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SPATIOTEMPORAL DYNAMICS OF URBAN SPRAWL IN VARANASI: SHANNON ENTROPY AND GIS APPROACH

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Abstract

In India's fast expanding cities, urban sprawl has become a major problem that has drastically changed land use, ecological balance, and urban sustainability. Through the integration of multi-temporal Landsat imagery, census data, and GIS-based analytical techniques, this study investigated the spatiotemporal dynamics of urban expansion in Varanasi between 1990 and 2020. A nearly threefold increase in built-up area was found through supervised classification, mostly at the expense of agricultural land. Decadal change detection revealed that urbanization was constant throughout all time periods, with 1990–2000 seeing the biggest shift. Growing Shannon's entropy values (0.62 in 1990 to 0.89 in 2020) quantitatively confirmed the trend of built-up growth shifting from a compact, core-centered pattern to a dispersed peri-urban form, as shown by zonal analysis. Concerns regarding land sustainability, ecological resilience, and future urban planning are raised by the findings, which verify Varanasi's shift towards unplanned, fragmented sprawl. This study's integrated remote sensing, GIS, and entropy-based framework offers a trustworthy method for evaluating sprawl dynamics and crucial information for urban planners and policymakers.

Keywords: *Urban Sprawl, Varanasi, GIS, Remote Sensing, Shannon's Entropy*

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1. INTRODUCTION

One of the most urgent issues facing the modern urbanization process is urban sprawl, especially in developing nations like India where cities are growing at previously unheard-of rates (Verma & Garg, 2021; Chettry, 2022a). The urban environment and land resources are under tremendous strain due to a combination of socioeconomic changes, rapid population growth, and rising rural-to-urban migration (Chettry, 2022b; Gogoi & Debbarma, 2025). Unchecked growth frequently results in wasteful land use, agricultural encroachment, ecological resource loss, and a decline in urban life quality (Das & Angadi, 2021; Biswas et al., 2025). Therefore, it is crucial for sustainable urban planning and policy-making to comprehend the trends, causes, and effects of urban sprawl (Ahuja et al., 2022; Mishra & Deshmukh, 2024). An exceptional setting for researching these dynamics is provided by Varanasi, one of the world's oldest surviving cities and a significant center of culture, religion, and commerce (Dutta & Banerjee, 2024; Singh et al., 2023). It is a representative case for examining the spatiotemporal features of urban growth in medium-sized Indian cities due to its unchecked land use change, peri-urban expansion, and ongoing population growth (Banerjee & Dutta, 2024; Devi, 2024). It is now feasible to systematically evaluate urban sprawl over time and across space thanks to developments in geospatial technologies like remote sensing and GIS, as well as analytical models like Shannon's entropy. This provides a scientific basis for well-informed decision-making (Das & Angadi, 2021; Ahuja et al., 2022).

A more comprehensive historical and socioeconomic backdrop that explains the city's growth trajectory forms the basis of the study of Varanasi's urban sprawl. Varanasi, which is located beside the Ganga River, has long been a hub for trade, culture, and religion, drawing visitors from all over the nation and abroad. Infrastructure development, educational institutions, industrial establishments, and growing commercial activities have all contributed to the city's increased urbanization over the past three decades. Population growth, which increased from about 1.1 million in 1991 to over 1.6 million by 2011, has further contributed to this growth, with forecasts indicating even more dramatic increases in the decades that follow (Chettry, 2022a). Land use conversion, particularly the conversion of productive agricultural land into residential colonies, commercial centers, and informal settlements, is a manifestation of the pressure to accommodate this population (Mishra & Deshmukh, 2025). Varanasi is an example of unplanned and fragmented development that spreads unevenly into peri-urban areas, in

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contrast to metropolitan cities like Delhi or Mumbai where urban growth is comparatively better managed (Chettry, 2022b; Gogoi & Debbarma, 2025). Such expansion calls into question the viability of current urban governance structures in addition to causing worries about environmental degradation and food security (Biswas et al., 2025; Saha et al., 2024). In light of this, it is crucial to examine the temporal and spatial trends of Varanasi's urban sprawl. Entropy models, GIS-based spatial analysis, and multi-temporal satellite imagery provide the methodological foundation for capturing these changes, measuring the extent of sprawl, and providing insights into the underlying processes influencing the city's transformation (Banerjee & Dutta, 2024; Tiwari & Kumar, 2025).

The objectives of the Study are given below:

- To analyze the spatiotemporal changes in land use/land cover (LULC) of Varanasi between 1990 and 2020 using multi-temporal satellite imagery.
- To quantify the decadal rate and magnitude of urban expansion and its impact on agricultural and ecological land covers.
- To examine the spatial distribution and dispersion of built-up areas across concentric zones from the city center.
- To measure and interpret the degree of urban sprawl using Shannon’s entropy model for different time periods.

2. LITERATURE REVIEW

Dutta and Banerjee (2024) examined the spatio-temporal dynamics of urban sprawl in the Varanasi Planning Region through the utilization of multi-temporal satellite imagery and GIS methodologies (Dutta & Banerjee, 2024). Their research showed that the city had grown quickly and without planning over the past thirty years, mostly at the expense of farmland. They showed how socioeconomic factors and infrastructure development sped up the growth of built-up areas, with peri-urban areas becoming new hot spots for growth. The study showed that urbanization is not a smooth process and stressed the need for long-term planning in old cities like Varanasi.

Singh, Nathawat, and Delhi (2023) used multi-temporal remote sensing data and geospatial techniques to figure out the different kinds and amounts of urban growth in Varanasi. Their results showed that urban growth was not only ongoing but also becoming more spread out,

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which changed how land was used and put pressure on natural resources (Singh, Nathawat, & Delhi, 2023). By classifying the types of urban growth, they showed how Varanasi went from compact development to fragmented sprawl patterns. The study also confirmed that built-up growth happened more in peri-urban areas, which led to the loss of fertile cropland and natural areas.

Verma and Garg (2021) utilized satellite datasets and GIS-based analysis to investigate spatio-temporal urban dynamics in eleven smart cities in Uttar Pradesh, including Varanasi. Their research revealed substantial urban expansion in all chosen cities, with Varanasi distinguished by its unplanned and land-intensive development. The authors observed that demographic pressures and migration were significant catalysts of the transformation, with urbanized land consistently supplanting agricultural zones (Verma & Garg, 2021). Their work put Varanasi in a bigger context, which helped us understand how medium-sized historic cities in the state were having trouble finding a balance between modernization and sustainability.

Das and Angadi (2021) assessed urban sprawl in the Barrackpore sub-divisional region of India utilizing landscape metrics and Shannon's entropy model. Their research illustrated how entropy can accurately measure the extent of dispersion in urban areas over time. The results showed that sprawl followed a broken and scattered pattern, mostly because of population growth and poor planning controls (Das & Angadi, 2021). The study was mainly about Barrackpore, but it gave good methodological advice by using entropy-based models to compare urban compactness and dispersion. This was very useful for studies of cities like Varanasi.

Ahuja, Kumari, and Somvanshi (2022) examined the urban growth patterns of Dehradun City utilizing Shannon's entropy methodology in conjunction with geospatial tools. Their research showed how the city's growth changed from dense development to urban sprawl, especially in areas near the city (Ahuja, Kumari, & Somvanshi, 2022). The research illustrated the utility of entropy values in assessing sprawl intensity and established a systematic framework for monitoring spatial transformations over time. Even though the case study was in a different part of the world, the way it was done was very similar to how it was done in Varanasi, which showed that using entropy-based analysis to look at urban growth is reliable.

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3. STUDY AREA

One of the world's oldest continuously inhabited cities, Varanasi is known as the "spiritual capital of India" and has great historical, cultural, and religious significance. The city, which is situated on the left bank of the Ganga River and is in the eastern region of Uttar Pradesh, India, is greatly influenced by the sociocultural and economic life of the region.

Figure 1: Location Map of Varanasi District, India

Source: BurningCompass (2025)

Varanasi is roughly 250 km² in size, spanning both the densely populated urban core and the quickly changing peri-urban fringes. It is located between latitudes 25°10′N to 25°25′N and longitudes 82°50′E to 83°05′E. With major roads and rail networks connecting it, it serves as the administrative center of Varanasi district and is a major hub for trade, commerce, and education in eastern Uttar Pradesh.

Over the past few decades, the city's population has steadily increased, placing strain on its natural resources and land. Varanasi's population grew from roughly 1.1 million in 1991 to

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over 1.6 million in 2011, according to the Indian Census, and future growth is expected to continue. Rapid urbanization has been fueled by this expansion, as well as an increase in economic activity and migration from rural hinterlands. A large portion of this expansion has been brought about by the transformation of open green spaces and productive agricultural land into residential colonies, business complexes, and infrastructure projects.

Varanasi is a perfect case study for examining the dynamics of urban sprawl because of its distinctive fusion of its ancient heritage and contemporary urban pressures.

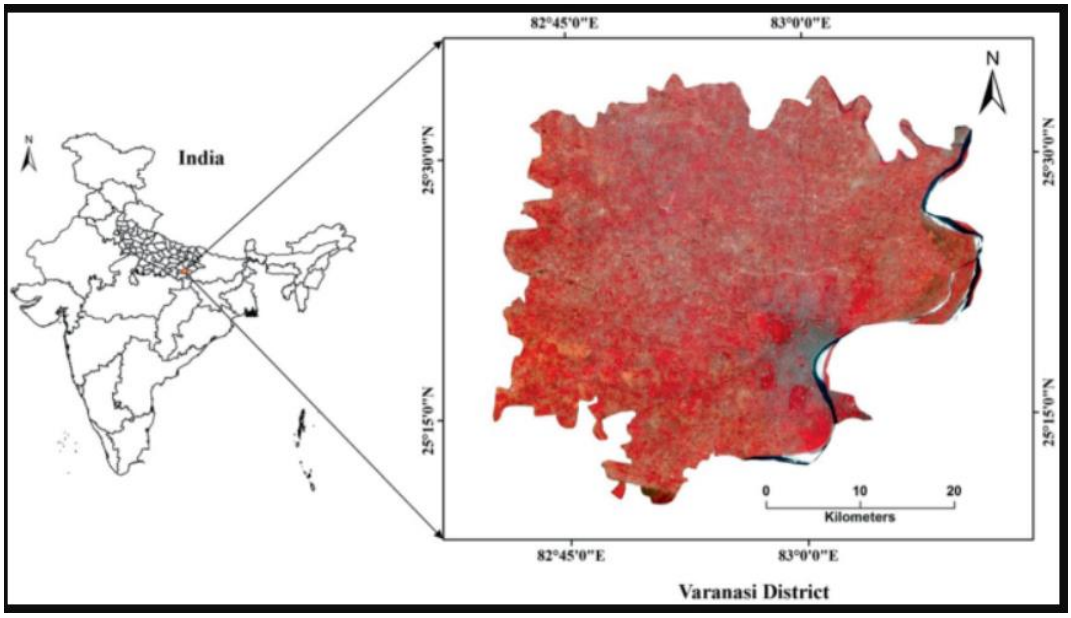

Figure 2: Varanasi with Concentric Zones

Source: Mishra (2022)

The analysis focuses on the core and peri-urban area within the district, which for methodological purposes, was divided into ten concentric zones radiating from the city center, as shown in Figure 2.

The city is a prime example of how India's traditional urban centers are changing spatially, with modernization frequently coming at the expense of land sustainability and ecological balance. Varanasi is a good example to understand the larger issues of spatiotemporal urban expansion in historic Indian cities because of its dual nature of rapid urban transformation and cultural preservation.

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Varanasi's geographic, demographic, and cultural traits draw attention to the increasing conflict between environmental sustainability and urban growth. The study offers deeper insights into how India's historic cities are changing under the strain of contemporary urbanization by placing the analysis within this particular socio-spatial context.

4. DATA AND METHODOLOGY

Combining multi-temporal satellite imagery, census data, and sophisticated geospatial tools was necessary to comprehend the spatiotemporal dynamics of urban sprawl in Varanasi. A combination of remote sensing, GIS techniques, and Shannon's entropy model was applied to analyze the degree and nature of urban expansion over the past three decades. The methodology was created to guarantee accuracy, consistency, and comparability across time periods.

4.1.Data Used

The study utilized both primary (satellite imagery) and secondary (census and municipal records) data sources. The details of the datasets used are presented in **Table 1**.

Table 1: Data Sources and Specifications

Data Type	Source	Sensor/Version	Year(s) Used	Resolution/Scale	Purpose
Satellite Imagery	USGS Earth Explorer	Landsat TM, ETM+, OLI	1990, 2000, 2010, 2020	30 m	Land use/land cover classification
Census Data	Census of India	-	1991, 2001, 2011	District level	Population and demographic trends
Land Use Maps	Varanasi Municipality	-	2000, 2010	1:25,000	Validation and reference

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Google Earth Images	Google Earth Pro	High-resolution	2010, 2020	< 5 m	Accuracy assessment and visual check

The satellite datasets provided temporal coverage of three decades, while census data offered insights into population pressure that influenced spatial growth.

4.2.Software Tools

GIS software and remote sensing were combined. ERDAS Imagine was used to pre-process and classify images. Entropy zone creation, digitization, and spatial analysis were done using ArcGIS 10.8 and QGIS. Entropy calculations and statistical calculations were supported by Microsoft Excel.

4.3.Image Pre-processing

In order to reduce atmospheric distortions, the Landsat images were downloaded in GeoTIFF format and then atmospherically corrected using the Dark Object Subtraction (DOS) technique. To guarantee spatial consistency, each image was geo-referenced to UTM Zone 44N using the WGS-84 datum. After that, the pictures were cropped to the 250 km² or so that made up Varanasi city and its peri-urban areas.

4.4.Land Use/Land Cover (LULC) Classification

Supervised classification was carried out using the **Maximum Likelihood Algorithm (MLA)**. Four land use/land cover categories were identified:

1. **Built-up areas** (residential, commercial, industrial)
2. **Agricultural land** (cropland, fallow land)
3. **Water bodies** (rivers, ponds, tanks)
4. **Vegetation/Green cover** (forests, orchards, grassland)

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Training samples were selected for each category with the aid of high-resolution Google Earth imagery. Classification accuracy was assessed using a confusion matrix and Kappa coefficient, which yielded overall accuracies above 85% for all years considered.

4.5.Change Detection Analysis

To identify temporal and spatial changes in built-up areas between 1990, 2000, 2010, and 2020, post-classification comparison was used. Both in square kilometers and as a percentage of the entire study area, the extent of built-up expansion was computed. This made it possible to determine the patterns of land conversion as well as the rate of urbanization.

4.6.Shannon's Entropy Calculation

Shannon's entropy (H_n) was calculated for each time period in order to measure the extent of urban sprawl. To capture the gradient of urban expansion, the study area was separated into ten concentric zones that radiate outward from the city center (Dashashwamedh Ghat).

The entropy formula used was:

$$H_n = -\sum_{i=1}^{n} P_i \log P_i$$

Where:

- Pi = proportion of built-up area in the *i-th* zone,
- n = number of zones (10 in this study).

Interpretation:

- **Hn → 0:** Compact urban growth concentrated in a few zones.
- **Hn → 1:** Dispersed, fragmented growth across multiple zones.

Entropy values were calculated for each time period (1990, 2000, 2010, 2020), allowing a comparative assessment of compactness versus dispersion.

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5. ANALYSIS AND RESULTS

Significant changes in land use and the extent of urban sprawl were found during the 1990–2020 study period in Varanasi, according to the spatiotemporal analysis. The findings demonstrated the extent and trend of urban growth using change detection, Shannon's entropy model, and satellite-derived LULC classifications.

5.1. Land Use/Land Cover Changes (1990–2020)

The land use classifications showed a progressive increase in built-up areas, mainly at the expense of agricultural land.

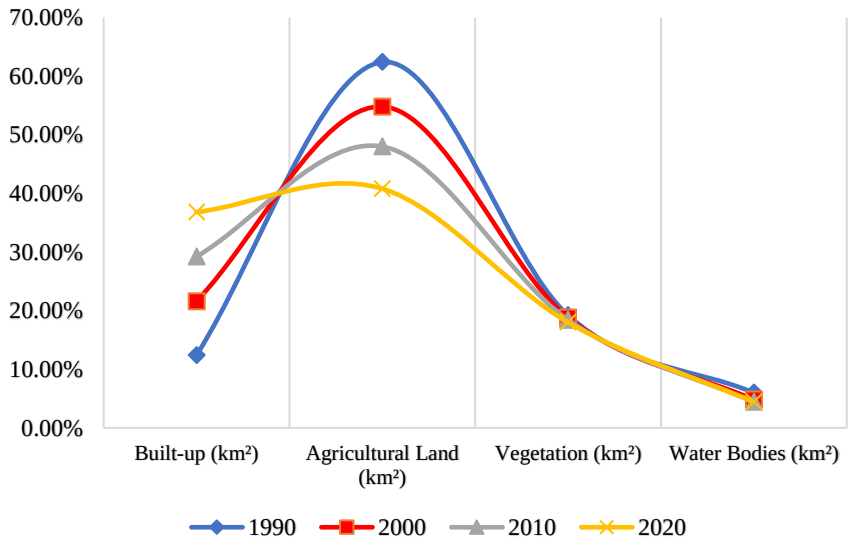

Figure 3: Land Use/Land Cover Distribution in Varanasi (1990–2020)

Urban expansion nearly tripled over three decades, as evidenced by the LULC analysis, which showed a sharp increase in built-up area from 31.0 km² (12.4%) in 1990 to 92.0 km² (36.8%) in 2020. Fertile croplands were gradually transformed into urban settlements, as evidenced by the decline in agricultural land from 156.0 km² (62.4%) to 102.0 km² (40.8%), which was the main cause of this growth. Reflecting localized encroachments, vegetation cover and water bodies underwent relatively minor changes, with vegetation slightly decreasing from 48.0 km² to 45.0 km² and water bodies decreasing from 15.0 km² to 11.0 km². Overall, the table showed that Varanasi's urban growth was primarily land-intensive and agriculturally oriented, which raised questions about sustainability.

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5.2. Decadal Change in Land Use

To quantify the magnitude of transformations, decadal changes were computed. The built-up category consistently gained land, while agriculture was the most negatively affected.

Table 2: Decadal Change in Land Use (km²)

Period	Change in Built-up	Change in Agriculture	Change in Vegetation	Change in Water Bodies
1990–2000	+23.0	-19.0	-1.0	-3.0
2000–2010	+19.0	-17.0	-1.0	-1.0
2010–2020	+19.0	-18.0	-1.0	0.0
1990–2020	**+61.0**	**-55.0**	**-3.0**	**-4.0**

According to the decadal change analysis, the period between 1990 and 2000 saw the greatest urban expansion, with built-up areas growing by 23.0 km² and agriculture declining by 19.0 km². Outward sprawl started during this time due to early infrastructure development and growing population density. The built-up area grew steadily over the next few decades, increasing by 19.0 km² in 2000–2010 and 2010–2020, respectively. Throughout all decades, agriculture continuously lost land; from 1990 to 2020, the total decline was 55.0 km². Marginal losses of 4.0 km² and 3.0 km² were observed in water bodies and vegetation, respectively. This table demonstrated that Varanasi's urban growth was steady and uninterrupted throughout all decades, with agriculture continuing to be the most susceptible land cover type.

5.3. Zonal Distribution of Built-up Areas

The division of the city into **10 concentric zones** helped capture the spatial dispersion of built-up land. Initially, built-up areas were concentrated within the first three zones, but later decades showed significant expansion into outer zones.

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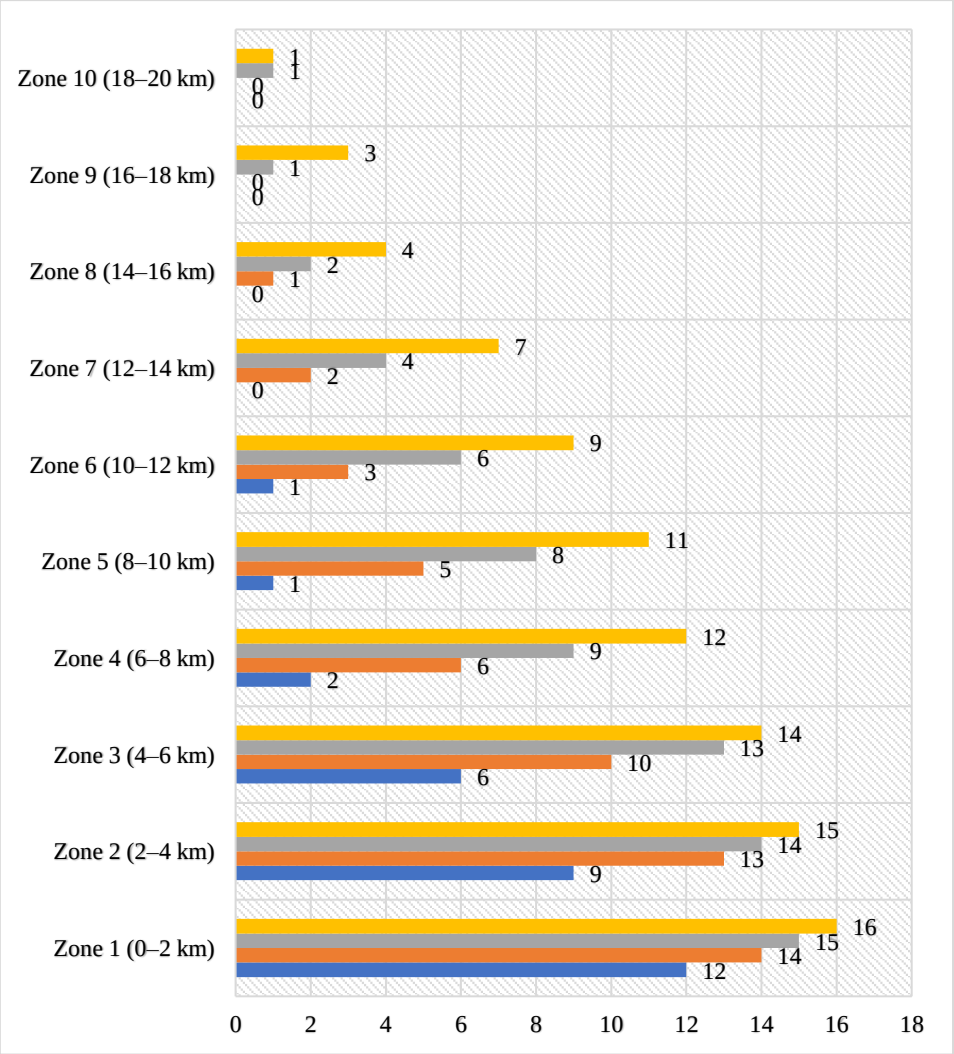

Figure 4: Zonal Distribution of Built-up Area (in km²)

The spatial distribution of urban growth was brought to light by the zonal distribution analysis. In 1990, 27.0 km² of the 31.0 km² total area was made up of built-up areas, which were primarily concentrated in the first three zones (within 6 km of the city center). However, growth began to spread into Zones 4 and 5 by 2000, marking the beginning of peri-urban expansion. Significant outward expansion into Zones 6–10 was observed in 2010 and 2020, and built-up land was first observed in the outermost zones (16–20 km). Compared to just 4.0 km² in 1990, 26.0 km² of the entire built-up area was situated outside of the core by 2020. This showed that Varanasi's growth had changed from a compact, core-centered structure to a multi-nodal, fragmented pattern, which is a classic indication of sprawl.

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5.4. Shannon's Entropy Results

The entropy values confirmed the sprawl trend.

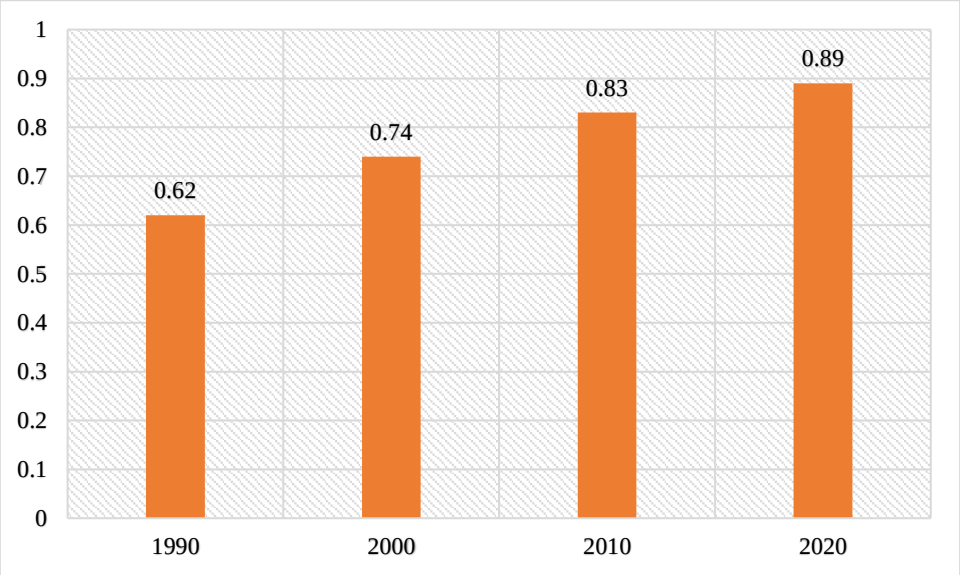

Figure 5: Shannon's Entropy Values for Varanasi (1990–2020)

The findings from zonal analysis and LULC were confirmed by the Shannon's entropy results. With an entropy value of 0.62 in 1990, the city's core appeared to be the only area experiencing relatively compact urban growth. The entropy increased to 0.74 by 2000, signaling the start of outward dispersion. A high degree of sprawl was confirmed by the 2010 (0.83) and 2020 (0.89) values, which showed that built-up areas were becoming more dispersed throughout the outer zones. The efficiency of entropy in capturing the dynamics of urban expansion was demonstrated by the steady increase in entropy over the study period, which represented a shift from a dense urban core to diffused, peri-urban sprawl.

6. DISCUSSIONS AND CONCLUSIONS

Using multi-temporal satellite imagery, GIS methods, and Shannon's entropy model, the study sought to understand the spatiotemporal dynamics of urban sprawl in Varanasi. The findings demonstrated the extent and spatial patterns of urban growth, offering important new perspectives on the changes in the city's landscape over the previous thirty years. The conclusion enumerates the main conclusions and ramifications of the study, while the discussion analyzes the trends that were noticed in light of these findings.

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6.1.Discussion

The analysis of Varanasi's urban sprawl over the past three decades revealed a clear trajectory of outward and dispersed growth, largely at the expense of agricultural land. The supervised classification and multi-temporal satellite data revealed a consistent pattern of land consumption, with built-up areas nearly tripling between 1990 and 2020. The census data shows that this trend is highly consistent with socioeconomic drivers and population growth. According to the decadal analysis, the biggest change happened between 1990 and 2000, which also happened to be the time of increased rural-to-urban migration and infrastructure development. In keeping with global trends of unplanned sprawl in quickly expanding cities, the zonal distribution also verified Varanasi's urban form shift from a compact, core-centered city to a fragmented peri-urban structure. This finding was supported quantitatively by Shannon's entropy values, which showed how well entropy works as a reliable indicator of sprawl by verifying the increasing degree of dispersion (from 0.62 to 0.89). These results are consistent with comparable research done in Indian cities like Delhi, Lucknow, and Patna, where the main victim of unchecked urban growth was agricultural land. Furthermore, despite its slight magnitude, the observed decrease in vegetation and water bodies suggests environmental ramifications such as diminished ecological resilience and amplified urban heat island effects. Entropy analysis, GIS, and remote sensing combined to provide a thorough framework for comprehending the spatiotemporal dynamics of Varanasi's urban sprawl and for offering practical advice for sustainable urban planning.

6.2.Conclusion

According to this study, Varanasi saw significant built-up growth, the loss of agricultural land, outward dispersion across peri-urban zones, and an increase in entropy values during the 1990s and 2020s. All research objectives were successfully met by the GIS and entropy-based framework, which successfully captured the pattern and magnitude of change. The results emphasize how urgently policy changes are needed to strike a balance between ecological preservation, agricultural sustainability, urban growth, and infrastructure planning. Higher-resolution datasets and socioeconomic modeling might be used in future research to improve the assessment of sprawl and encourage data-driven urban management in Varanasi.

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