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Mathematical and Geospatial Modelling of Urban Expansion Using Land Use/Land Cover Change in Jhajjar City, Haryana

Bharat Bhushan* and Surender Singh

ABSTRACT: One of the most dominant spatial processes in the transformation of land surfaces in newly emerging cities in India is urban expansion. The current research focuses on the pattern and extent of urban growth in the newly emerging city of Jhajjar, located in the state of Haryana. A mathematical and geospatial modelling technique using Land Use Land Cover (LULC) change analysis is applied to understand the pattern and extent of urban growth. Multi-temporal Landsat 8 and 9 OLI and TIRS Collection 2 Level 2 data for the years 2015, 2020, and 2025 were downloaded from the USGS Earth Explorer platform. Supervised classification using the Maximum Likelihood Classification algorithm is applied to classify the land surface into four major land cover classes, namely Built-up Area, Vegetation, Barren Land, and Water Bodies. From the analysis, it is evident that the built-up area is showing rapid growth, increasing from 3.34 km^2 (37%) in 2015 to 6.85 km^2 (76%) in 2025. Simultaneously, vegetation cover shows a sharp decline, reducing from 4.62 km^2 (51%) in 2015 to 0.69 km^2 (8%) in 2025. Moreover, the extent of water bodies and barren land also shows significant changes. Using the mathematical model, the Urban Growth Rate (UGR), Land Use Change Rate (LUCR), and Annual Expansion Rate (AER) were applied to understand urban transformation. The results indicate that the Urban Growth Rate is 105.09%, with an average annual expansion of 0.351 km^2.

Keywords: Urban expansion, Land Use/Land Cover (LULC), geospatial analysis, remote sensing, mathematical modelling, Jhajjar City.

Contents

* Corresponding author.
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1. Introduction

The urbanization process is dynamic and entails the development of urban settlements in terms of population, infrastructure, and geographical area. It does not simply imply a demographic shift from rural to urban areas, but may also be regarded as encompassing broader social, economic, and environmental changes associated with industrialization and development [1,2]. Recent decades have been characterized by an accelerated pace of urbanization in India due to growing economic opportunities, infrastructure development, and rural-urban migration. Consequently, urban sprawl has led to rapid growth in urban areas, resulting in significant changes in land use and land cover (LULC) patterns [3,4]. Land use/land cover analysis is essential for understanding the spatial expression of urban growth. Land cover refers to the physical and biological characteristics of the Earth's surface, including vegetation, water bodies, and built-up areas, whereas land use refers to the human utilization of these land resources [5,6,7]. LULC data helps in identifying spatial patterns, regional changes, and environmental impacts resulting from land transformation [15]. Geospatial technology, particularly Remote Sensing and Geographic Information Systems (GIS), has become essential for monitoring and analyzing urban growth. Multi-temporal satellite imagery can be used to detect changes in land cover over time, while GIS enables spatial analysis, visualization, and interpretation of urban growth patterns [8,9]. In recent years, there has been increasing interest in integrating mathematical and quantitative methods into geospatial studies. Mathematical indices can be used to measure the rate, magnitude, and intensity of urban expansion, thereby enhancing the analytical rigor of LULC-based studies. The use of statistical and mathematical tools in spatial analysis provides deeper insights into the processes and trends of land transformation [10,11]. Jhajjar City in Haryana, India, has experienced significant urbanization in recent years due to its location within the National Capital Region (NCR) and increasing development pressure. Previous studies indicate that LULC patterns in Jhajjar district have undergone substantial changes, with an increase in built-up areas and a decline in agricultural and open land [12]. Therefore, the present study aims to analyze urban expansion in Jhajjar City using a mathematical and geospatial modelling approach based on multi-temporal LULC data. The study seeks to provide a systematic understanding of the pattern, magnitude, and trends of urban growth by integrating geospatial techniques with quantitative indices.

2. Methodology

2.1. Study Area

Jhajjar City, located in the state of Haryana, India, was selected as the study area for the present investigation. The city is located in the larger influence zone of the National Capital Region (NCR) and has undergone significant spatial growth in recent times. From a geographical perspective, this district is located in the region of $28°25'$N to $28°42'$N latitude and $76°38'$E to $76°43'$E longitude. The district is flanked by Rohtak district in the north, Gurugram district in the east, and Charkhi Dadri district in the west. The region has a semi-arid climate with hot summers, moderate rainfall, and a flat terrain. The land use pattern in this region comprises agricultural land, constructed surfaces, open land, and water bodies, amongst other features. Considering its recent spatial growth and land change, Jhajjar City has emerged as a significant region for investigating land use/land cover change dynamics using geospatial and mathematical tools.

2.2. Data Sources

The present study is based on secondary satellite data acquired from the United States Geological Survey (USGS) Earth Explorer platform. Multi-temporal Landsat 8–9 OLI/TIRS Collection 2 Level-2

(C2L2) surface reflectance datasets were used to examine land use/land cover change in Jhajjar City over time. To maintain temporal consistency and ensure comparability, satellite images for three different years, 2015, 2020, and 2025, were selected from the month of March. Images were chosen on the basis of minimal cloud cover and similar seasonal conditions. All images correspond to Path 147 and Row 040, which spatially cover the study area. The selected satellite scenes were as follows: 23 March 2015- Cloud Cover: 0.00%, 04 March 2020- Cloud Cover: 0.03%, and 02 March 2025 – Cloud Cover: 0.03%. The Landsat Collection 2 Level-2 products are atmospherically corrected and provide surface reflectance data, making them suitable for land use/land cover classification and spatio-temporal urban growth analysis. The Landsat Collection 2 Level-2 products are atmospherically corrected and provide surface reflectance data, making them suitable for land use/land cover classification and spatio-temporal urban growth analysis.

2.3. Data Processing and Software

All satellite image processing, classification, and spatial analysis were carried out using ArcMap (version 10.8) with the Spatial Analyst extension. The selected Landsat scenes were first prepared for analysis through basic pre-processing operations. Since the Landsat Level-2 products are already atmospherically corrected, no additional atmospheric correction was required. The following pre-processing steps were undertaken: Band combination and layer stacking of the relevant spectral bands, Extraction of the study area using the Extract by Mask tool, and preparation of imagery for classification and visual interpretation. To improve visual discrimination of land cover features, a False Color Composite (FCC) was generated using Band 5 = Near Infrared (NIR), Band 4 = Red, and Band 3 = Green. The FCC images enhanced the contrast between vegetation, built-up areas, water bodies, and barren land, thereby facilitating more accurate training sample selection and classification. In order to enhance the map clarity and reduce the classification noise at the pixel level, post-classification smoothing techniques such as the Majority Filter and Boundary Clean were employed. To improve visual discrimination of land cover features, a False Color Composite (FCC) was generated using Band 5 = Near Infrared (NIR), Band 4 = Red, and Band 3 = Green. The FCC images enhanced the contrast between vegetation, built-up areas, water bodies, and barren land, thereby facilitating more accurate training sample selection and classification. In order to enhance the map clarity and reduce the classification noise at the pixel level, post-classification smoothing techniques such as the Majority Filter and Boundary Clean were employed.

2.4. Land Use/Land Cover Classification and Analysis Method

Land Use/Land Cover classification was carried out using the Supervised Classification method, and the algorithm used is the Maximum Likelihood Classification algorithm. Maximum Likelihood Classification is one of the most frequently used statistical classifiers in remote sensing. It is based on the assumption that the distribution of the data in each band is normally distributed. It assigns the class with the maximum probability to the pixels based on the statistical characteristics. In the context of the current research, the training data set is selected manually for four major land cover classes:

- Built-up Area
- Vegetation
- Barren Land
- Water Bodies

Training sites were selected based on visual interpretation of FCC images, satellite image characteristics, and reference support from Google Earth. This classification process was done individually for the years 2015, 2020, and 2025 to obtain similar LULC maps for the purpose of temporal analysis. After the classification process, the post-processing techniques were applied to the maps to refine the results and reduce isolated pixel effects. Finally, the classified maps were used to calculate the areas, percentages, change detection, and mathematical modeling of the urban growth.

2.5. Accuracy Assessment

In order to verify the reliability of the classified land use/land cover maps, an accuracy assessment was carried out using high-resolution reference imagery and visual interpretation techniques. A confusion matrix was generated to compare the classified results with reference data.

The accuracy measures considered include Overall Accuracy (%) and the Kappa Coefficient. The Overall Accuracy of the classification was found to be **97.87%**, while the Kappa Coefficient was **0.979**, indicating an almost perfect level of agreement between the classified data and the reference data [13].

These results demonstrate that the classification accuracy is highly satisfactory and meets the standard requirements for LULC analysis, thereby ensuring the reliability of the data for further quantitative and spatial analysis.

2.6. Area Estimation of Land Use/Land Cover Classes

After classification, the spatial extent of each land use/land cover class was determined for the years 2015, 2020, and 2025. Area statistics were generated in square kilometers (km^2) to quantify the spatial distribution of the four land cover classes within the study area. This area calculation was necessary to compare land transformation over time, thus facilitating an examination of the extent of urban growth. Special emphasis was given to the area of built-up as a principal measure of urban growth in this research work. The area statistics were utilized to generate percentages and mathematical indices of urban growth.

2.7. Mathematical Modelling of Urban Expansion

Mathematical indices were used to quantify the rate, magnitude, and intensity of urban growth.

2.7.1. Urban Growth Rate (UGR).

$$UGR = \frac{U_2 - U_1}{U_1} \times 100 \tag{2.1}$$

where U_1 is the built-up area in the initial year and U_2 is the built-up area in the subsequent year.

2.7.2. Land Use Change Rate (LUCR).

$$LUCR = \frac{A_2 - A_1}{A_1} \times 100 \tag{2.2}$$

where A_1 and A_2 represent the area of a land use class in the initial and later year.

2.7.3. Annual Expansion Rate (AER).

$$AER = \frac{U_2 - U_1}{T} \tag{2.3}$$

where T is the time interval (in years).

2.7.4. Urban Expansion Intensity Index (UEII).

$$UEII = \frac{U_2 - U_1}{T \times A} \times 100 \tag{2.4}$$

where A is the total study area.

2.8. Change Detection Analysis

To identify the spatial pattern of urban transformation, post-classification change detection was used. The method involves comparing classified LULC maps from different years to determine the nature and magnitude of land conversion over time. The study specifically examined the changes between the years 2015 and 2020, 2020 and 2025, and 2015 and 2025. Analysis was done on change detection to identify the increase in built-up area, decrease in the vegetation cover, conversion of barren/ open land to urban land, and the general spatial trend of urban development. To visually display changes in the newly urbanized areas over the years, a built-up expansion map had to be created to show the yearly variation in the same. Moreover, a land use transition matrix was estimated to determine the categories of land that made the biggest contribution towards the urban growth. This was a key move in the realization not just of the degree of the urban growth, but also the actual land changes that have brought about this growth.

2.9. Analysis and Interpretation of Data

The classified maps, area statistics, and mathematical indices were integrated to interpret the pattern of urban expansion in Jhajjar City. Both spatial and quantitative approaches were employed in understanding the temporal progression of built-up growth and the associated changes in other land cover classes. The analysis focused on: an increase in built-up land over time, a decline in vegetation and water bodies, changes in barren land, and the mathematical characterization of urban growth using selected indices. The integration of geospatial methods with mathematical modelling provided a systematic and objective framework for understanding land transformation and urban growth in Jhajjar City.

3. Results and Discussions

3.1. Spatio-Temporal Pattern of Land Use/Land Cover (LULC)

The classified Land Use/Land Cover (LULC) maps for the years 2015, 2020, and 2025 indicate that there is a significant change in the spatial pattern of Jhajjar City, Haryana, during the study period. The results clearly indicate that the city is experiencing rapid growth in terms of urban sprawl, mainly through the conversion of vegetation and open land to built-up areas.

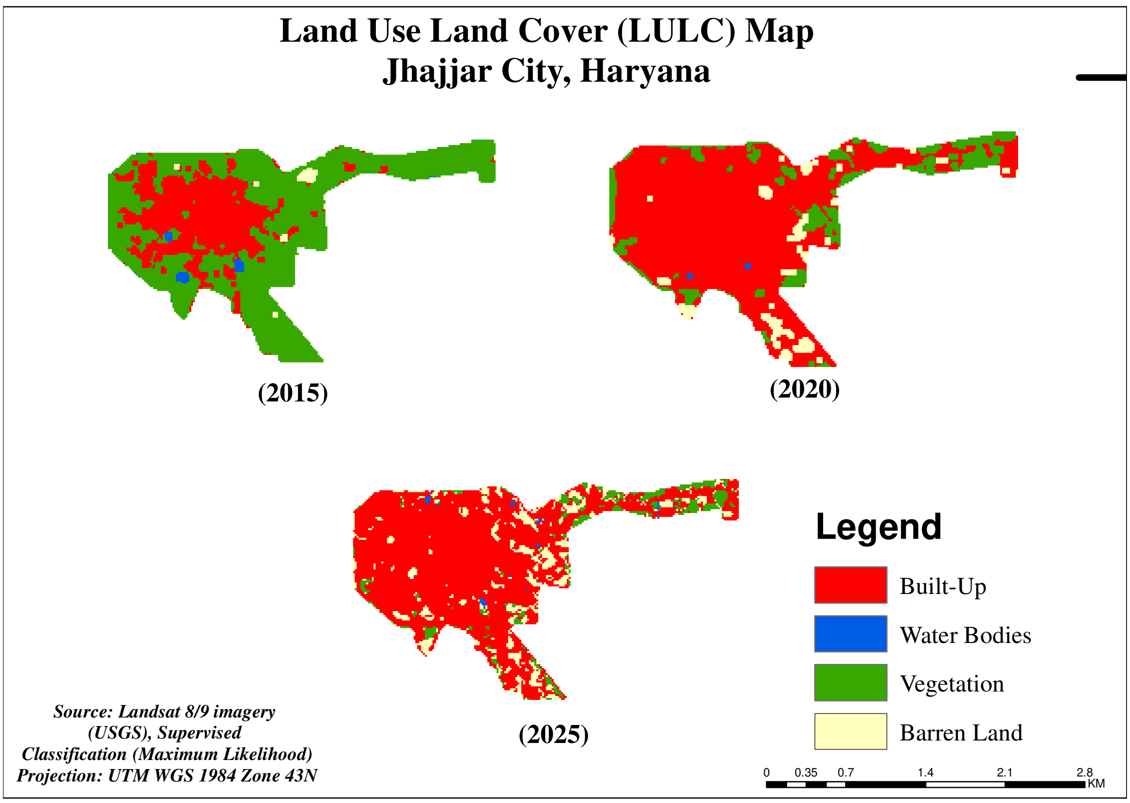

Figure 1: Spatio-temporal Land Use/Land Cover (LULC) classification of Jhajjar City

The spatial analysis of the LULC maps (Fig. 1) reveals that urban expansion in Jhajjar City is primarily concentrated around the central urban core and progressively extends towards the peripheral regions. The growth pattern indicates a clustered and continuous expansion rather than scattered development. It is also observed that urban expansion follows major road networks and transportation corridors, suggesting that accessibility and connectivity play a significant role in shaping the spatial pattern of growth.

Furthermore, certain zones at the urban fringe can be identified as emerging hotspots of urban expansion, where rapid conversion of vegetation and open land into built-up areas is evident between 2015 and

2025. This indicates that the city is expanding outward in a directional manner, driven by infrastructure development and increasing urban demand.

3.2. Land Use/Land Cover Distribution in 2015

The study area in 2015 was mainly covered by vegetation, which comprised 4.62 km^2 (51%) of the total area. The next major class of land use in the year 2015 was built-up area, which comprised 3.34 km^2 (37%) of the total area. This reveals that the city is in a comparatively less urbanized stage. Water bodies covered 0.58 km^2 (6%) of the total area, while barren land covered 0.47 km^2 (5%) of the total area. The LULC pattern of 2015 reveals that the city of Jhajjar has a comparatively balanced landscape, with considerable coverage of vegetation. The built-up area is mainly concentrated in the urban center, while the periphery of the urban area is mainly covered by vegetation and open land.

3.3. Land Use/Land Cover Distribution in 2020

The year 2020 revealed a considerable change in the composition of land use. The built-up area has shown a sharp increase in coverage, reaching 6.09 km^2 (68%) of the total area. Vegetation has shown a drastic reduction in coverage, reaching only 1.50 km^2 (17%) of the total area. Barren land has shown considerable growth in coverage, reaching 1.39 km^2 (15%) of the total area. Water bodies have shown a drastic reduction in coverage, reaching only 0.03 km^2 of the total area. This reveals that water bodies have almost disappeared in the urban area.

Table 1: Area (km^2) and percentage distribution of land use/land cover classes in Jhajjar City for 2015, 2020, and 2025

LULC Class	2015 Area	2015 %	2020 Area	2020 %	2025 Area	2025 %
Built-up	3.34	37	6.09	68	6.85	76
Vegetation	4.62	51	1.50	17	0.69	8
Water Bodies	0.58	6	0.03	0	0.05	1
Barren Land	0.47	5	1.39	15	1.41	16
Total	9.00	100	9.01	100	9.00	100

This change indicates an accelerated phase of urban growth between 2015 and 2020, during which the city expanded outward and absorbed surrounding vegetated and open areas.

3.4. Land Use/Land Cover Distribution in 2025

In the LULC map for the year 2025, the pattern shows the continuation of the same urban growth. It is seen that the urban growth is still continuing with the increase in the built-up area to 6.85 km^2 (76%), showing the dominance of urban land. It is also seen that the vegetation is further decreasing to 0.69 km^2 (8%), showing the severe reduction in the green cover. Barren land is slightly increasing to 1.41 km^2 (16%), and the water body is still very low at 0.05 km^2 (1%). From the 2025 map, it is seen that the entire area is being occupied by urban land with small patches of vegetation.

3.5. Urban Expansion and Built-Up Growth

The most dominant change noticed during the three time periods is the growth in the built-up area. The built-up growth is seen to increase from 3.34 km^2 in 2015 to 6.09 km^2 in 2020, and further to 6.85 km^2 in 2025. This represents a total increase of 3.51 km2 in urban land over the study period. Further, the percentage growth in the built-up area is seen to increase from 37% in 2015 to 68% in 2020, and finally to 76% in 2025. This indicates that the built-up area has nearly doubled over the last decade, reflecting rapid urban growth in Jhajjar City. This is a clear indicator that the city of Jhajjar is growing rapidly. It is also seen that the growth in the built-up area is largely at the expense of the vegetation and to some extent the open/barren land. The expansion in built-up area can be seen to have largely come at the expense of vegetation and to some extent, open/barren land, which indicates that the expansion in urban areas is related to the conversion of important land categories.

3.6. Decline in Vegetation and Land Transformation

One of the major environmental changes noticed during this time period is the decline in vegetation. Vegetation decreased from 4.62 km^2 (51%) in 2015 to 1.50 km^2 (17%) in 2020, and further to 0.69 km^2 (8%) in 2025. This represents a loss of 3.93 km^2 of vegetation over the study period, which indicates extensive land transformation linked to urban growth. The drastic reduction in vegetation suggests increasing pressure on natural and semi-natural land resources due to urban encroachment, infrastructure development, and land conversion processes. Similarly, the near disappearance of water bodies indicates growing ecological stress within the urban landscape. The reduction of blue-green spaces can have long-term implications for environmental sustainability, local climate, and urban resilience.

3.7. Mathematical Interpretation of Urban Expansion

To understand the magnitude and rate of growth in the expansion of the city, selected mathematical indices were applied to the classified land use/land cover data. These indices helped to quantitatively understand the expansion of the built-up area and the corresponding changes in the other land cover categories.

3.7.1. Urban Growth Rate (UGR). In this study, the Urban Growth Rate (UGR) index was applied to the built-up area to understand the percentage growth in the urban land cover between 2015 and 2025.

$$UGR = \frac{6.85 - 3.34}{3.34} \times 100 \ = 105.09\% \tag{3.1}$$

This indicates that the built-up area in Jhajjar City has recorded an increase of 105.09% between 2015 and 2025, which is substantial growth in the urban land cover.

3.7.2. Land Use Change Rate (LUCR). The Land Use Change Rate (LUCR) for each land use/land cover category over the period of 2015-2025 was calculated to quantify the percentage change in land use/land cover.

Built-up Area

$$LUCR = \frac{6.85 - 3.34}{3.34} \times 100 = 105.09\% \tag{3.2}$$

Vegetation

$$LUCR = \frac{0.69 - 4.62}{4.62} \times 100 = -85.06\% \tag{3.3}$$

Barren Land

$$LUCR = \frac{1.41 - 0.47}{0.47} \times 100 = 200.00\% \tag{3.4}$$

Water Bodies

$$LUCR = \frac{0.05 - 0.58}{0.58} \times 100 = -91.38\% \tag{3.5}$$

The result obtained from the LUCR analysis indicates a significant increase in built-up and barren land use classes and a sharp decrease in vegetation and water body classes. This confirms that the expansion of Jhajjar City is taking place by converting land use/land cover into built-up land use classes.

3.7.3. Annual Expansion Rate (AER). The Annual Expansion Rate (AER) analysis was conducted to calculate the average annual increase in built-up land use/land cover over the period of 2015-2025.

$$AER = \frac{6.85 - 3.34}{10} = 0.351 \ km^2/year \tag{3.6}$$

The result indicates that Jhajjar City is expanding by an average of 0.351 km/year built-up land use/ land cover over the period of 2015-2025.

3.7.4. Urban Expansion Intensity Index (UEII). Further analysis of the intensity of urban expansion in Jhajjar City compared to the total study area was conducted by calculating the Urban Expansion Intensity Index (UEII). The total study area is assumed to be around 9.00 km^2. The index is calculated as follows:

$$UEII = \frac{6.85 - 3.34}{10 \times 9.00} \times 100 = 3.90\% \tag{3.7}$$

The value of the UEII index is 3.90%, which indicates a moderate to high intensity of urban expansion in Jhajjar City during the study period 2015-2025. This implies that a significant part of the study area has been converted into built-up land over time. The collective results of these three indices show that Jhajjar City has undergone a significant process of urbanization during 2015-2025. The increase in built-up land, coupled with a decrease in vegetation and water bodies, further supports this fact, as these changes indicate a high rate of urbanization at the expense of environmentally significant land cover classes.

3.8. Spatial Implications of Urban Growth

The pattern of change in land use/land cover indicates a high rate of urban concentration and spatial expansion in Jhajjar City. The increase in built-up land, coupled with a significant decrease in vegetation and water bodies, indicates a clear trend of urbanization in Jhajjar City. The changes in land use/land cover indicate a significant transformation of the landscape, which may have implications for environmental balance, green spaces, water bodies, and urban management in Jhajjar City. Therefore, the urban growth in Jhajjar City not only indicates a change in land use/land cover, but this change may further reflect a significant change in land systems, which may have implications for environmental quality and sustainability in Jhajjar City.

3.9. Discussion

The results of the present study show a clear trend of urban development and land transformation in Jhajjar City over the period 2015–2025, as indicated by the significant increase in built-up land and the corresponding decrease in vegetation and water bodies. This pattern is consistent with broader urbanization trends in India, where rapid and often unplanned urban growth has led to the conversion of natural and semi-natural land into built-up areas [14]. However, beyond the observed changes, it is important to understand the underlying drivers of this transformation. The rapid urban expansion in Jhajjar City can be largely attributed to its strategic location within the National Capital Region (NCR). Improved connectivity, expansion of transportation networks, and increasing proximity to major urban centres such as Delhi and Gurugram have accelerated infrastructure development and land conversion. In addition, rural-to-urban migration and rising population pressure have increased the demand for housing and urban services, further contributing to the expansion of built-up areas. The decline in vegetation and water bodies reflects the environmental consequences of such rapid urbanization. The loss of green and blue spaces may lead to ecological imbalance, increased surface temperatures, and reduced environmental sustainability in the long term. The results of the present study are also consistent with previous studies on the application of geospatial techniques in land transformation analysis, which highlight the effectiveness of multi-temporal satellite data in capturing urban expansion and vegetation decline [15]. Furthermore, similar patterns of rapid urban growth and land transformation have been observed in other NCR cities such as Gurugram and Sonipat, indicating that the trends in Jhajjar are part of a broader regional urbanization process. The land transformation trends in Jhajjar City may also be explained through the framework of land system science, which emphasizes that land use change is driven by the interaction of socio-economic processes and environmental factors [16]. Thus, the increasing proportion of built-up land and the decline of ecological land cover clearly indicate the transformation of Jhajjar into a more urbanized landscape..

4. Conclusion

The present study examined the pattern and rate of urbanization in Jhajjar City, Haryana, through a mathematical and geospatial analysis of Land Use/Land Cover (LULC) changes from 2015 to 2025.

By integrating multi-temporal Landsat 8 and 9 imagery with quantitative indices, the study provides a comprehensive understanding of land transformation dynamics in the region. The results clearly indicate that Jhajjar City has experienced rapid urban growth during the study period. The most significant change is the expansion of built-up area, which increased from 3.34 km^2 in 2015 to 6.85 km^2 in 2025. This growth has occurred primarily at the expense of vegetation cover, which declined substantially over time, along with noticeable changes in water bodies and barren land. The application of mathematical indices, including Urban Growth Rate (UGR), Land Use Change Rate (LUCR), and Annual Expansion Rate (AER), has strengthened the analytical framework by providing quantitative insights into the magnitude and rate of urban expansion. The findings indicate that Jhajjar City is undergoing a rapid transformation into an urbanized landscape, driven by the conversion of natural and semi-natural land into built-up areas. The study demonstrates the effectiveness of integrating Remote Sensing, GIS, and mathematical modelling techniques in analyzing urban growth patterns in emerging cities. The results are valuable for urban planners, geographers, and policy-makers in supporting sustainable land management and informed urban development planning in Jhajjar City and similar medium-sized urban centres. In addition, the present study is based on retrospective analysis of LULC changes between 2015 and 2025. Future research can incorporate predictive modelling approaches such as Cellular Automata (CA-Markov) and SLEUTH models to simulate future urban growth scenarios and support sustainable urban planning.

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Bharat Bhushan,
Department of Geography,
Lovely Professional University, Phagwara, Punjab
Orcid ID: https://orcid.org/0009-0009-1768-0755
E-mail address: bharatranila@gmail.com

and

Surender Singh,
Department of Geography,
Lovely Professional University, Phagwara, Punjab,
Orcid ID: https://orcid.org/0009-0003-4417-0263
E-mail address: surenders340@gmail.com