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Decadal Assessment of Built-up Growth in Tirap District of Arunachal Pradesh (1993-2023) Using NDBI

Sainon Jenny Wangsa[a], Nandini C. Singh[b], Manaswita Dutta[a], Suman Bhujel[a], Habung Hagio[a]

([a] Ph.D. Scholar, Department of Geography, Rajiv Gandhi University, Doimukh, Arunachal Pradesh, India)
([b] Professor, Department of Geography, Rajiv Gandhi University, Doimukh, Arunachal Pradesh, India)

Abstract

Urban expansion in ecologically sensitive and topographically complex regions requires careful monitoring to ensure balanced land management and sustainable development. This study analyses the spatial and temporal dynamics of built-up growth in Tirap district over a thirty-year period (1993–2023) using the Normalized Difference Built-up Index (NDBI) derived from multi-temporal Landsat imagery. Surface reflectance data from four decadal intervals were processed to generate NDBI layers, which were subsequently classified into built-up and non-built-up categories using a defined threshold. The results indicate a steady increase in built-up area from 14.79 sq. km in 1993 to 76.37 sq. km in 2023, reflecting gradual but consistent spatial expansion. Growth patterns reveal clustering around established settlement nodes and progressive outward extension influenced by terrain and accessibility. Despite this increase, large portions of the district remain under vegetation cover, suggesting that development has been spatially concentrated rather than widespread. The findings demonstrate the usefulness of index-based remote sensing techniques for long-term monitoring of land-use transformation in mountainous districts. The study provides a spatial baseline to support informed planning strategies that seek to balance infrastructural development with environmental sustainability in Arunachal Pradesh’s eastern Himalayan region.

Keywords: NDBI, Built-up growth, Spatio-temporal analysis, Urban expansion, Development

Introduction

Urbanization at the global scale has significantly reshaped land surfaces, resulting in extensive land-use and land cover transitions (Wahid & Mushref, 2026). One of the most visible outcomes of this process is the spatial expansion of built-up areas, frequently occurring at the cost of natural ecosystems, agricultural lands, and open spaces. Such transformations often contribute to habitat fragmentation and biodiversity decline (Dutta, 2026; Wahid & Mushref, 2026). In the Indian context, the intensified infrastructure development, population growth, and industrial activities have amplified this change, necessitating advanced monitoring approaches to understand and manage urban expansion and its ecological implications (Kumar et al., 2023).

Monitoring these land transitions becomes particularly crucial in fragile mountain ecosystems such as the Himalayas. Regions including Arunachal Pradesh are experiencing evolving socio-spatial dynamics, where increasing anthropogenic pressures are reshaping regional land-use patterns (Patil et al., 2024). While extensive research has focused on India's megacities, smaller Himalayan districts often lack such studies. The Tirap district, located in the eastern part of the state, represents one such setting where administrative growth and settlement expansion are unfolding within a rugged, forested landscape. Understanding the spatial structure of settlements in such regions is crucial for formulating context-specific planning strategies that promote development while safeguarding environmental sustainability.

Remote sensing and Geographic Information Systems have become indispensable for performing comprehensive spatial and temporal assessments of urban expansion (Karanam, 2018). Among the various spectral indicators, the Normalized Difference Built-up Index is widely recognized for its ability to distinguish built-up areas from other land covers with high precision (Shaikh et al., 2023; Wahid & Mushref, 2026). By leveraging the unique spectral contrast between Short-Wave Infrared and Near-Infrared reflectance, NDBI allows for the automated extraction of impervious surfaces, providing a quantitative measure of urban growth over time (Dutta, 2026).

Despite the recognised importance of long-term land-use monitoring, there is a limited body of research documenting the decadal growth of built-up areas in the Tirap district. The present study seeks to address this gap through a spatio-temporal assessment of the district conducted across four stages: 1993, 2003, 2013, and 2023. By analysing NDBI maps derived from multi-temporal Landsat imagery, the research aims to quantify the rate and spatial orientation of built-up expansion, thereby generating a foundational dataset to support sustainable regional planning and resource management in the Eastern Himalayas.

Study Area

The Tirap district is situated in the southeastern region of Arunachal Pradesh, India. Owing to its geographic position, it forms an important linkage between the Assam plains and the Indo-Myanmar international boundary. The district occupies a largely hilly and forested landscape along the transition zone between the Himalayan foothills and the plains to the south. It is bordered by Changlang district to the east, the state of Nagaland to the west, and the districts of Dibrugarh and Sibsagar in Assam to the north. Characterized by rugged topography and the presence of the Patkai Bum range, the district features elevations ranging significantly across its 2,362 km area. The region experiences a humid subtropical climate with an average annual rainfall of approximately 2,754 mm and temperatures ranging between 10°C in winter to 35°C in summer. Settlements are dispersed and clustered along roads and river valleys; built-up extents are typically small but expanding around administrative centres and transport nodes. These land-use patterns influence the spectral signature of built and non-built surfaces, and are central to interpretation of NDBI outputs.

Data Sources and Image Pre-processing

To monitor decadal changes from 1993 to 2023, multi-temporal satellite data were obtained from the United States Geological Survey (USGS) Earth Explorer. The study utilized data from three different Landsat missions to maintain temporal continuity:

- 1993: Landsat 5 Thematic Mapper (TM)
- 2003: Landsat 7 Enhanced Thematic Mapper Plus (ETM+)
- 2013 & 2023: Landsat 8 Operational Land Imager (OLI)

The images were selected from post-monsoon and winter periods to reduce atmospheric and seasonal variability such as cloud cover and vegetation interference. Pre-processing steps included atmospheric correction and radiometric calibration to ensure that the spectral reflectance values were comparable across the four decades.

Normalized Difference Built-up Index Calculation

The NDBI was employed as the primary spectral indicator to extract built-up area information. This index leverages the high reflectance of urban materials in the Short-Wave Infrared region compared to the Near-Infrared region (Karanam, 2018; Wahid & Mushref, 2025). The NDBI index produces values between -1 to +1, where positive (higher) values are associated with impervious surfaces and constructed surfaces, while negative (lower) values typically represent vegetated areas and water bodies.

The mathematical formula for NDBI is defined as:

$$NDBI = \frac{\mathrm{SWIR} - \mathrm{NIR}}{SWIR + NIR}$$

For each Landsat sensor, the corresponding SWIR and NIR bands were selected according to the sensor-specific spectral configuration as follows:

- Landsat 5 (TM) & Landsat 7 (ETM+):

$$NDBI = \frac{BAND\ 5 - BAND\ 4}{BAND\ 5 + BAND\ 4}$$

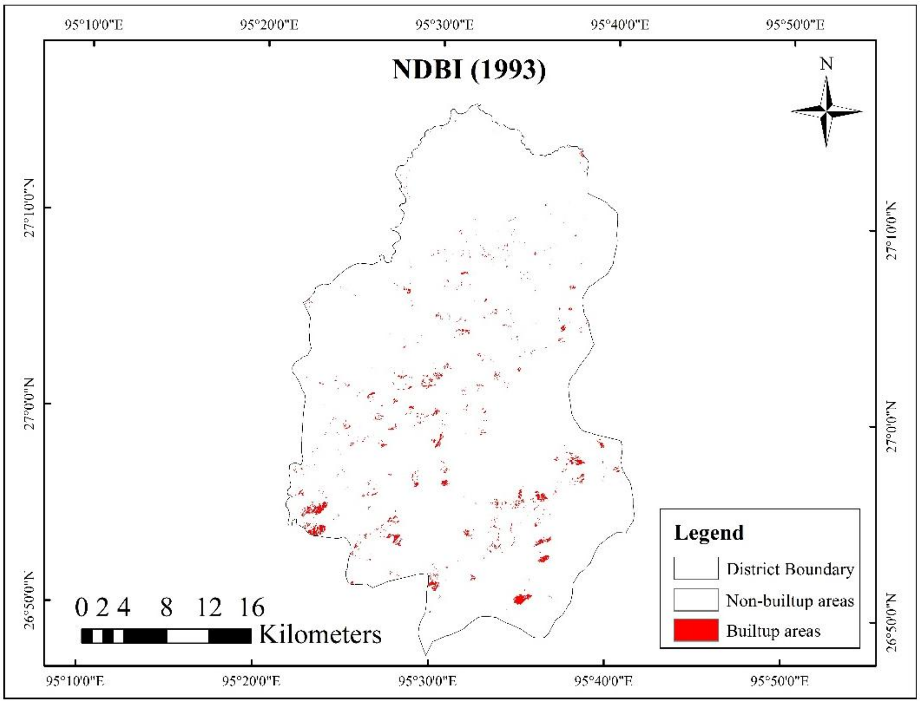
- Landsat 8 (OLI):

$$NDBI = \frac{BAND\ 6 - BAND\ 5}{BAND\ 6 + BAND\ 5}$$

Results

The NDBI outputs reveal that built-up expansion in the district has been gradual and spatially uneven, largely concentrated around existing settlement cores and transport corridors. Given the predominantly forested and hilly terrain of the district, urban development appears to follow valley bottoms and gentler slopes. The following sub-sections present a year-wise analysis.

Figure 1: NDBI Map of 1993

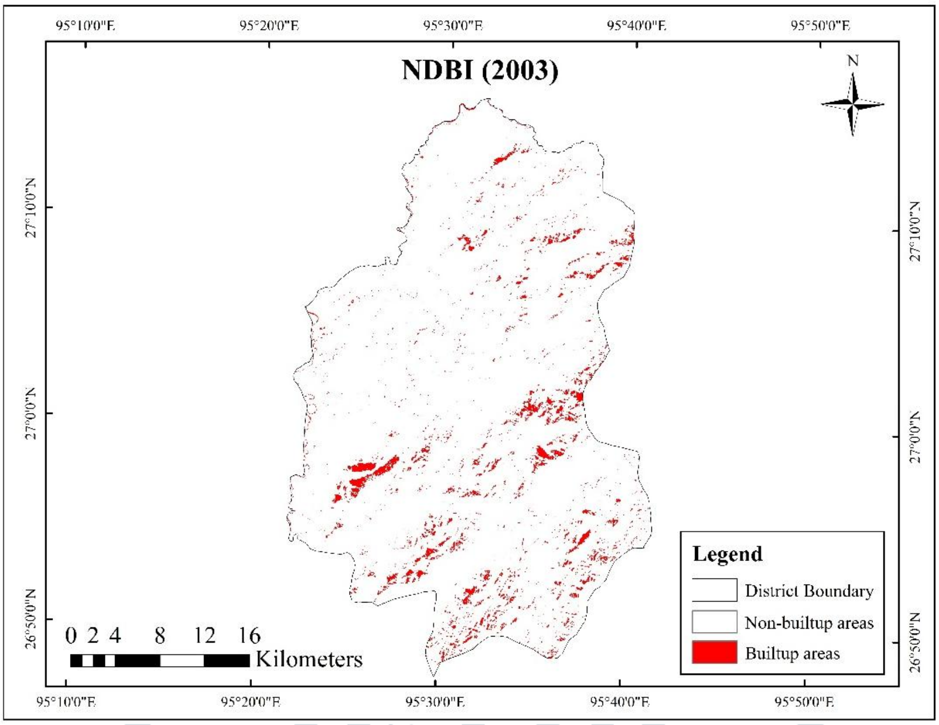


Source: USGS Earth Explorer

The spatial analysis of the 1993 NDBI map indicates that built-up development in Tirap district were limited in extent and highly fragmented. The total built-up area was estimated at 14.79 sq. km, indicating a very modest level of urban presence within the district during this period. Spatially, built-up patches appear scattered rather than consolidated. The distribution pattern suggests that settlements were primarily confined to localised clusters, most likely corresponding to administrative centres, market nodes, and habitation areas situated along accessible valley regions. There is no evidence of continuous or expansive urban sprawl, instead, development appears discontnous and dispersed.

Large portions of the district show absence of significant positive NDBI values, reflecting the dominance of vegetated and natural landscapes. The sparse concentration of built-up pixels further reinforces the predominantly rural characterof the district in 1993 and represents an early-stage or low-intensity development phase.

Figure 2: NDBI Map of 2003



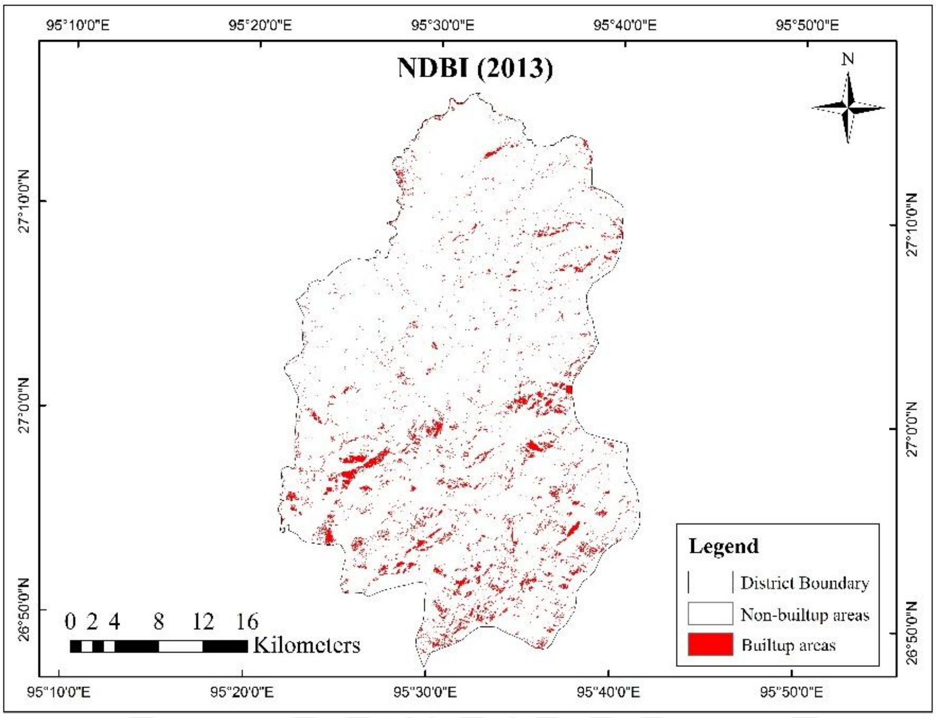
Source: USGS Earth Explorer

The NDBI analysis for 2003 reveals a substantial increase in built-up extent within Tirap district compared to the baseline year of 1993. The total built-up area was estimated at 43.86 sq. km, indicating a marked expansion over the previous decade.

Spatially, built-up patches appear more numerous and more spatially dispersed across the district. Unlike the highly localized and fragmented pattern observed in 1993, the 2003 distribution reflects outward expansion from existing settlement cores. The southern and central portions of the district exhibit relatively higher concentrations of built-up pixels, indicating gradual consolidation of settlement areas. Although development remains discontinuous rather than forming a continuous urban mass, the increase in spatial density suggests a transition from isolated habitation clusters toward more structured growth.

Despite this expansion, large parts of the district continue to show low NDBI values, confirming the persistence of forested and vegetated landscapes. However, the increase from 14.79 sq. km in 1993 to 43.86 sq. km in 2003 reflects a significant phase of spatial transformation, marking the beginning of more noticeable urban and infrastructural development within the district. This decade appears to represent a formative stage in the district's urban growth trajectory, setting the foundation for subsequent expansion observed in later years.

Figure 3: NDBI Map of 2013



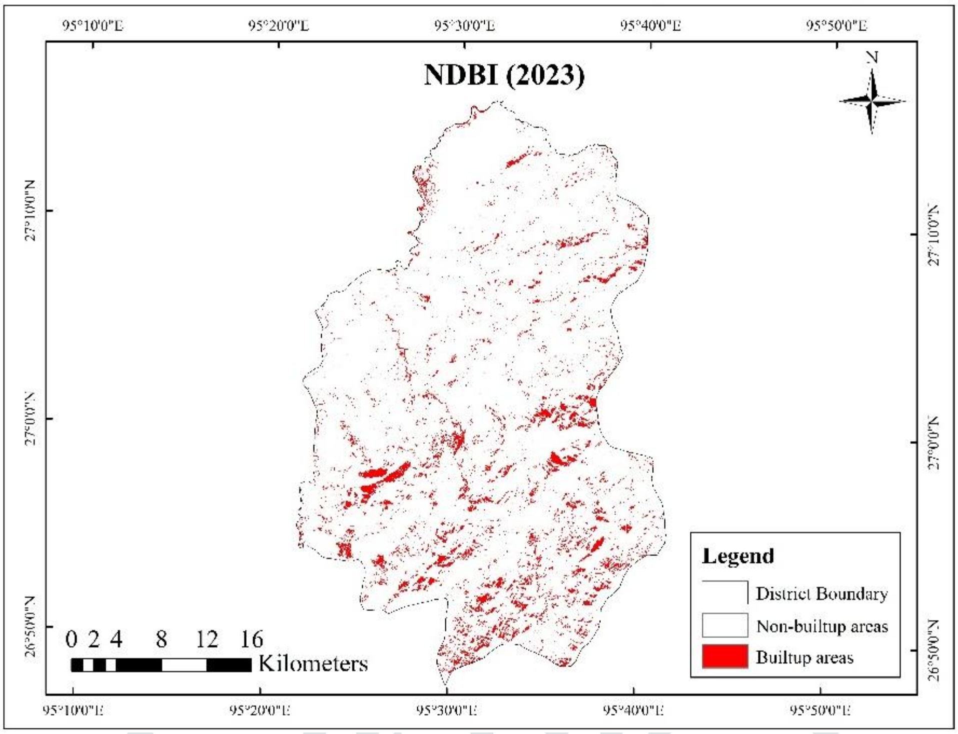
Source: USGS Earth Explorer

The NDBI-derived map for 2013 indicates a continued expansion of built-up areas in Tirap district, with the total built-up extent increasing to 60.79 sq. km. This represents a sustained growth trend when compared to both 1993 and 2003, reflecting progressive spatial transformation over two decades. The spatial pattern in 2013 shows not only an increase in the number of built-up patches but also a noticeable intensification around previously established settlement nodes. Several built-up clusters appear more consolidated, particularly in the southern and central portions of the district.

Unlike the highly fragmented pattern observed in 1993, the 2013 configuration demonstrates partial spatial continuity in some areas, indicating gradual infilling and outward expansion. While development remains non-uniform due to the district's rugged topography and forest dominance, the density of built-up pixels is significantly higher than in earlier years. Despite this increase, large sections of the district still exhibit low NDBI values, confirming the persistence of vegetated and natural landscapes. However, the growth from 43.86 sq. km in 2003 to 60.79 sq. km in 2013 suggests that the district entered a more active development phase during this period, characterized by both spatial spread and consolidation of settlement areas.

Overall, the 2013 pattern reflects a transitional stage between dispersed rural settlements and emerging localized urban intensification, marking a critical phase in the district's evolving land-use structure.

Figure 4: NDBI Map of 2023



Source: USGS Earth Explorer

The NDBI map for 2023 demonstrates a continued expansion of built-up surfaces within Tirap district, with the total built-up area reaching 76.37 sq. km. This represents the highest recorded extent within the study period, confirming a sustained upward trend in settlement growth over the past three decades.

Spatially, the 2023 distribution reflects both outward expansion and increasing consolidation of previously established settlement clusters. Built-up areas appear more spatially continuous in certain pockets, particularly in the southern and central segments of the district, whereas, expansion along valley systems and transportation routes remains evident, indicating that terrain accessibility continues to guide development patterns. Compared to earlier years, the 2023 pattern suggests a maturing phase of growth. While the district retains large areas of vegetation and forest cover, the density and spread of built-up pixels are noticeably greater. The transformation is not uniform across the landscape but instead, it follows a corridor-based and node-centred structure, consistent with the district's rugged topography and dispersed settlement system.

The increase from 60.79 sq. km in 2013 to 76.37 sq. km in 2023 indicates continued infrastructural development and settlement intensification rather than abrupt spatial sprawl. This gradual but persistent expansion suggests an ongoing restructuring of land-use patterns, moving from predominantly rural dominance toward localized urban consolidation.

Discussion

The temporal progression of built-up expansion in Tirap district reveals a pattern that is both incremental and spatially structured. Unlike metropolitan regions where expansion often manifests as rapid and continuous urban sprawl, the growth observed in this district reflects a gradual transformation shaped by topography, accessibility, and pre-existing settlement hierarchies.

The spatial configuration indicates that built-up expansion is not random but guided by physical suitability and connectivity and accessibility appears to be a major determinant of spatial growth. Areas with improved road connectivity and administrative significance show comparatively higher intensification of built-up surfaces over time. The expansion from 1993 to 2003 represents a significant structural shift, suggesting increased infrastructural activity and settlement consolidation during this period. Subsequent growth between 2003 and 2023 indicates continued, though more measured, expansion and infilling around established nodes rather than the emergence of entirely new urban centres.

Another important observation is the coexistence of expanding built-up areas with dominant vegetative landscapes. Despite the increase from 14.79 sq. km to 76.37 sq. km over three decades, a substantial proportion of the district remains under forest and natural cover. This indicates that development has so far been spatially concentrated rather than widely dispersed. The absence of extensive contiguous impervious surfaces suggests that the district has not experienced uncontrolled urbanization but rather incremental transformation aligned with demographic and infrastructural needs.

The progressive consolidation observed in later years may also indicate a shift from dispersed rural settlement patterns toward emerging semi-urban clusters. Such transitions are typical in districts undergoing infrastructural modernization, administrative strengthening, and improved service provision. However, continued expansion into environmentally sensitive zones could potentially alter ecological stability if not carefully managed.

From a planning perspective, the findings highlight the importance of proactive land-use regulation in hilly and ecologically fragile regions. The steady upward trajectory of built-up expansion underscores the need for balanced development strategies that accommodate infrastructural growth while preserving forest cover and slope stability. Remote sensing-based monitoring, as demonstrated in this study, provides a reliable framework for tracking such transformations over time.

In summary, the built-up expansion pattern between 1993 and 2023 reflects a gradual restructuring of spatial organization within the district. The growth is characterized by terrain-influenced clustering, connectivity-driven expansion, and progressive consolidation rather than abrupt sprawl. These dynamics illustrate the evolving relationship between human settlement and the natural landscape, offering important insights for sustainable regional planning in similar mountainous contexts.

Conclusion

The present study examined the spatio-temporal dynamics of built-up expansion in Tirap district over a thirty-year period (1993-2023) using the Normalized Difference Built-up Index (NDBI) derived from multi-temporal Landsat imagery. The findings reveal a clear and sustained increase in built-up extent, rising from 14.79 sq. km in 1993 to 76.37 sq. km in 2023. This steady growth trajectory reflects a gradual but consistent transformation of the district's spatial structure.

The temporal progression indicates that early development was highly localized and fragmented, primarily concentrated around established settlement cores. Over time, expansion became more pronounced, extending outward along major road networks and accessible low-lying terrain. By 2023, built-up areas exhibited greater spatial continuity in select pockets, suggesting not only outward growth but also localized consolidation and infrastructural intensification.

Taken together, the findings underscore the importance of remote sensing-based indices in monitoring long-term land-use transitions in hilly and ecologically sensitive regions. The findings provide a quantitative and spatial baseline for future planning, enabling policymakers and planners to balance infrastructural development with environmental sustainability. It also offers a consistent and comparable framework for assessing long-term built-up transformation in a topographically complex and ecologically sensitive region. Future research may integrate higher-resolution imagery, ground verification, and socio-economic datasets to further refine the understanding of urban growth processes. Subsequently, continued monitoring of built-up dynamics will be essential to ensure that growth remains structured, inclusive, and ecologically responsible in the decades ahead.

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