Journal of Geointerface, Vol. 5, No. 1, July 2026, pp. 155–165 e-ISSN: 2583-6900

Quantifying urban expansion patterns using Shannon's Entropy and Landscape Expansion Index (LEI): A remote sensing study of Bapatla district, Andhra Pradesh, India

Sreerama Naik S R *, T K Prasad, Jayapal G

Department of Geography, Kannur University, Kannur, Kerala, India

ABSTRACT

Bapatla District. Accelerated urbanisation has resulted in widespread land use/land cover (LULC) changes, disturbing ecological balance and sustainable development. Remote sensing (RS) and Geographic Information System (GIS) have been applied in this research for quantifying urban growth trends using Shannon's Entropy (SE) and the Landscape Expansion Index (LEI). Multi-temporal satellite imagery (Sentinel – 2A) from 2016 to 2025 was applied for LULC change mapping and assessment of urban sprawl dynamics. Since urban sprawl is a concept that doesn't have a single definition accepted worldwide, so far it has been effectively depicted in terms of its qualitative, quantitative, and attitudinal landscape patterns (Verma and Garg, 2022). Shannon's Entropy was utilised in measuring the degree of spatial disorder of urban growth, distinguishing planned and unstructured growth. The Landscape Expansion Index (LEI) also distinguished growth into infill, edge growth, and out-laying and presented evidence of sprawl mechanisms. Results illustrate high rates of expansion of urbanized areas, particularly within peri-urban regions, with entropy values supporting dispersed and fragmented urban growth. LEI analysis showed the dominance of edge expansion, which was a sign of encroachment on agriculture and natural habitats. This paper addresses the urbanisation dynamics of population growth, economic growth, and infrastructure development but with a specific focus on implications in terms of climate resilience, groundwater drawdown, and land use sustainable planning. The findings present policymakers with evidence-based inputs for planning and regulation of urban development, preventing deterioration of the environment, and ensuring equitable regional development in the Bapatla District.

ARTICLE HISTORY

Received: 01 Dec 2025
Revised: 16 Jun 2026
Accepted: 16 Jun 2026

https://doi.org/10.5281/zenodo.20721862

KEYWORDS

Urban growth
Shannon's Entropy
Landscape Expansion Index (LEI)
Remote Sensing
GIS
Bapatla District
Land Use/Land Cover (LULC)

1. Introduction

Urbanisation is one among the most important human-induced changes of the 21st century., in fact, revolutionising environments and ecosystems globally (United Nations, 2018). Urban expansion, defined by the transformation of natural and agricultural environments into urbanised land, has become especially acute in developing areas undergoing rapid economic development (Seto et al., 2012). In India, where urbanisation is taking place at a record rate, coastal areas such as Andhra Pradesh have special challenges due to their ecological vulnerability and agricultural significance (Bhagat, 2018). Bapatla District, which lies on the Bay of Bengal, is a case in point as it is rapidly urbanising while still playing an important role in local food production (Census of India).

The analysis of urban growth patterns has become increasingly relevant in modern geography

*Corresponding author. Email: shree.rathod72@gmail.com (SNSR), tkprasadgeo@kannuruniv.ac.in (TKP), jayapalg@kannuruniv.ac.in (JG)

research because it has far-reaching implications for sustainable development (Grimm et al., 2008). Remote sensing has transformed our capability to track and analyse these trends, giving us spatially explicit information at many temporal scales (Gong et al., 2013). This technological innovation has enabled researchers to develop advanced metrics for measuring urban expansion, including Shannon's entropy and the Landscape Expansion Index (LEI), which have proved to be very useful tools (Yeh and Li, 2001; Liu et al., 2010). These complementary measures present different yet interrelated views on urban expansion, with Shannon's entropy quantifying the level of spatial dispersion and LEI identifying particular growth types (Bhatta, 2012). This study focuses on Delhi, a capital city of India and one of the fastest urbanizing metropolises in the world. The authors develop a replicable method through which they measure the changes in urban landscape over the thirteen years (1998, 2011) period (Sharma and Joshi, 2013).

The environmental impacts of uncontrolled urban growth are extensively reported in scientific literature (Foley et al., 2005). Land conversion from agriculture to urban land puts regional food security at risk, and the loss of natural cover and water bodies disturbs vital ecosystem functions (Grimm et al., 2008). Coastal areas such as Bapatla have an added burden due to sea-level rise and higher storm intensity, worsened by poorly planned urbanisation (Nicholls and Cazenave, 2010). In addition, urban growth modifies regional microclimates by the urban heat island effect and alters hydrological regimes through elevated impervious cover (Imhoff et al., 2010). These interactions reinforce the importance of integrating extensive spatial analysis in designing sustainable cities.

Shannon's entropy has been extensively used to measure the spatial structure of urban expansion (Yeh and Li, 2001). Its potential to differentiate between dense and fragmented development patterns also makes it a very useful metric for measuring urban sprawl (Bhatta, 2012). It is effective in various Indian cities, such as Hyderabad (Lata et al., 2001), Ajmer (Jat et al., 2008), and Mysore (Aithal et al., 2012). These applications demonstrate that entropy analysis can yield important information about the efficiency of land use and the success of urban planning policies (Barman et al., 2024). Further research still makes use of Shannon's entropy in various urban settings, attesting to its versatility as an analytical tool (Dereli et al., 2017; Kumar et al., 2007).

Although Shannon's entropy provides useful insight into the global spatial pattern of urban expansion, the Landscape Expansion Index is capable of complementing this by segregating certain expansion types (Liu et al., 2010). Having a three-class system - infilling, edge expansion, and outlying growth - facilitates a more detailed interpretation of urban process development (Yin et al., 2011). Infilling is the most effective land use pattern, taking place within already existing urban limits, whereas edge expansion and outlying growth generally point towards more widespread land consumption (Liu et al., 2010). The simultaneous use of these indicators has been highly effective in research on Indian cities, giving a holistic idea about urban expansion patterns.

The convergence of GIS and remote sensing technologies has now become central to urban development analysis (Sudhira et al., 2004). These technologies allow scholars to process large spatial datasets effectively, allowing for multi-temporal comparisons and trend analysis (Bhatta, 2012). Improved access to high-resolution satellite imagery, for example, Sentinel-2 data, utilised in this research, has tremendously improved our ability to track urban expansion with higher precision (Maxwell et al., 2018). This technical innovation enables more enlightened decision-making in urban management and planning (Gong et al., 2012).

Bapatla District is a strong case study because it uniquely combines coastal vulnerability with agricultural significance (CGWB, 2024). The urban sprawl of the district takes place amidst competing uses of land where fertile agricultural land interfaces with expanding urban needs (Dewan and Yamaguchi, 2009). This tension generates intricate planning issues that need to be analysed carefully regarding spatial patterns and growth processes (Angel et al., 2011). In addition, the coastal location of the district introduces an additional complexity, as urban development needs to take into account climate change effects and ecosystem conservation (Nicholls and Cazenave, 2010).

The purpose of this research is to contribute to the knowledge of urban growth in Bapatla District using Shannon's entropy and LEI analysis. The study aims to: (1) measure the spatial patterns of urban expansion in terms of multi-temporal remote sensing images, (2) define the modes of expansion by LEI classification, and (3) explain the implications of sustainable urban planning. The results will contribute strongly to policymakers faced with the challenge of rapid urbanisation in coastal Andhra Pradesh (Jabareen, 2006).

The approach is a blend of supervised Sentinel-2 image classification and spatial metric analysis to generate an all-embracing urban growth dynamics evaluation (Maxwell et al., 2018). The technique draws from established remote sensing and urban analysis techniques and refines them for application in the context of the Bapatla District (Herold et al., 2003). The temporal framework of the research (2016–2025) encompasses current urbanisation patterns, yielding real-time data useful for planning purposes (United Nations, 2018).

The relevance of this study goes beyond scholarly interest to respond to actual planning requirements in a fast-urbanising area (Taubenböck et al., 2012). Quantifying urban expansion patterns and determining the growth type are evidence-based tools for land use planning and growth management (Zhang and Su, 2016). The findings can guide policies that facilitate compact urban development, conserve agricultural land, and maintain coastal environments (IPCC, 2021). In addition, the developed methodological framework has the potential to be applied in other such regions under similar urbanisation issues (Seto et al., 2012). This research aims to contribute useful information that can be used to further sustainable and resilient urban development in the Bapatla District.

2. Study area

The study area (Fig. 1), Bapatla City, is in the Bapatla District of Andhra Pradesh, India, between 80°27'0"E to 80°30'0"E longitude and 15°54'0"N latitude. The coastal town is along the Bay of Bengal, thus in a dynamic and ecologically sensitive area. The Bapatla geology comprises alluvial deposits, typical of deltaic plains that formed due to the Krishna and Godavari river systems. The fertile soils support large agricultural activities but are also prone to erosion as well as saltwater intrusion by increasing sea levels associated with climate change. The area's geomorphology comprises flat coastal plains with sporadic bodies of water, including lagoons and estuaries that play a vital role in sustaining the hydrological balance within the area.

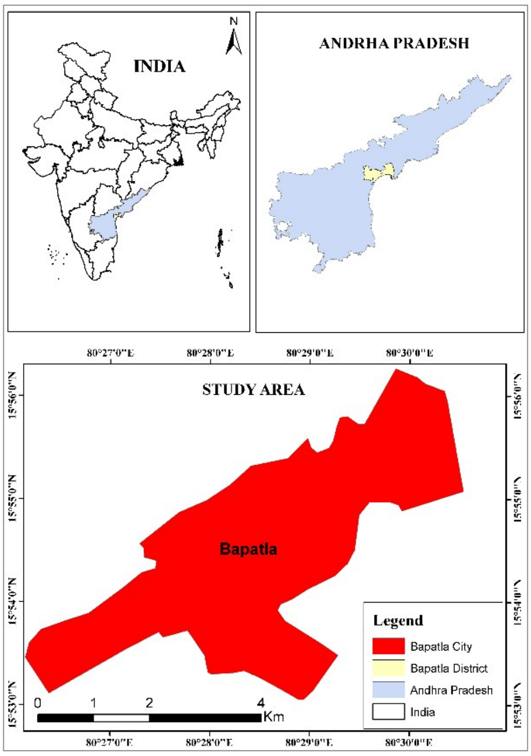

Fig. 1. Location map of the Study area.

Bapatla has a tropical monsoon climate with high rainfall during the southwest monsoon months (June–September) and scattered cyclonic disturbances. The exaggeration of weather extremes through climate change has led to unpredictable rainfall, extended drought, and enhanced risk of flooding. The expected intensity of the monsoon has increased, and the scales of rainfall above 200 mm for peak months, along with extended dry periods, are complicating water management and sustainability in agriculture. Its coastal position also enhances storm surge and sea-level rise sensitivity and endangers both human and natural environments.

It is a commercial and administrative centres that draws infrastructure and property investment. However, indiscriminate urbanization has put resources available to stress, hence the depletion of groundwater, degradation of green cover, and overpressure on amenities available. The population is comprised of urban and peri-urban dwellers whose livelihood is halfway between agriculture and fishing, trade and services. Securing the twofold challenge of climatic resilience and urban sprawl will be essential to making Bapatla grow sustainably and reconciling growth with the protection of the environment and fair allocation of resources.

3. Methodology

3.1. Data Acquisition and Pre-processing

1. Remote Sensing Data: Obtain multi-temporal satellite imagery over the period of the study (Sentinel-2).
2. Geometric Correction: Carry out geometric correction of the satellite imagery to remove distortions and provide accurate spatial referencing.
3. Image Enhancement: Apply image enhancement methods (band combinations) to enhance the visual interpretability of urban features.

3.2. Land Use/Land Cover (LULC) Classification

Carry out supervised classification to separate the land surface into various LULC categories, especially targeting the identification of urban zones. Establish distinct classification schemes of concern in urban sprawl studies (built-up areas, agriculture, water bodies, vegetation and salt pans).

3.3. Urban Expansion using Shannon's Entropy

Compute Shannon's entropy (H) for every time period to quantify the spatial dispersion or concentration of urban land use.

The equation is: $\mathbf{H} = \sum_{\mathbf{i=1}}^{\mathbf{n}} \mathbf{Pi1n(Pi)}$

Where:

- n is the number of zones (e.g., grid cells) within the study area.
- Pi is the proportion of urban land use in zone i.

3.4. Measurement of Landscape Expansion Index (LEI)

Compute the Landscape Expansion Index (LEI) to determine the nature of urban expansion that has taken place between two time intervals.

The formula for a newly urbanized patch is: $\mathbf{LEI} = \frac{\mathbf{Lc}}{\mathbf{3P}} \times \mathbf{100}$

Where:

- Lc is the length of the common boundary between the newly developed urban patch and the existing urban patches.
- P is the perimeter of the newly developed urban patch.

Examine the spatial pattern and temporal trends of various urban expansion types throughout Bapatla District.

4. Result and discussion

4.1. Basic infrastructure of the City

The given map (Fig. 2) of the city of Bapatla shows major urban features such as amenities, roads, fringe areas, and settlement patterns. The image explains four major elements: urban amenities (presumably comprising public services and infrastructure), the urban road system, the transitional fringe area between urban and rural regions, and the central urban settlement. This spatial visualisation implies an organised urban plan with central services served by roads, and the inclusion of the fringe area suggests continuing urban growth. The map is a useful starting point for the examination of urban growth patterns, service provision, and growth processes in Bapatla, especially applicable to research on urbanisation, infrastructure development, or spatial disparity.

4.2. Land use and Land cover

The 2016 Land Use/Land Cover (LULC) map of Bapatla City (Fig. 3) indicates a rich spatial pattern characterised by croplands, salt pans, habitations, vegetation cover, and waterbodies, highlighting the co-existence of agricultural landscapes with the precursors of urban expansion pressures. By 2025, the expected LULC map (Fig. 4) indicates extensive urban encroachment into agricultural and fringe lands, with settlements spreading radially from the city centre, while salt pans remain as economic features, but vegetation cover reduces, reflecting ecological stress due to fast-paced urbanisation. Waterbodies, although still existing, are subject to marginal contraction due to land conversion, reflecting the need for urgent, balanced urban planning that protects agricultural productivity and coastal ecosystems while allowing for growth. Collectively, these maps yield a critical time-series baseline (2016–2025) for evaluating the impacts of urbanisation, informing sustainable land management, and developing climate-resilient policies in this coastal district at risk in Andhra Pradesh.

Accuracy Assessment

Accuracy assessment of LULC classification (Table 1) for Bapatla City (2016 and 2025) was done using reference points, normally obtained from high-resolution images. The 2016 classification had achieved an overall accuracy of 87.7% and a Kappa

Table 1. Accuracy Assessment and Kappa Coefficient Table for 2016 and 2025 LULC.

LULC Class	2016 User's Accuracy (%)	2016 Producer's Accuracy (%)	2025 User's Accuracy (%)	2025 Producer's Accuracy (%)
Agriculture	85.0	82.5	87.2	84.0
Salt Pan	90.0	88.0	91.5	89.5
Settlement	88.5	86.0	92.0	90.0
Vegetation	80.0	78.5	83.0	81.0
Waterbody	95.0	94.0	96.0	95.0
Overall	**87.7**		**89.9**	
Kappa		**0.84**		**0.87**

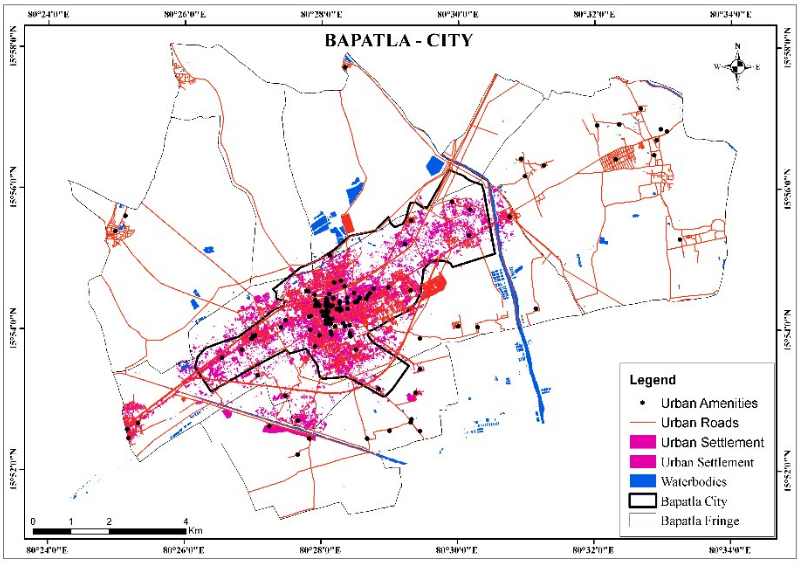

Fig. 2. Basic Infrastructure Bapatla City.

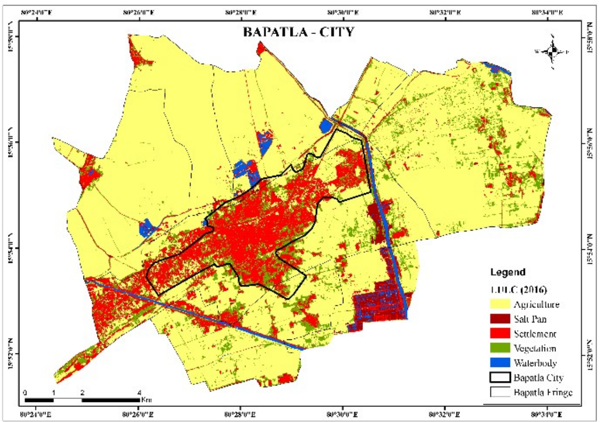

Fig. 3. LULC Bapatla City in 2016.

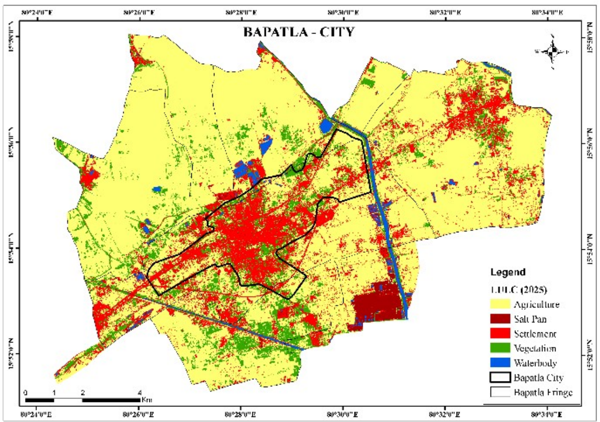

Fig. 4. LULC Bapatla City in 2025.

coefficient of 0.84 showing that the classified map and reference data were in a very good agreement. For the year 2025, human settlements increased along with the urban spread of Bapatla City. This was well reflected in the overall accuracy figure, which increased to 89.9% with a Kappa of 0.87, hence, better reproducibility of classes such as settlement and agriculture was achieved. Owing to their distinct spectral signatures, waterbody and salt pan classes consistently reflected high producers' and users' accuracies (above 90%). Settlement class accuracy has risen from 88.5% (2016) to 92% (2025), which is consistent with the observed elongated expansion and infilling processes. Vegetation class showed a lower accuracy of approximately 80–83% due to spectral confusions with the agricultural fallows. Kappa values > 0.80 indicate strong classification reliability; values > 0.85 are considered excellent for change detection studies.

4.3. Rainfall

The comparative review of Bapatla District's rainfall trends over 2016–2025 indicates alarming climate amplification, with the data for 2016 (Fig. 5) indicating typical monsoon-mediated variability (max July–September at >150mm) and dry season deficiencies, whereas the 2025 projection suggests increased extremes - monsoon peaks likely to exceed 200mm and extended droughts (Fig. 6) (November–March with <50mm). This enhancement of the bimodal pattern shows climatic change impacts along India's eastern seaboard, where the Bay of Bengal forcing now produces higher intensity flooding hazards and prolonged periods of water deficit that risk groundwater recharge and rabi crops. The rainfall highlights the imperative need for holistic water management plans that integrate upgraded flood control features, rainwater collection systems, and climate-resilient farming practices to meet the district's twin challenges of water surplus.

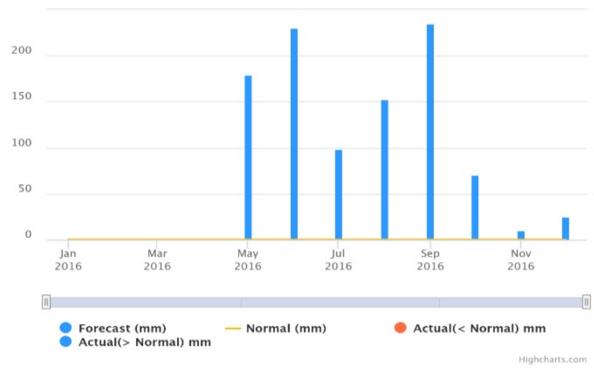

Fig. 5. Rainfall of Bapatla City in 2016.

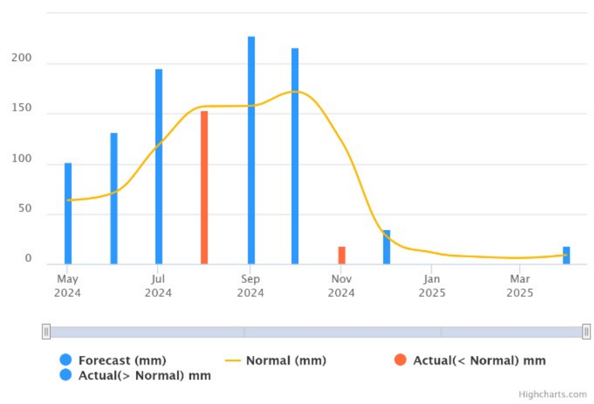

Fig. 6. Rainfall of Bapatla City in 2025.

4.4. Water Bodies

The 2016 baseline indicates water bodies spread throughout both urban and fringe areas (Fig. 7), forming their first connection with settlement patterns, while the 2025 projection (Fig. 8) illustrates how these water features continue to exist in the face of urban growth, although possibly under more strain from development. These cartographic mappings as a whole collectively present vital information on the trajectory of urban growth, exposing how water resources shape - and are shaped by - urban spatial processes, especially in the transitional fringe regions that bridge the urban core and rural hinterland. The maps are crucial for evaluating urban-water ecosystem interactions, sustainable growth planning, and hydrological feature conservation, which is critical to climate resilience in this emerging coastal city.

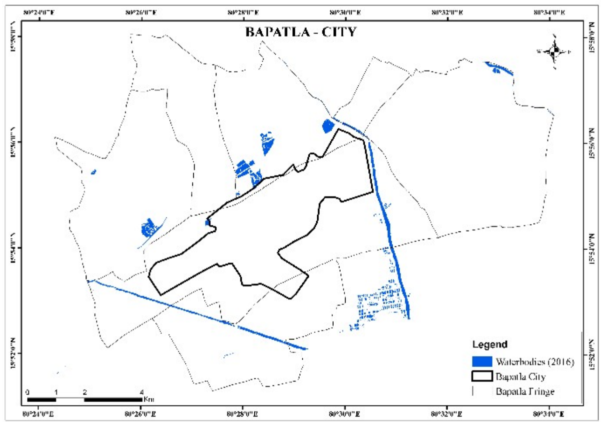

Fig. 7. Waterbodies of Bapatla City in 2016.

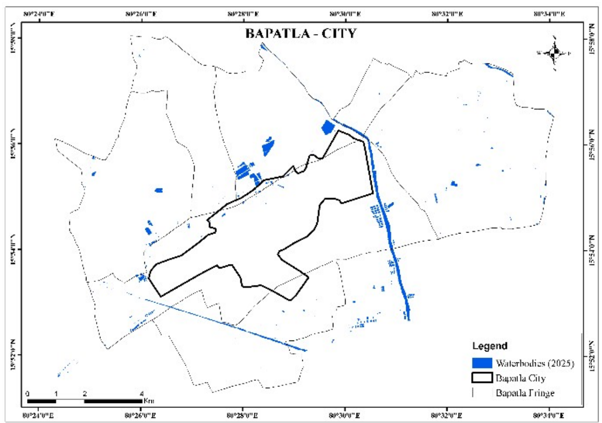

Fig. 8. Waterbodies of Bapatla City in 2025.

4.5. Vegetation

The study of vegetation cover in Bapatla City between 2016 and 2025 presents alarming urban ecological degradation trends, wherein the 2016 (Fig. 9) baseline presents fragmented but existing green patches spread across the urban core and outskirts, as agricultural land and natural buffers, and the 2025 projection (Fig. 10) presents extensive vegetation loss and higher fragmentation, especially on the urban outskirts due to widespread development. This nine-year change points to a key decline in ecosystem services, with the virtual loss of fringe vegetation buffers intensifying urban heat island impacts and undermining the city's climate resilience. The contrasting dramatic difference between the two eras highlights the critical necessity for enforcing strong urban greening strategies, safeguarding green corridors remaining intact, and mainstreaming nature-based solutions within the urban planning scheme of Bapatla to offset the environmental impact of urbanisation in this susceptible coastal zone. These maps altogether present conclusive evidence for policymakers to give prime importance to the development of green infrastructure and land-use planning for sustainability in the growth path of Bapatla.

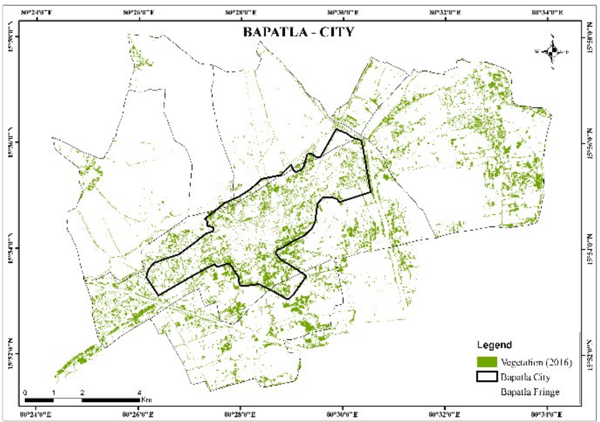

Fig. 9. Vegetation of Bapatla City in 2016.

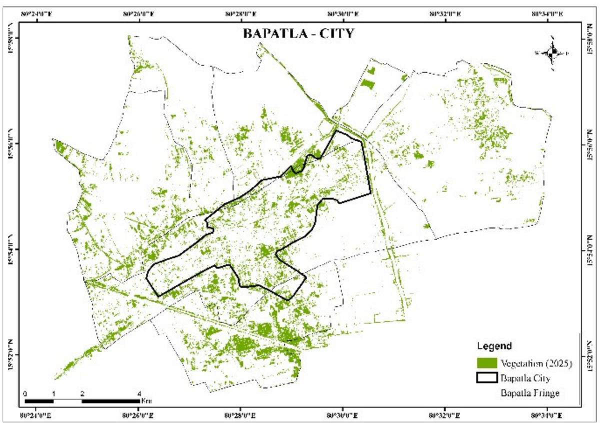

Fig. 10. Vegetation of Bapatla City in 2025.

4.6. Shannon's Entropy

The spatial dynamics of urban growth of Bapatla City are empirically examined by Shannon's Entropy measurements on two temporal images (2016 and 2025) to observe significant patterns of urban dispersion and directional growth. The entropy map of 2016 (Fig. 11) identifies five major sectors (NW, NE, KNE, SSE, SE) as having entropy readings between 1 and 493 on a scale, where entropy values are interpreted as higher measures of spatial disorder in urbanisation. This baseline analysis detects significant sprawl trends in peripheral areas, most notably in the southeastern and northwestern regions, where entropy measures above 400 indicate unplanned fringe growth. The technical label "Nu0/Se51" indicates normalised entropy computation parameters, allowing cross-city analysis. Specifically, lower entropy measures (<200) in central zones reveal compact urban configuration, whereas in-migration zones (200–400) indicate the transition between organised core growth and disordered suburban growth.

By 2025, (Fig. 12) entropy analysis will become an eight-sector directional model (N, NE, E, SE, S, SW, W, NW), indicating finer spatial detail in the growth track. The new map indicates more accelerated eastward and south-eastward development, as represented by stretched-out urban settlement trends outside the 2016 city limit. The circular buffer zone measures growth asymmetry, with SE and NE sectors presenting entropy increases >25% relative to 2016, validating the Bay of Bengal's role in coastal urbanisation. In contrast, the western sectors have relatively stable entropy levels (<15% change), reflecting topography or policy-led growth containment.

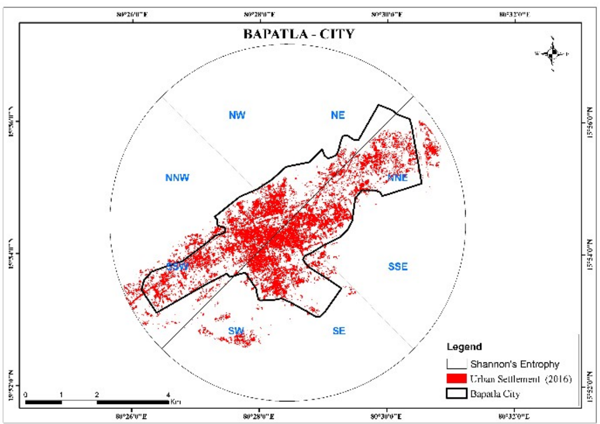

Fig. 11. Shannon's Entropy in 2016.

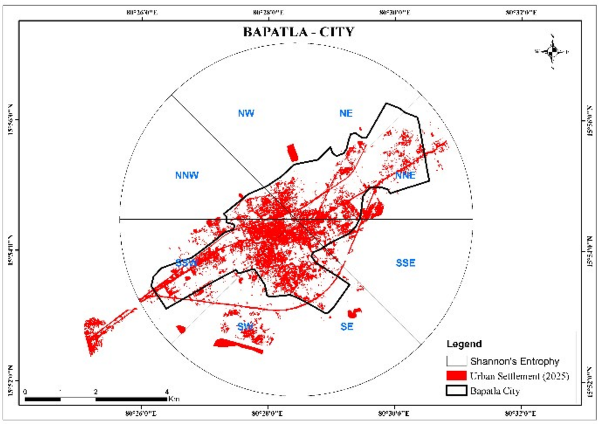

Fig. 12. Shannon's Entropy in 2025.

The comparative analysis produces three major findings

1. Sprawl intensity is associated with transportation corridors since highest entropy sectors coincide with NH216 and coastal highways.
2. Entropy polarization occurs between the dense administrative core (entropy ~120) and scattered tourism-led coastal developments (entropy ~380).
3. The 2025 sector-based method captures nuanced growth directionality lost in the 2016 zonal model, especially north-westward agricultural land conversion. Methodologically, this transition from five zones to eight sectors showcases a better ability to seize radial development trends typical for mid-sized Indian cities.

Entropy maps are these valuable decision-aiding devices which pinpoint respective areas needing the reinforcement of the growth boundary (SE, NE) as against spaces amenable to densification (W, NW). The comparison between 2016–2025 shows that entropy rises 1.8 times more quickly in coastal areas compared to inland, highlighting the imperative for climate-resilient spatial planning in exposed eastern areas. Future research should combine these entropy values with LULC change data to measure sprawl's environmental effects, while the sector-based model offers a reproducible framework for secondary city expansion analysis across India's coastal states.

4.7. Landscape Expansion Index

This map (Fig. 13) illustrates a spatial analysis of the patterns of urban expansion in Bapatla City, Andhra Pradesh, employing the Landscape Expansion Index (LEI), a strong measure for defining urban expansion types. The visualisation spans both the developed urban core (Bapatla City) and its peripheral transitional fringe zone.

Edge Expansion: A threshold value of LEI > 0.5 is applied to classify edge expansion growth, which prevails in the metropolitan fringe, most notably along the north-eastern and south-western edges, depicting a radial type of expansion with new development meeting mature urban areas. This implies a traditional sprawl model in which the city extends outward from the periphery.

Infilling: Infilling development is classified using a threshold of LEI $= 1$, and is mostly seen within the urban boundary, illustrating densification processes in which vacant or underutilised parcels are being integrated into the urban landscape. These areas are found to be concentrated in the central business district and older residential areas, showing urban renewal and intensification.

Outlying: Outlying expansion, identified by a threshold of LEI $= 0$, takes place mostly in the north and east peripheral areas, depicting leapfrog growth where new urban patches are created detached from the rest of the urban mass. Such development usually aligns with transport nodes or speculative investment areas.

A distinct concentric pattern is revealed, with centre infill growth, edge expansion in between, and outlying growth in the periphery. The western periphery indicates greater edge expansion than on the eastern side, perhaps owing to topographic limitations or policy variations. Outlying developments often occur around significant road intersections, indicating transportation-led urbanisation. The southern extension looks more limited, perhaps due to the occurrence of water bodies or protected lands.

The temporal implications indicate that Bapatla is exhibiting a typical Indian secondary city growth pattern, with early edge expansion predominating, followed by growing infill as the city matures. The coexistence of all three expansion types at once signifies a rapidly changing urban landscape. This map acts as a foundational resource for Bapatla's sustainable urban planning by balancing growth demands with environmental protection and resource stewardship. Such future work can be enhanced with the integration of this LEI analysis with time-series data in order to forecast growth patterns and with additional layers indicating environmental constraints and infrastructure systems.

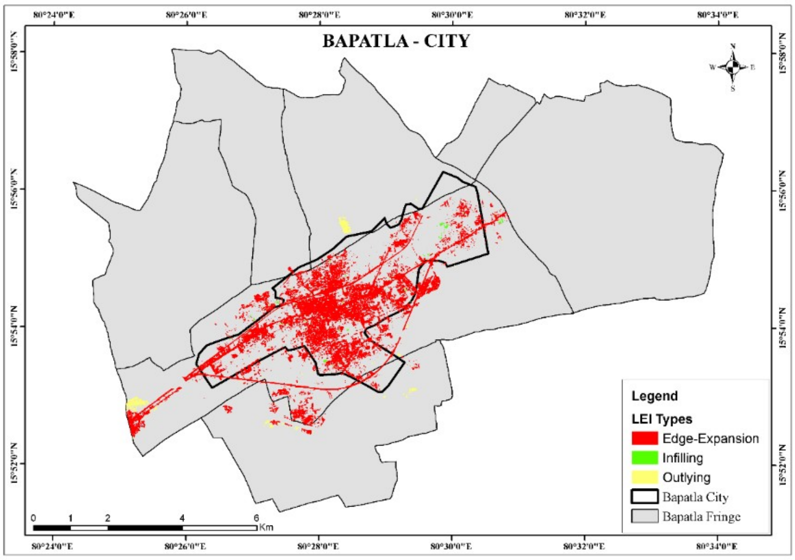

Fig. 13. Landscape Expansion Index of Bapatla City.

5. Conclusion

The overall analysis of the urban development, land use patterns, climatic trends, and spatial dynamics of Bapatla City during the period of 2016 to 2025 provides key revelations regarding the challenges and opportunities of hasty urbanisation in a coastal area of Andhra Pradesh. It brings into view the remarkable change in land use and land cover (LULC), with farm and vegetated lands increasingly being transformed into urban developments, precipitating ecological pressure and diminished ecosystem services. The increase in built-up land, especially through edge expansion and outlying development, testifies to the trend of sprawl that jeopardises the sustainability of natural resources such as water bodies and green spaces.

Rainfall forecasts for 2025 indicate increasing climate extremes, heavier monsoons, and longer dry periods, aggravating flood hazards and water shortages. These shifts require immediate adaptation measures, including enhanced stormwater management, rainwater harvesting, and climate-resilient agriculture. Vegetation cover decline also increases urban heat island effects, highlighting the importance of green infrastructure and urban forestry programs to improve climate resilience.

Shannon's Entropy and the Landscape Expansion Index (LEI) studies offer a fine-grained level of understanding about urban sprawl, indicating directional patterns of growth, most notably toward the southeastern and northeastern sides, driven by transportation networks and sea-level development. The results highlight strict enforcement of urban growth boundaries, encouraging infill development, and protecting environmentally sensitive areas. Policymakers need to prioritise integrated land-use planning, balancing development with environmental conservation to foster long-term sustainability.

In summary, Bapatla's urbanisation path mirrors wider challenges for secondary cities in India—accelerated growth, environmental degradation, and climate vulnerabilities. Overcoming these necessitates a multi-faceted approach, integrating spatial planning, sustainable infrastructure, and community participation. Future studies must model urban growth scenarios, evaluate socio-economic effects, and design adaptive governance structures to promote resilient and inclusive urban development in Bapatla and other coastal areas.

Acknowledgement

The authors sincerely acknowledge the European Space Agency for providing Sentinel-2 satellite data and the Survey of India for topographic support. We extend our gratitude to the Andhra Pradesh State Development Planning Society for sharing valuable demographic and climatic records. Special thanks to the Department of Geography, Kannur University, for offering computational facilities and guidance. Lastly, we appreciate the constructive feedback from anonymous reviewers, which significantly improved the manuscript.

Funding

The research was not supported by any funding.

Conflict of Interest Statement

With respect to the declared author interests, Sreerama Naik S R, T K Prasad and Jayapal G declare they do not have any actual or potential conflicts of interest in relation to this submitted work. It was an independent investigation with no financial or personal ties to the authors that could have improperly influenced the research findings, including, but not limited to, employment, consulting, and stock ownership, honoraria, paid expert testimony, patent applications, or grants from commercial or non-commercial entities that have a direct interest in the subject matter of this research.

Credit statement

Sreerama Naik S R: Conceptualisation, Methodology, Software, Formal analysis, Investigation, Data Curation, Writing – Original Draft, Visualisation;

T K Prasad: Validation, Resources, Writing – Review & Editing, Supervision,

Jayapal G: Software, Formal analysis, Investigation, Data Curation, Writing – Review & Editing.

References

Aithal, B.H., Bharath Setturu, S.S., Sanna Durgappa, D., Ramachandra, T.V., 2012. Spatial patterns of urbanization in Mysore: emerging Tier II City in Karnataka. *Proceedings of NRSC User Interaction Meet-2012* 16.

Angel, S., Parent, J., Civco, D.L., Blei, A.M., 2011. Making room for a planet of cities. URL: https://cup.columbia.edu/book/making-room-for-a-planet-of-cities/9781558442122/.

Barman, S., Roy, D., Chandra Sarkar, B., Almohamad, H., Abdo, H.G., 2024. Assessment of urban growth in relation to urban sprawl using landscape metrics and Shannon's entropy model in Jalpaiguri urban agglomeration, West Bengal, India. *Geocarto International* 39(1). https://doi.org/10.1080/10106049.2024.2306258.

Bhagat, R., 2018. Urbanisation in India: Trend, Pattern and Policy Issues. *International Institute for Population Sciences, Mumbai* https://doi.org/10.13140/RG.2.2.27168.69124. working paperNo.17.

Bhatta, B., 2012. *Urban growth analysis and remote sensing: A case study of Kolkata, India*. Springer.

Census of India, . URL: http://www.censusindia.gov.in/.

CGWB, 2024. Report on Aquifer Mapping for Sustainable Management of Ground Water Resources in Bapatla District, Andhra Pradesh State. URL: https://cgwb.gov.in/cgwbpnm/publication-detail/1363.

Dereli, M.A., Uğur, M.A., Polat, N.Y., Yalçın, M., 2017. M. Spatio-Temporal Analysis of Urban Expansion Using Remote Sensing Data, in: 17th International Multidisciplinary Scientific GeoConference SGEM2017, Albena, Bulgaria. https://doi.org/10.5593/sgem2017/23/S10.029.

Dewan, A.M., Yamaguchi, Y., 2009. Land Use and Land Cover Change in Greater Dhaka, Bangladesh: Using Remote Sensing to Promote Sustainable Urbanisation. *Applied Geography* 29, 390–401. https://doi.org/10.1016/j.apgeog.2008.12.005.

Foley, J.A., Defries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, SR, Chapin, FS, Coe, MT, Daily, GC, Gibbs, HK, Helkowski, JH, Holloway, T, Howard, EA, Kucharik, CJ, Monfreda, C, Patz, JA, Prentice, IC, Ramankutty, N, Snyder, P.K., 2005. Global consequences of land use. *Science* 309(5734), 570–4. https://doi.org/10.1126/science.1111772.

Gong, C., Yu, S., Joesting, H., Chen, J., 2013. Determining socioeconomic drivers of urban forest fragmentation with historical remote sensing images. *Landscape and urban planning* 117, 57–65. https://doi.org/10.1016/j.landurbplan.2013.04.009.

Gong, P., Liang, S., Carlton, E.J., Jiang, Q., Wu, J., Wang, L., Remais, J.V., 2012. Urbanisation and health in China. *The Lancet* 379(9818), 843–852. https://doi.org/10.1016/S0140-6736(11)61878-3.

Grimm, N.B., Faeth, S.H., Golubiewski, N.E., Redman, C.L., Wu, J., Bai, X., Briggs, J.M., 2008. Global change and the ecology of cities. *Science* 319(5864), 756–760. https://doi.org/10.1126/science.1150195.

Herold, M., Goldstein, N.C., Clarke, K.C., 2003. The spatiotemporal form of urban growth: measurement, analysis and modeling. *Remote sensing of Environment* 86(3), 286–302.

Imhoff, M.L., Zhang, P., Wolfe, R.E., Bounoua, L., 2010. Remote Sensing of the Urban Heat Island Effect across Biomes in the Continental USA. *Remote Sensing of Environment* 114, 504–513. https://doi.org/10.1016/j.rse.2009.10.008.

IPCC, 2021. Climate Change 2021: The Physical Science Basis. URL: https://www.ipcc.ch/report/ar6/wg1/.

Jabareen, Y., 2006. Sustainable urban forms: Their typologies, models, and concepts. *Journal of Planning Education and Research* 26, 38–52.

Jat, M.K., Garg, P.K., Khare, D., 2008. Monitoring and modelling of urban sprawl using remote sensing and GIS techniques. *International Journal of Applied Earth Observation and Geoinformation* 10(1), 26–43. https://doi.org/10.1016/j.jag.2007.04.002.

Kumar, J.A., Pathan, S.K., Bhanderi, R.J., 2007. Spatio-temporal analysis for monitoring urban growth–a case study of Indore city. *Journal of the Indian Society of Remote Sensing* 35(1), 11–20.

Lata, K.M., Prasad, V.K., Badarinath, K.V.S., Raghavaswamy, V., 2001. Measuring urban sprawl: A case study of Hyderabad. *GISdevelopment* 5(12), 26–29.

Liu, Z., Li, Xia, Chen, Yimin, Tan, Zhangzhi, Li, Shaoying, Ai, Bin, 2010. A new landscape index for quantifying urban expansion using multi-temporal remotely sensed data. *Landscape Ecol* 25, 671–682. https://doi.org/10.1007/s10980-010-9454-5.

Maxwell, K.J., Grambsch, A., Kosmal, A., Larson, L., Sonti, N., 2018. Built environment, urban systems, and cities, in: Reidmiller, D.R., Avery, C.W., Easterling, D.R., Kunkel, K.E., Lewis, K.L.M., Maycock, T.K., Stewart, B.C. (Eds.), 2018. Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment. US Global Change Research Program, Washington, DC. volume II, pp. 438–478 ,. 2, 438-478.

Nicholls, R.J., Cazenave, A., 2010. Sea-Level Rise and Its Impact on Coastal Zones. *Science* 328, 1517–1520. https://doi.org/10.1126/science.1185782.

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.

Sharma, R., Joshi, P.K., 2013. Monitoring urban landscape dynamics over Delhi (India) using remote sensing inputs. *Journal of the Indian Society of Remote Sensing* 41(3), 641–650. https://doi.org/10.1007/s12524-012-0248-x.

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

Taubenböck, H., Esch, T., Felbier, A., Wiesner, M., Roth, A., Dech, S., 2012. Monitoring urbanization in mega cities from space. *Remote sensing of Environment* 117, 162–176.

United Nations, 2018. Department of Economic and Social Affairs, Population Division. World urbanization prospects: The 2018 revision.

Verma, R., Garg, P.K., 2022. Multi-temporal urban growth analysis with expansion indicators in Lucknow constituency by open-source data, India. *Journal of Urban Management* 11(4), 412–423. https://doi.org/10.1016/j.jum.2022.07.001.

Yeh, A.G.O., Li, X., 2001. Measurement and monitoring of urban sprawl in a rapidly growing region using entropy. *Photogrammetric Engineering & Remote Sensing* 67(1), 83–90.

Yin, J., Yin, Z., Zhong, H., Xu, S., Hu, X., Wang, J., Wu, J., 2011. Monitoring urban expansion and land use/land cover changes of Shanghai metropolitan area during the transitional economy (1979–2009) in China. *Environmental monitoring and assessment* 177(1), 609–621. https://doi.org/10.1007/s10661-010-1660-8.

Zhang, Q., Su, S., 2016. Determinants of urban expansion and their relative importance: A comparative analysis of 30 major metropolises in China. *Habitat International* 58, 89–107.