086 ($p = 0.872$). Lucknow, at 66.21 per cent urban, lies far outside the range of the other five districts, which run from 9.69 to 17.10 per cent, and the linear coefficient rests almost entirely on that one observation. Remove Lucknow and the association reverses ($r = -0.898$, $p = -0.900$). These coefficients are exploratory, resting on six observations, four degrees of freedom and a fourteen-year gap between the census characteristics and the imagery, and we make no causal claim. They are enough to show that census urbanisation is not a dependable indicator of physical built-up extent here.

The two quantities measure different things, and Figure 3 makes the difference visible. Census urbanisation classifies people by the administrative status of the settlement they live in and carries no information about how much land is built over. Where a large share of a district's population lives in dense but administratively rural settlements, which is what the fine-grained scatter in the Barabanki, Raebareli and Sitapur panels represents, substantial built-up land is generated without any of it registering as urban population. Barabanki illustrates the point: second-highest built-up intensity in the region at 18.59 per cent, second-lowest

urban share at 10.15 per cent. This supports, from the physical side, the divergence *Pandey and Seto*⁹ report between satellite-derived urban extent and census figures for India, and the wider argument of *Denis et al.*¹⁹ that the census urban definition understates settlement transformation outside recognised towns.

This has a practical consequence, and a methodological one. Planning instruments triggered by urbanisation thresholds will not reach districts where built-up land is accumulating inside administratively rural settlements. And rank correlation should be reported alongside linear correlation whenever a small sample contains a dominant unit, since one capital district among six can produce a coefficient that looks strong and is an artefact of its own position.

4.4 The Present Estimates in Relation to Published Work

Published estimates for Lucknow allow a partial external check. *Khan and Khan*¹² report built-up cover of 25.47 per cent (297.74 km²) for Lucknow city in 2021. This study returns 26.89 per cent for Lucknow district in 2025. The figures are close but the areal bases are not: the earlier study covers roughly 1,170 km², whereas Lucknow district covers 2,528 km², and a district-wide figure that includes extensive rural territory would normally fall below a city-focused one. The two figures are not directly comparable because they refer to different spatial units. The comparison nevertheless places the present estimate within a plausible range, while the difference in areal coverage helps explain why the district-level estimate may capture both the metropolitan core and more dispersed rural settlement.

The finding of *Chetty*¹¹ that built-up land in the Lucknow agglomeration grew by 291 per cent between 1991 and 2021, with edge expansion accounting for most of the increase, corresponds well to the radial arms in Figure 3a and to the intensification along the Lucknow-facing side of Barabanki in Figure 3b. Whether that intensification represents the agglomeration extending across an administrative boundary, or independent development within Barabanki, cannot be settled from a single date. These two possibilities carry different planning implications: the first calls for managing contiguous metropolitan growth across a jurisdictional line, the second for treating Barabanki as a secondary centre in its own right. The Delhi National Capital Region offers a precedent worth keeping in view. Four decades of formal regional planning there did not prevent the 328 per cent increase in built-up area between 1990 and 2018 reported by *Naikoo et al.*,¹⁰ concentrated around the metropolitan core. The UPSCR is at a much earlier stage, and its low concentration ratio suggests a built environment that has not yet consolidated around its capital. Whether it follows the same path is a question only repeated observation can answer, which is one reason for establishing a baseline now.

4.5 Implications for Regional Planning and Monitoring

Within the limits of this evidence, three things follow for regional planning. Built-up extent should be reported to the regional authority in both of the forms used here, because the two measures identify different priorities. Infrastructure provision keyed to absolute stock points to Sitapur, Barabanki and Raebareli, while land-use pressure keyed to intensity points to Lucknow and Barabanki. Barabanki alone ranks high on both, and it is also the district whose built-up

gradient is oriented towards the capital, which argues for treating it explicitly in the regional plan rather than as an undifferentiated part of the periphery.

Census urbanisation should not be used as a proxy for physical development here, for the reasons given in Section 4.3. Monitoring will need to rest on direct physical measurement rather than demographic classification, and on measures sensitive to settlement form as well as to quantity. The procedure demonstrated here is inexpensive, uses freely available imagery and standard geographic information system operations, and can be repeated whenever suitable cloud-free imagery is available. Future applications could strengthen the baseline by refining the treatment of water and exposed river sediment, testing the consistency of the classification thresholds and incorporating systematic reference samples. Repeated observations would also allow the region to be monitored for changes in the intensity and spatial concentration of built-up development.

4.6 Limitations

Several considerations should be kept in mind when interpreting these findings, though they reflect the standard constraints of index-based regional mapping at this scale rather than shortcomings specific to this study, and none undermines the comparisons reported above on its own. First, the analysis represents a single observation window in October 2025 and therefore provides a cross-sectional baseline rather than evidence of temporal change.

The NDBI classification also involves some uncertainty. Elevated NDBI responses can occur over exposed river sand, bare or recently harvested fields and other non-built surfaces, particularly in the more agrarian districts. The maps indicate this effect most clearly along some river margins. Thresholds were calibrated separately for each district because their NDBI distributions differed, allowing local spectral conditions to be considered while retaining the same overall classification procedure. The visual checking against high-resolution imagery provided a useful spatial consistency check, although a systematic reference sample and error matrix were not included in the present analysis. The 20 m native resolution of the SWIR band, despite resampling to a 10 m grid, may also limit the discrimination of very fine peri-urban and ribbon development.

The absolute built-up areas are calculated using the district areas reported in the 2011 Census, while the boundary polygons used in the analysis may differ slightly from those administrative figures. This is particularly relevant where differences between districts are small. The district scale also provides a regional comparison but does not capture finer variation within individual districts. Finally, the relationships between 2011 census characteristics and the 2025 built-up estimates indicate association rather than causation. These considerations do not alter the main purpose of the study, which is to establish a comparable regional baseline and identify broad differences in built-up intensity, stock and spatial concentration.

5. Conclusion

This study mapped built-up land across the six districts of the Uttar Pradesh State Capital Region using NDBI derived from nine Sentinel-2 Level-2A scenes acquired in October 2025, and examined the results in terms of intensity, concentration and spatial form. Built-up intensity ranges from 10.11 per cent of district area in Unnao to 26.89 per

cent in Lucknow, with a coefficient of variation of 36.8 per cent. The regional Gini coefficient of 0.159 indicates relatively low inequality in the distribution of built-up land, while a two-district concentration ratio of 39.33 per cent shows that the built-up land is not strongly concentrated in a small number of districts. Only Lucknow shows a clearly agglomerated built-up form; elsewhere, built-up land remains more dispersed, with notable density along the Lucknow-facing side of Barabanki.

The findings show that built-up disparity within the UPSCR is expressed more strongly through intensity and spatial form than through differences in overall distribution. A single built-up percentage per administrative unit therefore does not fully capture the spatial organisation of the region's built environment. Considering built-up intensity alongside its concentration and spatial form provides a more informative basis for understanding regional development patterns.

These findings establish a physical baseline for a planning region for which, to our knowledge, no comparable regional assessment had previously been published. Future applications can build on this baseline through repeated observations, improved treatment of water and exposed sediment, systematic reference sampling and analysis at finer spatial scales such as tehsil or block level. Such extensions would help distinguish persistent settlement patterns from short-term spectral responses and provide a stronger basis for monitoring change across the UPSCR.

Acknowledgement

The authors acknowledge the European Space Agency Copernicus programme for open access to Sentinel-2 imagery, and the Office of the Registrar General and Census Commissioner, Government of India, for the district-level data used in this study.

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