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Original Research

An Analytical Investigation of Urban Expansion Patterns in the Kolkata Metropolitan Development Authority (KMDA) Region Using Geoinformatics

Ratnadeep Ray[1], Abhinandan Das[2], Sameer Algburi[3], Konia Basu[1], Mohd Sayeed Ul Hasan[4], Nehal Ahamed[4], Ahmed M. Abdulhadi[5*] and Ali Majdi[6]

[1]Department of Earth Sciences and Remote Sensing, JIS University, Kolkata, West Bengal India; ratnadeep.ray123@jis-university.ac.in , koniabs234@gmail.com

[2]Department of Humanities and Social Sciences, IIT-KGP, West Bengal, India; abhinandan1994@iitkgp.ac.in

[3] Al-Kitab University, Kirkuk 36015, Iraq. Email: sameer.algbury@uoalkitab.edu.iq

[4]Department of Civil Engineering, Aliah University, Kolkata, West Bengal, India; sayeed.ce1@aliah.ac.in; nehal.ce123@aliah.ac.in

[5]Al-Safwa University College, Kerbala, 56001, Iraq, researchg61@gmail.com

[6]Department of Buildings and Construction Techniques Engineering, College of Engineering, Al-Mustaqbal University, 51001 Hillah, Babylon , Iraq. Email: alimajdi@uomus.edu.iq

†Corresponding author: Ahmed M. Abdulhadi; researchg61@gmail.co

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ABSTRACT

Urban expansion has been significant and rapid in the last 30 years with an outward growth of the Kolkata Metropolitan Area (KMA). Much of this growth has followed a low-density, disparate development pattern—commonly known as urban sprawl. The proposed study aims to examining the spatial expansion pattern in Kolkata metropolitan development area (KMDA) in between the years 1990–2020 through the application of advance geoinformatics tools and spatial metrics. We analyzed Landsat Satellite images from the years 1990, 2000, 2010, and 2020 to evaluate urban including its extent and trends. Patterns of directional expansion, assessed using standard deviation ellipses and wedge analysis, showed a clear north-to-south axis of growth. The expansion of urbanisation by 2020 was therefore more concentrated in the south-western region. The Urban growth rates were measured by means of Annual Urban Expansion Rate (AUER), Urban Expansion Intensity Index (UEII) and Landscape Expansion Index (LEI). The urban land cover of the study area increased by 446.71 km2. The highest growth rate was from 1990 to 2000 (5.42%) and then saw a decline in subsequent decades. LEI analysis revealed edge expansion as the prevalent growth type which is a typical feature of urban sprawl. A mixture of in-filling and peripheral growth patterns points to processes of urban diffusion and clustering. Results for the Department of Labrador were obtained using the Area-Weighted Mean Patch Fractal Dimension (AWMPFD) which classified the urban spatial patterns into four types: major core, secondary core, suburban fringe, and dispersed settlements. Central aggregation and peripheral fragmentation relate in a straightforward manner. Multiple correspondence analysis (MCA) further confirmed this spatial distribution pattern, which has valuable implications for both resource managers and urban planners.

INTRODUCTION

Urban expansion constitutes a spatio-demographic phenomenon (Clark, 1982). It describes how a hamlet or village's basic characteristics are changed in order to boost population density in an urban area. (Chettry et al. 2022). The process is complex and dynamic, involving changes to the built environment's functional and physical components, which speeds up the conversion of rural areas into urbanized forms. (Castle & Crooks, 2006, Dahal et al. 2017). A multifaceted phenomenon rigorously analyzed by researchers in various fields, including urban planning, geography, sociology, economics, and environmental science. There exists a causal relationship between urban expansion and urbanization. Urban growth leads the urbanization. Globally, urbanization has primarily resulted from the conversion of rural areas into urban zones, or from the influx of populations into pre-existing cities (Yildiz & Doker, 2016; Lima & Romanelli, 2019). Regions experiencing rapid urbanization, characterized by the transformation from rural to urban landscapes, undergo distinct socio-economic changes along with the spatial expansion of urban land, which significantly impacts resources and the environment (Carruthers & Ulfarsson 2003; Grimm et al., 2008). This process typically begins at a single point and then radiates outward in various directions. The growth patterns differ from one urban area to another, influenced by intra-urban variations in local conditions such as land availability (Jiao, 2015). Camagni et al. (2002) identified five types of urban growth: infilling, expansion, linear development, sprawl, and large-scale projects, while Wilson et al. (2003) categorized urban growth into infill, expansion, isolated, linear branch, and clustered branch. Each major city worldwide exhibits its unique growth pattern and nature, with geometric attributes and spatial distribution varying across different growth types. Moreover, the direction and speed of development may differ significantly. Spatio-temporal patterns of urban growth generally oscillate between diffusion and coalescence phases. It is typically assumed that urbanization progresses from the diffusion phase, characterized by an increasing number of impervious/built-up patches, to the coalescence phase, where these patches merge into continuous built-up areas (Dietzel, Herold, Hemphill, & Clarke, 2005).

Urban growth has accelerated significantly over the past few decades due to the large-scale migration of populations to cities. By 2005, over 50% of the global population resided in urban areas (UNEP 2005). At the current rate of growth, it is projected that by 2030, more than 60% of the global population will be living in urban areas (Moeller and Blaschke 2006; Odindi and Mhangara 2012). Rapid urbanization and the expansion of cities are among the most prominent global trends of this century (World Economic Forum, 2015, 2016, 2017). In contrast to 1950, when only 30% of the global population lived in urban areas, cities now accommodate over half of the world's population, with 54% residing in urban areas by 2014 (United Nations, 2015a). The global trend of urbanization has primarily resulted from the conversion of rural areas into urban zones and the influx of populations into existing cities (Yildiz & Doker, 2016; Lima & Romanelli, 2019). According to the United Nations, nearly half of the world's population lives in or near urban areas. The rate of urban growth is notably higher in developing countries compared to developed ones, driven largely by extensive infrastructure development and population migration to urban centers (Sui and Zeng 2000). The expansion of urban areas is outpacing the growth of urban populations themselves (Tewolde and Cabral 2011). In many regions, urbanization is being accelerated by the dynamics of the global economy, leading to significant transformations in the planet's physical landscape (Soja, 2013; Abbas, 2016). Metropolitan cities in developing countries around the world have experienced rapid growth in response to population surges and economic expansion (Al-sharif and Pradhan, 2015; Metzger et al., 2016).

Rapid urbanization is assessed through the extent of suburban expansion and the phenomenon of urban sprawl, as outlined by Harris and Ventura (1995) and Sajjad (2014). Detecting and quantifying urban expansion patterns and processes as well as been focussing on the spatial determinants of urban growth are standard practices in urban sprawl studies (Forman, 1995; Wasserman,2000; Ramachandra et al, 2012; Mithun et al, 2016; Mukherjee, 2012). Wilson and Chakraborty (2013) suggest that examining the physical attributes of urban growth as a pattern of urban development is a prevalent method for characterizing urban sprawl. Besides, several studies (Torrens et al, 2000; Rahman et al, 2011; Pandey et al, 2013; Li et al. 2013; Luo and Wei 2009; Schnaiberg et al. 2002; Yeh and Xia 2001; Dewan and Yamaguchi 2009; Jenerette et al. 2007; Pijanowski et al. 2010; Tian et al. 2012; Carrion Flores and Irwin 2004; Gustafson et al. 2005; Jiang et al. 2013; Rui and Ban 2011; Sudhira et al. 2004; Seto and Kaufmann 2003) attempted to determine the urban growth based on some determinants like change in the urban built-up area, proximity indicators, topographical factors, neighbourhood variables, variables among socio-economic attributes etc.

Urbanization in India has experienced significant growth since the post-independence period, particularly over the past three decades (Bhagat and Mohanty, 2009). The urban population has risen from 10.84% in 1901 to 17.29% in 1951, reaching approximately 31.16% in 2011 (MHUPA, 2016). With 377.16 million urban inhabitants, India is the second most urbanized country globally, accounting for 11% of the world's urban population, and this figure is projected to increase by 13% by 2030 (Lauther, 2011) and 50% by 2050 (Das et al., 2021). Recent Census of India data indicates that despite the relatively slow pace of urbanization, the absolute population increase in urban areas has surpassed the total rural population in the country (Census of India 1991, 2011). However, urbanization in the cities of developing countries continues without adequate planning or infrastructure expansion. Consequently, unlike in developed nations, rapid urbanization in developing countries (Montgomery 2008) often results in unplanned and disorderly urban expansion (Cohen 2006; Grimm et al. 2008). A notable aspect of India's urbanization is the rapid growth of metropolitan suburbs, contributing to spatial transformation (UNFPA, 2007; The World Bank, 2013). Since the last quarter of the twentieth century, India has predominantly experienced outward expansion in most large megacities, characterized by sprawl, where the peripheries have increasingly absorbed small towns and villages rather than accommodating rural migrants within the city core.

India has experienced rapid urbanization over the past three decades (Bhagat and Mohanty, 2009). Over time, the number of urban agglomerations (UA) has increased significantly each decade, as seen in the expansion of cities like Mumbai, Delhi, Kolkata, Bangalore, Chennai, and Hyderabad. It is anticipated that by 2021, India will have the largest concentration of urban agglomerations globally (Chakrabarti, 2017; Taubenböck et al., 2009). The Kolkata Urban Agglomeration is the tenth largest in the world and the third largest in India, particularly in Eastern India (UN, 2011). Over the past few decades, KUA has consistently expanded, with the city rapidly extending towards peripheral areas (Bhatta, 2009). Numerous studies have explored this phenomenon (Bhatta, 2009; Ramachandra et al., 2014; Mondal et al., 2015, Mondal et al., 2016, Sahana et al., 2018, Chakrabarty et al., 2021, Ray et al., 2023) to analyse urban growth as well as land transformation along with the effects on peripheral land use and land cover especially urban areas within Kolkata Municipal Corporation and its adjacent regions. But there is dearth of information about population growth as primary driving parameter of urbanization. Population growth drives urban expansion through processes of diffusion and coalescence (Dietzel, Herold, Hemphill, & Clarke, 2005), often at the expense of existing land use and land cover. Besides, the increasing gravity potentiality of the Statutory towns (ST) with increasing population growth those in turn cause the emergence and growth of Census towns (CT) and socio-economic transition in terms of occupational migration as well. Therefore, considering such gaps and the contextual background of growth dynamics of urban agglomeration within KMDA, the study aims to provide a parametric overview of the spatio-temporal urban growth within the KMDA region.

2. ABOUT THE STUDY AREA

The Kolkata Urban Agglomeration (UA) encompasses the administrative areas governed by the Kolkata Metropolitan Development Authority (KMDA), which includes 3 municipal corporations (Howrah, Kolkata, and Chandan Nagar), 38 municipalities, 77 non-municipal urban towns, 16 outgrowths, and 445 rural villages. KMDA operates as a statutory authority under the Urban Development Department of the Government of West Bengal, India. As illustrated in Figure 1, KMDA's jurisdiction covers 6 districts: Kolkata, Howrah, Hooghly, Nadia, North 24 Parganas, and South 24 Parganas. Kolkata UA is situated between latitudes 22°00'19" N and 23°00'00" N, and longitudes 88°00'04" E and 88°00'33" E, spanning an area of 1851 km^2.

The Kolkata Urban Agglomeration is marked by a concentrated population and dense settlements along both sides of the Hooghly River. According to the 2011 Census, the total population of the Kolkata Metropolitan Area (KMA) was recorded at 14.72 million, with a population density of 7,950 persons per square kilometer. The area's annual population growth rate was 1.8% by 2011, with projections suggesting an increase to 20 million by 2021 and 21.1 million by 2025 (Census of India 2011; KMDA 2011). Kolkata ranks among the 30 largest megacities worldwide, with a population of 10 million (UN 2007). The region has undergone substantial migration, resulting in numerous challenges including land scarcity, overpopulation, and heightened strain on available resources. These problems have profoundly influenced the anthropogenic landscape, leading to substantial alterations in land use and land cover (LULC), especially in urban centers such as Kolkata. The slums of the urban agglomeration display a heterogeneous land use pattern, incorporating residential, commercial, and industrial functions (Roy et al. 2014; Sugiyama 2008; Bhatta 2009). The eastern region of the KMA, encompassing locales such as Bidhan Nagar, Rajarhat, Maheshtala, and Sonarpur, features back swamps and marshy terrains that are progressively being invaded by local inhabitants for residential construction, frequently lacking adequate planning (Ghosh and Sen 1987; Dasgupta et al. 2013).

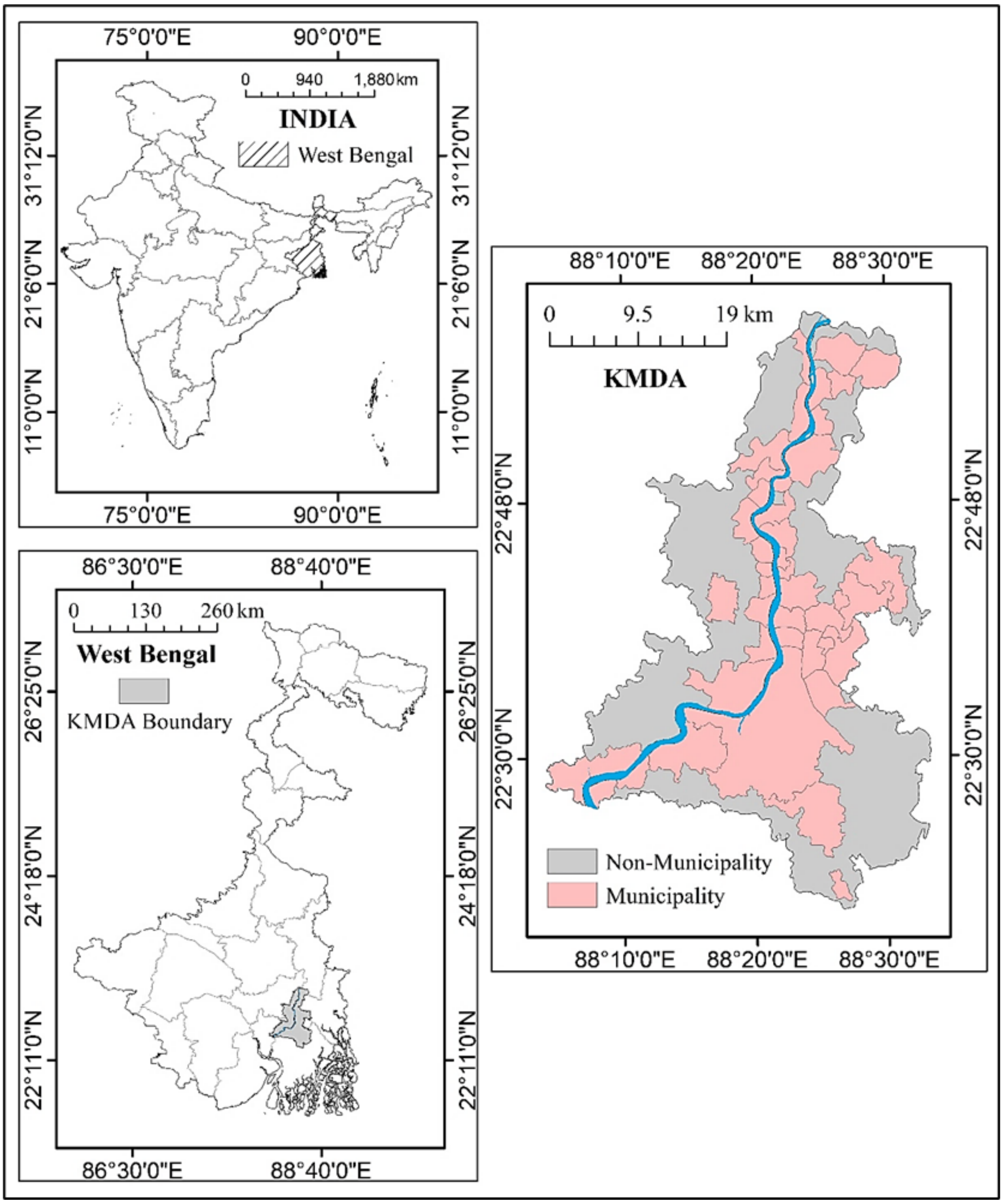

Figure 1. Location map of the study area

3. MATERIALS AND METHODS:

3.1. *Data Sources*

The study used Landsat digital data obtained from the TM, ETM+, and OLI/TIRS sensors for the years 1990, 2000, 2010, and 2020, sourced from the USGS Earth Explorer website (http://earthexplorer.usgs.gov, accessed on 5 December 2022). The selection of Landsat images was driven by their availability and their medium to high spatial resolution, making them suitable for this study. In contemporary research involving remote sensing and GIS, Landsat data has been widely used to assess urbanization processes. Detailed information about the data can be found in Table 1. These three sets of Landsat digital data are referenced to the UTM map projection (Zone 45 N) using the WGS84 geodetic datum and have been Level-1 Terrain corrected (L1T).

Table 1. Detailed features of the datasets analysed in the present case study, with different sensors.

<table>
<tr><th>Year</th><th>Sensor</th><th>Path/Row</th><th>Band Count</th><th>Spatial Resolution</th><th>Radiometric Resolution</th></tr>
<tr><td>1990</td><td>TM</td><td rowspan="4">138/44, 45</td><td>7</td><td>Optical 30 m,
Thermal 120 m</td><td rowspan="3">8 bits</td></tr>
<tr><td>2000</td><td>ETM+</td><td>9</td><td>Optical 30 m,
Thermal 60 m,
Pan 15 m</td></tr>
<tr><td>2010</td><td>ETM+</td><td>9</td><td>Optical 30 m,
Thermal 60 m,
Pan 15 m</td></tr>
<tr><td>2020</td><td>OLI, TIRS</td><td>11</td><td>Optical 30 m,
Thermal 100 m,
Pan 15 m</td><td>16 bits</td></tr>
</table>

Besides these, administrative maps (https://kmda.wb.gov.in/) and population census data (https://censusindia.gov.in) for the years of 1991, 2001 and 2011 have been used to enumerate the spatio-temporal nature of urban physical growth and the population growth dynamics as well. Along with all these, some literary sources have also been used as ancillary database. However, all the extracted data and information have been analysed to significantly fulfil the goal of the present study.

Although this study concerns the urban expansion characteristics of the Kolkata Metropolitan Development Area (KMDA) only, it is worthwhile to examine these findings in a wider comparative context. The same narrative of belt and sprawl emerging at the peripheries has also been observed in other metropolitan regions of like Delhi, Mumbai and Hyderabad providing for dynamics of urbanization shifting to the preferred edge due to land availability and corridor induced growth. For example, research in Hyderabad and Ahmedabad also suggests a similar pattern, but infill development seems to have been more prominent in cities with strict land-use regulations and redevelopment incentives. In KMDA's urban growth, therefore, there is a striking parallel to fast-growing cities in the Global South such as Jakarta, Indonesia and Lagos, Nigeria, where, in much the same way, unregulated peri-urban development is fueled by comparable forces—in-migration, investment in infrastructure, and informal land markets. Yet, unlike cities that have committed themselves to compact city policies (e.g., Barcelona or Portland), growth in infill is relatively weak in KMDA, flagging the need to include more intentional urban containment orientations. In this present study for the thematic depiction as well as quantitative analysis of the spatio-temporal pattern and nature of urban growth, multi-temporal satellite images had been used as the primary source of data generation.

Methodology:

3.2.1. Mapping of urban patches and its growth dynamics:

Following the modified methodology proposed by He et al. (2010) after Zha, Gao and Ni 2003, the urban patches of the study area has been extracted using an optimum threshold from the digital index called Built up Index (BUI). This index was comprised of three mathematical computations like:

i. Calculation of NDVI using the following equation (Rouse et al. 1974):

$$\frac{NIR\ (Band\ 4\ of\ TM\ or\ ETM+) - Red\ (Band\ 4\ of\ TM\ or\ ETM+)}{NIR\ (Band\ 4\ of\ TM\ or\ ETM+) + Red\ (Band\ 4\ of\ TM\ or\ ETM+)}$$ ………. Equation (1)

ii. Based on the high spectral response of the built-up areas to the wave length range of 1.55 - 1.75 µm (SWIR) and low spectral response to the wave length range of 0.76 - 0.90 µm (NIR), Normalised Built up Index (NDBI) had been calculated as:

$$\frac{SWIR\ (Band\ 5\ of\ TM\ and\ ETM+) - NIR\ (Band\ 4\ of\ TM\ and\ ETM+)}{SWIR\ (Band\ 5\ of\ TM\ and\ ETM+) + NIR\ (Band\ 4\ of\ TM\ and\ ETM+)}$$ ………. Equation (2)

iii. Finally, the Built-up Index (BUI) was computed by subtracting the NDVI from the NDBI. A higher BUI value for a pixel indicated a greater likelihood of it representing a built-up area.

$$BUI = NDBI - NDVI$$ ………… Equation (3)

For calculating BUI from Landsat 8/OLI sensor, according to Bhatti et al. (2014) a little modification in formulation has been applied. In Landsat 8/OLI sensor, bands 6 and7 are highly sensitive to the urban built up area and they are highly correlated. Besides in Landsat 8/TIRS sensor, two thermal bands (band 10 and 11) are also sensitive to urban built up area and correlated as well. So, for the optimum utilisations of those bands Principal component analysis (PCA) has been applied using band pairs 6,7 and bands 10,11. Finally first PC from each pair have been considered for their high variance and sum of those first PCs has been used as the replacement of band 5 (for TM and ETM+) in the original NDBI of Zha, Gao and Ni 2003.

$$NDBI_{OLI} = \frac{(PC1\ (PCA\ of\ OLI\ band\ 6{,}7) + PC1\ (PCA\ of\ TIRS\ band\ 10{,}11)) - OLI\ band\ 5}{(PC1\ (PCA\ of\ OLI\ band\ 6{,}7) + PC1\ (PCA\ of\ TIRS\ band\ 10{,}11)) + OLI\ band\ 5}$$ ………… Equation (4)

Finally, the Built-up Index (BUI_{OLI}) had been calculated by subtracting the $NDVI_{OLI}$ from $NDBI_{OLI}$, where a higher pixel value suggested a greater likelihood of it representing a built-up area.

$$BUI_{OLI} = NDBI_{OLI} - NDVI_{OLI}$$ ………… Equation (5)

After calculating the raster based built up information on temporal manner, using an optimum threshold urban built up patches has been extracted and applying the XOR operation the urban patch growth dynamics have been estimated.

3.2.2. ***Depiction of typical urban expansion****:*

The patterns of growth of urban built-up regions can be measured using a variety of techniques. Based on earlier studies (Camagni et al., 2002; Wilson et al., 2003; Forman, 1995), there are three different kinds of patterns of urban growth. The patterns comprise infilling, edge expansion, and outlying. Xu et al. (2007) assert that urban expansion can be evaluated as a result of the amalgamation of these three categories. Liu et al. (2010) employed the Landscape Expansion Index (LEI) in this study to determine the prevailing urban expansion trend in the KMDA region. The calculation for LEI may be:

LEI = $\frac{Ano}{Anu+Ano} \times 100$ ……………… Equation (6)

Where, Ano represents the area where the buffer zone of a new urban patch intersects with an existing urban patch, Anu refers to the area where the buffer zone overlaps with non-urban patches.

The patch is considered outlying expansion if LEI = 0, which is a range of 0 to 100. The patch can be considered edge-expansion if 0 < LEI < 50. Lastly, the patch can be categorized as an infilling expansion if LEI > = 50.

The analysis of the Landscape Expansion Index (LEI) revealed a dominance of edge expansion behind urban growth in the KMDA in addition to a supporting infill and outlying growth. This discovery is consistent with other findings about urban sprawl in Kolkata. Chakraborty et al. (2017) and Das and Das (2020) where peri-urban expansion is similar and edge-dominant [27]; and unregulated land conversion and the role of transportation corridors in patterning growth were also highlighted.

In other Indian metropolitan areas like Delhi and Bangalore, studies by Sudhira et al. (2004) and Jat et al. Early phases are characterized by edge expansion with infilling (2008) also indicating increasing infilling as the urban core develops. In Kolkata, the transition from edge to infill growth appears to be taking place at a much slower pace, which might be attributed to the fragmented nature of governance coupled with the belated provision of infrastructure in peripheral zones. These comparative perspectives are useful as they strengthen the understanding that urban sprawl in Kolkata is structurally similar to other metropolises, yet is shaped by the unique socio-political and infrastructural conditions that also shape the spatial patterns of urban growth (Sharma & Awasthi, 2019)

A hybrid approach of spatial metrics and geoinformatics techniques were applied for identifying the urban growth metrics in the Kolkata Metropolitan Development Area (KMDA) during 1990–2020. Landsat satellite images of 1990, 2000, 2010, and 2020 were processed to map the urban land cover subtypes using classification methods.

The spatial indices employed to quantify urban growth rate and intensity are:

Urban Growth Rate (Absolute): The average growth rate of built-up area from one year to the next (e.g. for 10 years calculate the mean), expressing how fast the built-up area is transformed from one year to another.

Urban Expansion Intensity Index (UEII): Measures the spatial intensity of urbanization within administrative units, facilitating the identification of urbanization hotspots.

To analyze growth trends: Landscape Expansion Index (LEI): This parameter characterizes urban growth categories such as edge expansion, infilling, or outlying, helping to understand the dominant mode of sprawl.

To describe the spatial shape and complexity of urban forms: Area-Weighted Mean Patch Fractal Dimension (AWMPFD) (m2): Analyzes the geometric complexity and compactness of urban patches, determining for types major core (or compact), secondary core, suburban fringe to dispersed settlements.

Finally, for exploring relationships between spatial forms and metrics: Multiple Correspondence Analysis (MCA): A statistical procedure for building and validating associations between categorical spatial patterns and indices, for the solid interpretation of urban spatial dynamics.

This index would collectively help to set a framework for understanding the scale, type and pattern of change over time.

In the 1990s and early 2000s, the rearward expansion of major transport corridors including National Highway 6 (Mumbai-Kolkata Highway) and Diamond Harbour Road aided in urban spread to the southwest. The establishment of industrial hubs like the Dankuni Industrial Belt and Kalyani Expressway Industrial Corridor also attracted residential and commercial development in those directions.

Changes in policy also had a big impact. Targeted infrastructure improvements—especially water supply, drainage, and transport—were excavated along the peri-urban fringe under the auspices of the KMDA's Metropolitan Development Plan (MDP) and through investments through the JNNURM (Jawaharlal Nehru National Urban Renewal Mission), thus indirectly shaping urban growth. Additionally, these fringes became attractive to lower and middle-income populations with the promotion of low-cost housing schemes in southern and south-western zones. Economic variables, such as the affordability of land and real-estate speculation in peripheral regions, also encouraged outward expansion, particularly in areas where laws governing land use were abrogated or otherwise weakly enforced. The contextual analysis sheds light on the directional bias in urban growth revealed by the spatial analysis.

3.2.3. Study of spatial and directional dynamics of urban patches:

In order to make sense of the spatial distribution and prevailing orientation of urban patches across time, this study makes use of the Standard Deviational Ellipse (SDE) (Qiao et al., 2018). The centroid of the urban land area is indicated by the center of the SDE. The temporal SDE centers' shifting locations show how the urban area's spatial orientation and layout are evolving. The density concentration of urban land is shown by the standard deviations of the longitudinal and transverse axes. According to Zhong et al. (2019), the azimuth angle of the SDE indicates the main direction of their distribution trend. the angle of rotation in clockwise direction from the north to the SDE's long axis. A greater difference in magnitude between the long and short axis values results in items, like urban land, having a more noticeable directionality. A range of standard deviations will include the centroids of around 68% of the total elements when the elements exhibit a definite spatial distribution, with the elements concentrating at the center and progressively decreasing toward the periphery. Two standard deviation intervals contain around 95% of the data points, whereas three standard deviation intervals include nearly 99% of the total data points.
The coordinates of the feature set are (x1, y1), (x2, y2) . . ., (xn,yn); then the direction angle θ of the SDE is calculated as follows (Zhao et al, 2014):

$$tan\ \vartheta = \frac{\sum_{i=1}^{m} \tilde{x}_i^2 - \sum_{i=1}^{m} \tilde{y}_i^2 + \sqrt{(\sum_{i=1}^{m} \tilde{x}_i^2 - \sum_{i}^{m} \tilde{y}_i^2)^2 + 4(\sum_{i=1}^{m} \tilde{x}_i \tilde{y}_i)^2}}{2\sum_{i=1}^{m} x_i y_i} \quad \text{................ Equation (6)}$$

The standard deviations of the long and short axes are δ_x and δ_y and are calculated as:

$$\delta_x = \sqrt{2}\sqrt{\frac{\sum_{i=1}^{m} 1(\tilde{x}_i cos\theta - \tilde{y}_i sin\theta)^2}{m}} \text{ .... Equation (7)}$$

$$\delta_y = \sqrt{2}\sqrt{\frac{\sum_{i=1}^{m} 1(\tilde{x}_i sin\theta + \tilde{y}_i cos\theta)^2}{m}} \text{ .... Equation (8)}$$

Where, $\tilde{x}_i$ and $\tilde{y}_i$ are the differences between the mean centre coordinates *x, y* and the feature coordinates x_i, y_i respectively.

In this present study, to estimate the temporal dynamics of the spatial distribution of the urban land area, concept of difference of main trend direction (DMTD) of an ellipse in regard to its long axis (Tang et al, 2021) has been implemented. The DMTD could be calculated as the difference between the azimuth angles of two consecutive temporal SDE (i.e. ϑ_1 of beginning year and ϑ_2 of ending year). However, if the difference between these two azimuth angles would greater than 90^0, the difference should be subtracted from 180^0.

Besides, another quantitative measure like spatial difference index (SDI) has been implemented to enumerate the degree of spatial difference between temporal distributions of urban land area (Zhao, 2014). The value of SDI is ranging between 0 and 1. A higher SDI value indicates a greater spatial variation. The definition of SDI is as follows:

$$SDI = 1 - \frac{Area(SDE_b \cap SDE_e)}{Area(SDE_b \cup SDE_e)} \text{ .... Equation (9)}$$

Where, SDE_b and SDE_e are the SDE of beginning year and ending year respectively.

Along with the application of SDE, another approach has been implemented to enumerate the directional dynamics of the spatio-temporal arrangement of the urban land surface. Considering the approach of SDE as the global assessment of directional trend of urban land surface, for the local level assessment of the same, the area under KMDA has been divided into eight segments (North, North-East, East, South-East, South, South-West, West and North-West) in a wedge like manner based on the mean centre of KMDA boundary. Finally, the areas of urban land under each wedge has been calculated on temporal manner.

3.2.4. *Study of urban metrices:*

Spatial matrices are commonly employed methods for assessing urban expansion, depending on data availability, different types of measures have been used in this study like Urbanization Index (UI), Urban Expansion Index (UEI), Annual Urban Expansion Rate (AUER), Urban Expansion Intensity Index (UEII), and Urban Expansion Differentiation Index (UEDI).

Urban Expansion Index (UEI):

The spreading of urban area could be explained by urban expansion. The urban expansion index illustrates the rapidity of urban landscape growth and is calculated using equation 12.

$$UEI = \frac{Urban\ patch\ area\ i_{EY} - Urban\ patch\ area\ i_{BY}}{Time\ interval} \text{ .... Equation (12)}$$

Where, '*i*' is the spatial unit. *BY* is the urban patch area at the beginning year and *EY* is the urban patch area at the ending year.

Urban Expansion Intensity Index (UEII):

The Urban Expansion Intensity Index (UEII), which emphasizes the ratio of a spatial unit's urban growth to the entire study area and duration, measures the variability of urban expansion (Hu et al., 2007). The UEII result shows how much a spatial unit has urbanized relative to the total research region.

That has been calculated as

$$UEII = \left(\frac{Urban\ patch\ area\ i_{EY} - Urban\ patch\ area\ i_{BY}}{Total\ area\ of\ municipality \times Time\ interval}\right) \times 100 \text{ .... Equation (13)}$$

Where, '*i*' is the spatial unit. *BY* is the urban patch area at the beginning year and *EY* is the urban patch area at the ending year.

Annual Urban Expansion Rate (AUER):

Regardless of the size of the geographical unit, the Annual Urban Expansion speed (AUER) calculates the average annual speed of land growth over two time intervals (Acheampong et al., 2017). Without any upper or lower bounds, the AUER result shows the amount of fluctuation in the Built-up land area over time. This was calculated to be:

$$AUER = \left\{\left(\frac{Urban\ patch\ area\ i_{EY}}{Urban\ patch\ area\ i_{BY}}\right)^{\frac{1}{Time\ interval}} - 1\right\} \times 100 \text{ .... Equation (14)}$$

Where, '*i*' is the spatial unit. *BY* is the urban patch area at the beginning year and *EY* is the urban patch area at the ending year.

3.2.5. Analysis of urban landscape fragmentation:

Urban landscape fragmentation is the outcome of contiguous urban built-up land cover eventually breaking up into different regions due to edge effects. The Rahman group (2016). Urban landscape fragmentation has been analyzed using a pattern metric called the Area Weighted Mean Patch Fractal Dimension (AWMPFD) Index. It is comparable to the Mean Patch Fractal Dimension (MPFD) Index. The usage of area as a weighting component for each patch is the only difference. Fragmentation will be lesser the higher the AWMPFD value and vice versa. The value is in the interval of 1 and 2. It can be calculated as:

$$P = \sum_{i=1}^{m} \sum_{i=1}^{n} \left[\left(\frac{2ln(0.25P_{ij})}{ln(a_{ij})}\right)\left(\frac{a_{ij}}{A}\right)\right] \text{.......... Equation (10)}$$

3.2.6. Multiple correspondence analysis (MCA):

MCA is a multivariate graphical method for analyzing categorical data and an exploratory data analysis methodology (Benzecri 1979; Sourial et al. 2010). The combined scaling of the row and column variables to reveal information on the relationships between the row and column variables is a crucial component of the study. Both qualitative and quantitative data can be subjected to correspondence analysis. Rescaling characteristic vectors into ideal scores is the last stage of the study. The assessment of the relative relevance of elements is made possible by normalising these ideal values. According to Weller et al. (1990), correspondence analysis can also be used to determine the best variable ordering for a particular collection of attributes. The maximum value between each row element and column element can be used to address the homogeneity between row and column elements, which defines the relationship between elements. The current study computes the correspondence between the typical zonal distribution of urban spatial pattern and the classified values of the AWMPFD index.

4. **Result and discussion**

4.1. Temporal urban expansion and directional dynamics

Urban spatial expansion is a continuous process. Assessment and analysis of spatio-temporal expansion of urban patches plays a significant role in the study of urban growth. In this present study, NDBI derived urban patches have been mapped (figure. 2) and analysed for the years of 1990, 2000, 2010 and 2020. Within this 30 year of span the urban patches has increased by 446.71 sq. km at the rate of 4.14%. The maximum areal growth was seen within 1990 to 2000. From 1990 to 2000 the area has increased by 195.30 sq.km at the rate of 5.42%. However, in the succeeding 20 years the rate of growth has certainly slowed down like 2.30% in the span of 2000 to 2010 and 1.80% in the span of 2010 to 2020. In 2010 the area has increased by 127.83 sq.km from 2000 and in 2020 the areal increase was by 123.57 sq.km from 2010 (table. 2).

Table. 2 Year wise urban area dynamics

Year	Area (sq. km)	Increased (sq. km)	Growth Rate
1990	359.88		
2000	555.18	195.30	5.42%
2010	683.01	127.82	2.30%
2020	806.59	123.57	1.80%

Over a span of 30 years, the KMDA region saw substantial changes in its urban area, with an Annual Urban Expansion Rate (AUER) of 2.73% and a growth rate of 4.14%. Between 1989 and 2019, the urban area expanded by 446.71 sq. km, with an Urban Expansion Intensity Index (UEII) of 0.86 (Table 3). Such UEII value is indicating an apparently faster areal growth (Ren et al., 2013).

Although the KMDA region experienced a general increase in the urban areal growth throughout the 30-years of span, there was varying growth patterns in decadal manner. Urban built-up areas of KMDA experienced a significantly faster growth (UEII of 1.12) between 1990 and 2000. Within this span the urban area expanded by 195.30 sq.km with the AUER and growth rate of 4.43% and 5.43% respectively. Whereas in the successive spans (from 2000 to 2010 and 2010 to 2020), the urban area expanded with decreasing growth rate as well as AUER. From 2000 to 2010 and 2010 to 2020 the urban area expanded by 127.83 sq.km and 123.57 sq.km with the growth rate of 2.30% and 1.81% and AUER of 2.09% and 1.68% respectively. Besides a slower rate of expansion within both of these spans were evident as having the UEII of 0.73 and 0.71 respectively (table. 3).

Year	Area (sq. km)	Increased (sq. km)	Growth Rate
1990	359.88		
2000	555.18	195.30	5.42%
2010	683.01	127.82	2.30%
2020	806.59	123.57	1.80%

Table. 3 Temporal nature of urban metrices to depict the urban growth pattern

Temporal Span	Growth Rate	Increased (sq. km)	UEII	AUER
1990-2000	5.42 %	195.30	1.12	4.43
2000-2010	2.30 %	127.83	0.73	2.09
2010-2020	1.80 %	123.57	0.71	1.68
1990-2020	4.14 %	446.71	0.86	2.73

The geometric characteristics of the Standard Deviation Ellipse (SDE) (table. 4) are describing the distribution pattern of urban patches, their spreading ranges and directional trends and the shifting of the gravity centres on temporal basis (figure. 3).

Within the overall span of the study the gravity centers of the urban built-up area have shifted by 5.83 km southward from its base position in 1990 (table. 5). Such shifting could truly hypothesize the spatial expansion of the urban built-up area southward. Out of the total span maximum shifting has seen from 2000 to 2010 (2.41 km).

Table. 4 Geometric nature of standard deviation ellipse showing urban expansion magnitude

Year	Long axis (km)	Short axis (km)	Rotation angle	Area (sq. km)	Flattening	Eccentricity	Aspect Ratio
1990	21.71	8.57	9.73	584.18	0.61	0.92	0.39
2000	22.65	9.41	6.70	669.71	0.58	0.91	0.42
2010	22.86	9.89	6.53	709.82	0.57	0.90	0.43
2020	21.88	10.83	8.39	744.19	0.51	0.87	0.49

Table. 5: Study on comparative elliptical geometry to assess urban land dynamics

Temporal Span	DMTD	SDI	Shifting distance of Gravity centres (km)
1990-2000	3.03	0.20	2.35 (South-West)
2000-2010	0.17	0.14	2.41 (South)
2010-2020	-1.86	0.11	1.07 (South-West)

The varying sizes of the temporal Standard Deviation Ellipses (SDEs) and the lengths of their long and short axes for the urban built-up area in KMDA illustrate spatial dispersion in terms of the areal dynamics of geographical features like urban built-up areas. Table 4 shows an evident increasing trend in the areas of these temporal SDEs. The most significant areal expansion within the SDE occurred between 1990 and 2000, with an increase of 85.53 sq. km. From 2000 to 2010, the area expanded by 40.11 sq. km, and from 2010 to 2020, by 34.47 sq. km. This growth in the SDE area suggests that urban built-up patches outside the standard deviation ellipse were expanding more rapidly than those within it. Furthermore, the orientation and distances of the long and short axis are depicting the directional trend and magnitude of expansion of the urbanized area. A larger difference between the long and short axes indicates a more obvious directional expansion of urbanized areas. Besides such directional expansion also could be analysed by the nature of flattening, eccentricity and compactness. Though the nature of directional orientations of temporal urban built-up areas as well as the representative long axis are seeming alike as North East -South West direction throughout the span of the study (figure. 3) having a mere rotational angular variation, the decrease in flattening and eccentricity and the corresponding increase in distance of short axis (table. 4) from 1990 to 2020 is indicating the gradual growth of new urban built-up patches about the east-west direction. The increasing aspect ratio or lowering of the compactness of SDEs could be the evident of such scenario. From the geometric aspects of the temporal SDEs, this could be enumerated that area under KMDA has experienced the maximum outgrowth about the East-West direction from its clustered centre within the span of 2010 to 2020.

However, in spite of having increasing area of SDEs of urban built-up patches on temporal manner, decreasing values of spatial difference index (SDI) is indicating the consistency in the spatial distribution of urban built-up patches and the higher degree of spatial concentration of the same inside the SDE rather than the outside (table. 5). The SDI is the function of the distribution discrepancies between the spatial objects within the SDEs and smaller the intersection areas of the SDEs, larger would be SDI and vice-versa. In the present study within the span of 2000 to 2020, almost alike trend in spatial growth rate of urban built-up patches (table. 3) and resultant SDE intersection areas are enumerating the consistency in the spatial distribution of urban built-up patches having the lesser values of SDI ranging between 0.14 to 0.11 (table. 5). Only exception is seen for the span of 1990 to 2000 within which maximum urban built-up growth rate as 31% (table. 2) is the enumerator of urban growth inconsistency and hence relatively higher SDI i.e. 0.20 (table. 5).

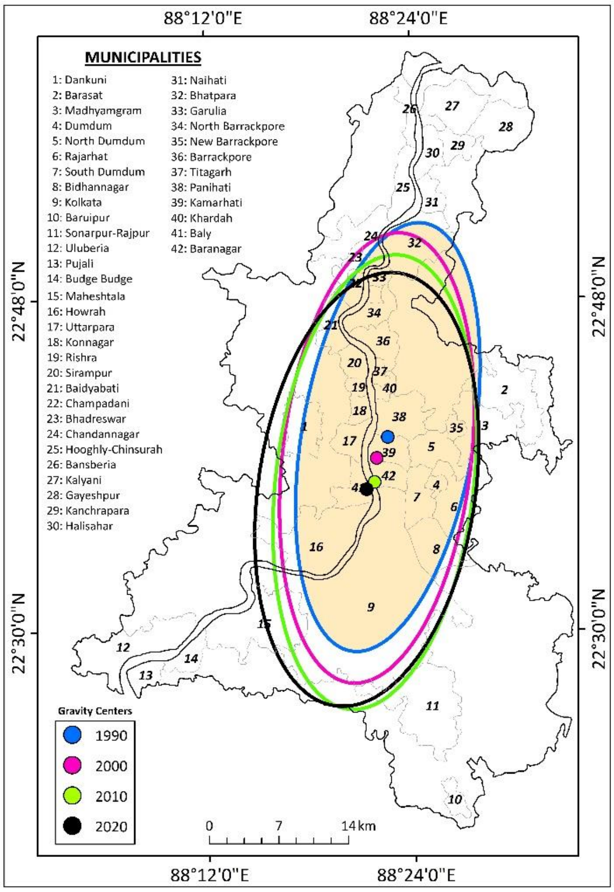

***Figure 2**. Plotting of Standard Deviation ellipse to describe the distribution pattern of urban patches and directional trends and the shifting of gravity centres on the temporal manner*

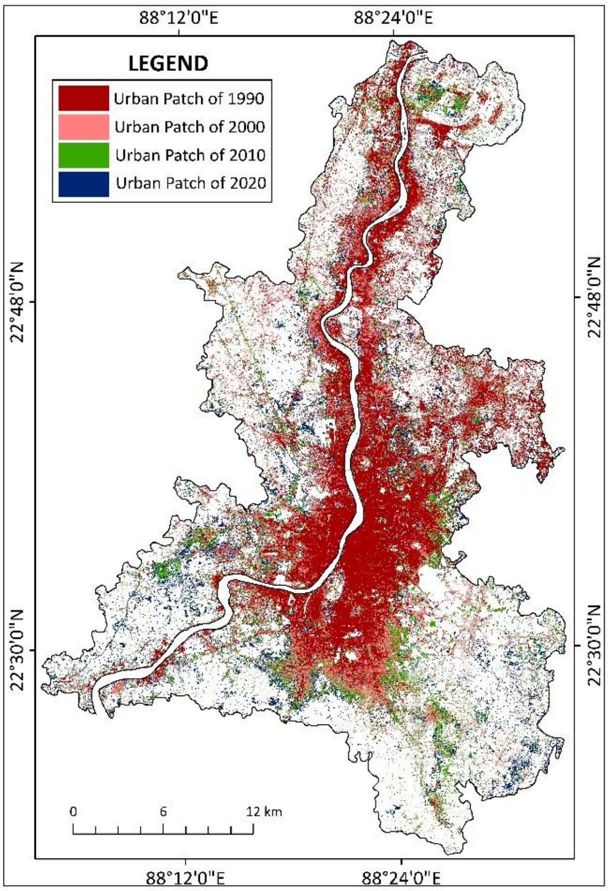

***Figure 3**. Spatio-temporal scenario of urban patches extracted using NDB from Landsat digital images of 1990, 2000, 2010 and 2020*

To assess urban expansion, the application of Standard Distance Ellipse (SDE) provides an overall description of urban growth, considering both statistical dispersion and the direction of growth based on the major axis's angular orientation. However, detailed insights into the directional growth dynamics of urban patches over time are better captured by transferring area information of urban patches (table.6) to directional wedges (figure. 4). Table 5 shows how the urbanization of the region has changed over the course of four decades (1990, 2000, 2010, and 2020), with the directions of urban expansion being North (N), Northeast (NE), East (E), Southeast (SE), South (S), Southwest (SW), West (W), and Northwest (NW). This dataset reflects the dynamics of urban sprawl and the changing landscape over time, showcasing how urban areas have grown in different parts of the region (Abdulhameed, Abdullah, Al-Masud, Abualhaija, et al., 2025; Abdulhameed, Abdullah, Al-Masud, Al Omari, et al., 2025; Wagh et al., 2025).

From 1990 to 2020, the data reveals a pronounced trend of urban expansion across all regions, with significant growth in each directional sector. The North (N) region, in particular, consistently maintained the largest urban area throughout these three decades. Beginning with an urban area of 111.16 square kilometers in 1990, the North's urban footprint expanded dramatically to 169.70 square kilometers by 2000, then to 197.06 square kilometers in 2010, and finally reaching 222.20 square kilometers by 2020. This represents a more than twofold increase over the 30-year span, underscoring the North's role as a primary hub of urban growth (table. 6).

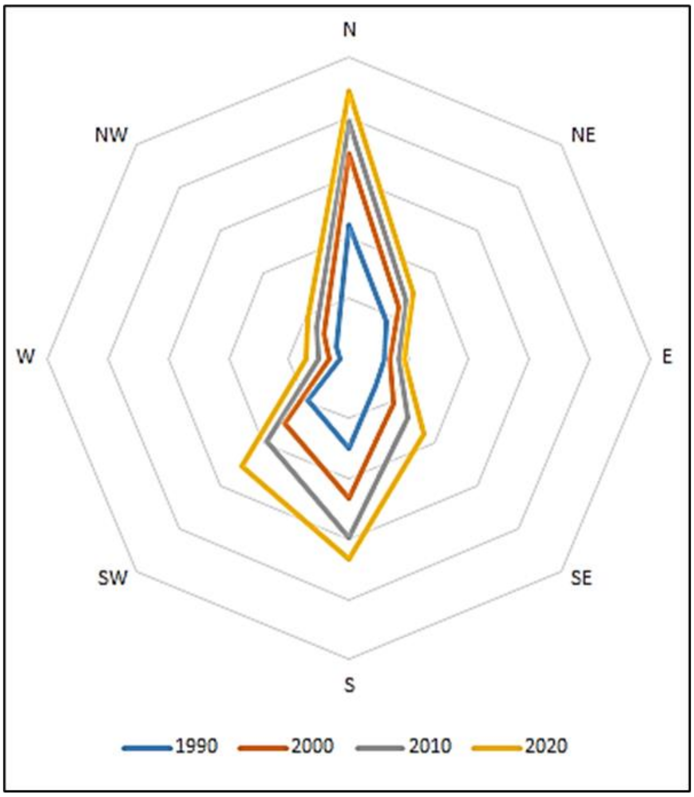

Figure 4. Radar diagram is depicting the directional pattern of temporal urban growth

This trend of urban expansion is not confined to the North but is mirrored in other regions, although to varying degrees. The Southeast (SE) region, for instance, saw its urban area increase from 31.49 square kilometers in 1990 to 52.77 square kilometers by 2000, a growth that continued to 69.89 square kilometers in 2010 and reached 88.33 square kilometers by 2020. Similarly, the Southwest (SW) region experienced substantial growth, with its urban area expanding from 48.46 square kilometers in 1990 to 76.27 square kilometers in 2000, further increasing to 96.71 square kilometers in 2010, and finally to 126.02 square kilometers by 2020. These expansions reflect broader patterns of urban sprawl, as the growth of cities and towns has increasingly pushed outward into surrounding areas (table. 6).

This outward expansion is indicative of several underlying factors. The consistent and significant growth in these regions suggests a combination of population increase, economic development, and possibly a demand for more residential, commercial, and industrial spaces as cities evolve. The data indicates the differing intensities of urban expansion among regions, influenced by factors such as land availability, infrastructural development, and regional planning strategies. The significant growth in the Southeast and Southwest regions can be ascribed to advantageous conditions for urban development, including relatively undeveloped land, closeness to economic centers, and particular municipal policies promoting expansion in these areas.

Furthermore, the data indicates that urban sprawl has not been uniform; instead, it has exhibited diverse patterns based on the location. The North, Southeast, and Southwest regions, which experienced substantial urban area expansion, presumably signify crucial growth corridors where infrastructure and economic activity have catalyzed intensified urbanization. Conversely, regions such as the West (W), which commenced with a modest urban area of

7.02 square kilometers in 1990 and expanded to 35.27 square kilometers by 2020, also underwent considerable relative growth, albeit the absolute extent of urbanization was lesser compared to the North, Southeast, and Southwest regions. This underscores the disparate roles of various locations in the overarching trend of urban sprawl, with certain areas emerging as significant growth hubs while others have evolved more incrementally.

Overall, the table (table 6) illustrates a significant and widespread expansion of urban areas across all directions from 1990 to 2020, with the North, Southeast, and Southwest regions standing out as major areas of growth. This data underscores the dynamic nature of urbanization, where economic, demographic, and policy factors converge to drive the expansion of cities and towns into new areas, reshaping the landscape over time. The growth observed in these regions reflects broader trends of urban sprawl, where increasing demands for space and resources have led to the continuous outward expansion of urban areas, influencing the development patterns and spatial organization of the regions over the past three decades.

Besides the key metrices like Growth Rate (GR), Urban expansion Intensity Index (UEII) and Annual Urban Expansion Rate (AUER) enumerate a comprehensive overview of urban expansion (table.7). The growth rate (GR) data reveals interesting patterns over the three decades. The West (W) and Northwest (NW) regions recorded the highest growth rates in the first decade (1990-2000), at 13.88 and 10.83, respectively. The elevated growth rates indicate a phase of swift urbanization in these areas during the 1990s. Nevertheless, the ensuing decades exhibit a significant decline in growth rates throughout all regions. The growth rate in the North (N) region decreased from 5.27 in the first decade to just 1.28 in the last decade (2010-2020). Urban areas have continued to expand, although at a significantly slower rate over time, as evidenced by the trend of declining growth rates in all directions. A number of factors, such as restrictions on available land, shifts in the economy, or modifications to urban planning laws, could lead to this.

Table. 6 Directional dynamics in urban area (sq.km.) showing urban expansion

Direction	1990	2000	2010	2020
	Areas in sq. km.			
N	111.66	169.70	197.06	222.20
NE	43.34	59.60	67.48	75.92
E	29.74	34.78	41.33	45.78
SE	31.49	52.77	69.89	88.33
S	75.11	116.65	149.06	165.80
SW	48.46	76.27	96.71	126.02
W	7.02	16.76	24.56	35.27
NW	13.76	28.66	36.92	47.27

Beyond this, the Urban Expansion Intensity Index (UEII) sheds light on the processes of urban growth. The Northwest (NW) region saw a drop to 0.52 between 2010 and 2020 from a high UEII of 0.94 between 1990 and 2000. The UEII decreased in the Southeast (SE) region from 0.84 in the first decade to 0.68 in the most recent decade. The decreases in UEII indicate a slowdown in the pace of urban growth in these locations, even while urban areas are still expanding. On the other hand, over the course of three decades, the UEII values in the Southern (S) region showed a rather constant pattern of urban expansion, suggesting that this pattern may be more durable.

This slowing in urban development is also indicated by the Annual Urban Expansion Rate (AUER). In the first decade, the West (W) area had the highest AUER of 9.10; however, in the second decade, it significantly decreased to 3.68. In line with this, throughout the same period, the AUER in the North (N) region decreased from 4.32 to 1.21. The steady decline in AUER in multiple sites suggests that while cities are still growing, the rate of new construction is slowing down. This could indicate that many regions are getting close to reaching urban saturation, which means there is less space available for further development.

The data demonstrates a distinct trend of substantial urban expansion in all directions during the past three decades, but with a marked deceleration in the rate of increase in the later years. The elevated growth rates and UEII values in the preceding decades indicate a phase of fast urbanization, presumably propelled by economic expansion, population growth, and maybe more permissive urban planning rules. Nonetheless, the diminishing growth rates, UEII, and AUER in recent decades indicate that these places are transitioning into a more advanced stage of urban development, wherein the emphasis may be shifting towards the management of existing urban areas rather than outward expansion. This could also reflect changes in policy towards more sustainable urban development, with an emphasis on improving infrastructure and services within existing urban areas rather than promoting unchecked sprawl.

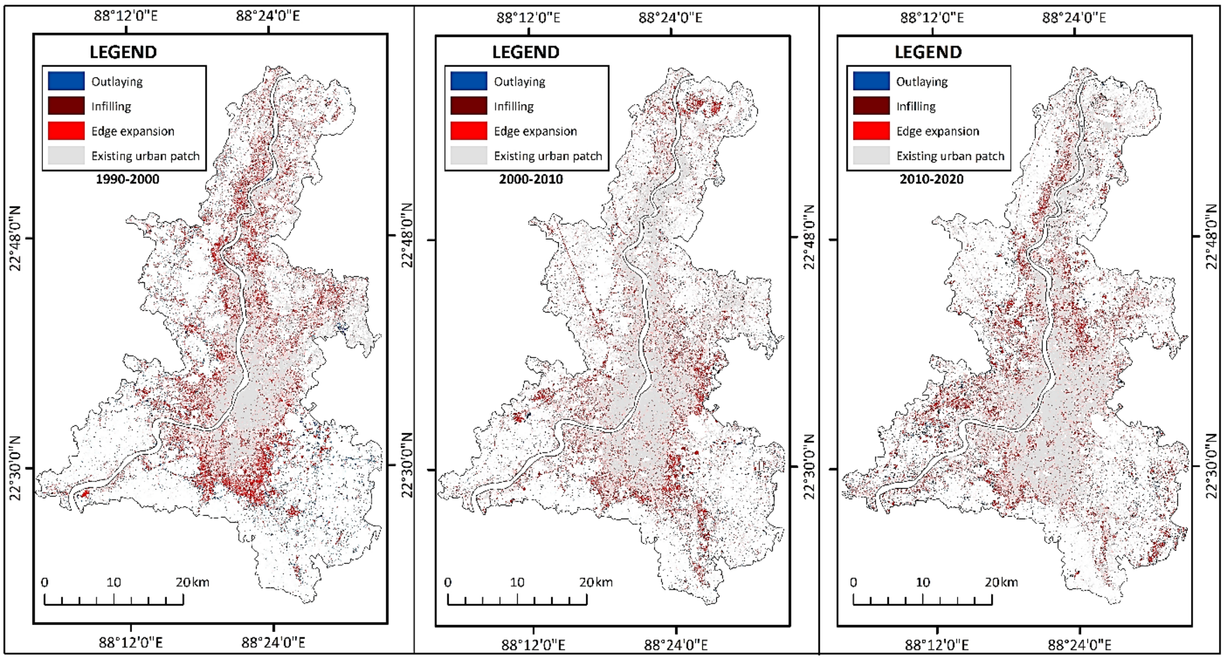

Figure 5. Scenario of typical urban expansions on temporal manner

Among the three temporal spans—1990 to 2000, 2000 to 2010, and 2010 to 2020—the first decade saw the most rapid urban growth in the KMDA, with an increase of 196.56 sq. km, accounting for 35.22% of the total urban area by 2000. In comparison, the newly developed urban patches in the subsequent periods, 2000 to 2010 and 2010 to 2020, constituted 18.71% and 15.34% of the total area, respectively. Based on these expansion figures and the concept of the Landscape Expansion Index (LEI), edge expansion was predominant, followed by outlying and infilling growth (Figure 5). The increasing trend of edge-expanding urban growth in the study area typically indicates the spread of sprawl, while infilling and outlying growth types reflect the agglomeration and dispersion of urban patches, respectively.

In the first temporal period, 148.11 sq. km area was as edge-expanding growth, which reduced to 107.19 sq. km and then again increased to 113.28 sq. km were in the next temporal periods respectively. From the first to second temporal period there was the maximum decline in edge expansion in northern sector (26.97 sq. km) followed by north-east (6.57 sq. km), south-west (3.67 sq. km), south (3.56 sq. km) and north-west (2.92 sq. km) sector. However, in the second temporal period there was a considerable increase in edge expansion in the east (5.11 sq. km), south-east (2.59 sq. km) and western sector (0.46 sq. km) as well. On the other hand, in the third temporal span there were an overall increase in edge expansion in every direction except southern and eastern sector. There was a decrease in edge expansion by 11.06 sq. km and 2.75 sq. km respectively (table. 8).

Table. 8. Temporal and Spatio-directional areal dynamics of typical urban expansion

Direction	Edge_ 1990-2000	Edge_ 2000-2010	Edge_ 2010-2020	infill_ 1990-2000	Infill_ 2000-2010	in-fill_2010-2020	leafrog_ 1990-2000	Leafrg_ 2000-2010	Leafrog_ 2010-2020
	Area in sq. km								
N	51.72	24.75	32.00	0.55	3.57	4.43	6.99	5.94	7.53
NE	14.50	7.93	12.88	0.76	1.53	0.36	1.34	1.61	1.94
E	3.50	8.62	5.86	0.38	0.05	0.11	1.19	1.72	1.02
SE	10.59	13.19	14.48	0.16	0.24	0.45	10.81	6.60	7.06
S	33.32	29.75	18.69	0.01	0.07	0.82	8.58	5.75	2.53
SW	21.98	18.31	26.80	0.03	0.23	0.38	6.49	5.13	9.63
W	6.76	7.22	10.80	0.01	0.14	0.06	3.33	1.17	2.93
NW	10.12	7.20	10.46	0.02	0.42	0.12	5.29	1.97	3.39

Alike edge expansion the urban growth in KMDA has significantly attributed by the outlying expansion. Though there was an overall decline from the first to second temporal span in areal growth as outlying in every direction except in north-east and eastern sector but third temporal span experienced an overall increase in outlying growth area except north-east, west and north-west sector. In this span the maximum areal expansion as outlying was in south-western sector followed by northern and south-eastern sector (9.62 sq. km, 7.53 sq. km and 7.06 sq. km respectively) (table. 8). Very little portion of the urban area has accounted for infilling type of urban growth. In each of the three temporal period there was an overall increasing trend in infilling growth. Specifically, the northern sector experienced the maximum amount of infilling growth like in the first temporal span there the infill growth was 0.54 sq. km. In the second and third span that was 3.56 sq. km and 4.43 sq. km respectively (table. 8).

4.2. Urban landscape fragmentation

The spatial arrangement of urban patches in regard to temporal dynamics of urban built-up land could be best explained by analysing the fragmentation of respective landscape through the computation of area weighted mean patch fractal dimension (AWMPFD). The value of AWMPFD tends to approach 1 for shapes with simple perimeters, like circles or squares, and approaches 2 for shapes with complex, plane-filling perimeters, while still adhering to the condition 1 ≤ AWMPFD ≤ 2. AWMPFD is a metric that quantifies a distinct aspect of the structure of urban land use. This metric specifically measures the level of fragmentation within each built-up patch, rather than providing an assessment of the overall homogeneity of urban patches, which is the focus of the contagion metric (Herold et al., 2002).

Generally, the outward growth of urban built-up landscape from the centre over time tends to be fragmented whereas this tends to be clustered towards the centre. This overall pattern is not an anomaly in the built-up landscape dynamics of KMDA except the situation of a steady state condition. This could be inferred from the comparative analysis between the distribution of AWMPFD value and the areal growth of urban built-up land on temporal manner. In this present study a comprehensive analysis of the metrics for each square block (measuring 2X2 km2) polygon has been conducted that encompasses the entirety of the study area.

The temporal AWMPFD index, in its thematic representation, portrays the dispersed growth pattern of urban built-up patches, those exhibit higher values as they extend towards the periphery of the KMDA boundary. Such increasing values of AWMPFD might be due to fragmented growth and emergence of new towns in and around the KMDA. On the other hand, the clustered growth pattern towards the centre is characterized by lower values (figure. 6).

4.3. ***Urban spatial pattern analysis***

In this present study, urban spatial pattern has been measured and analysed based on the percent coverage of urban pixels per 2 sq. km area. Following such percent coverages like ≥75%, 50% to 75%, 25% to 50% and ≤25%, study area has been classified in four categories like zone of primary urban core, secondary urban core, suburban fringe and scattered settlement respectively (figure. 7).

Table. 9. a. Correspondence Table, 1990

	L-VL	M-L	H-M	VH-H	Active Margin
SS	42	41	**190**	111	384
SUF	8	**40**	29	0	77
SC	**14**	**14**	12	3	43
PC	**15**	2	8	1	26
Active Margin	79	97	239	115	530

Table. 9. b. Correspondence Table, 2000

	L-VL	M-L	H-M	VH-H	Active Margin
SS	43	62	**229**	25	359
SUF	8	**40**	24	3	75
SC	12	**19**	16	4	51
PC	**21**	2	19	3	45
Active Margin	84	123	288	35	530

Table. 9. c. Correspondence Table, 2010

	L-VL	M-L	H-M	VH-H	Active Margin
SS	34	67	**216**	31	348
SUF	9	**43**	37	2	91
SC	**16**	14	11	2	43
PC	**24**	5	22	3	54
Active Margin	81	129	288	38	536

Table. 9. d. Correspondence Table, 2020

	L-VL	M-L	H-M	VH-H	Active Margin
SS	28	66	**225**	16	335
SUF	19	**53**	20	2	94
SC	13	**23**	17	0	53
PC	**28**	5	25	0	58
Active Margin	88	147	287	18	540

Distribution of such typical zonal patterns are very much analogous to the AWMPFD index. From the zone of primary urban core at the central position towards the zone of scattered settlement at outward situation, there is a perceptible increase in the values of the AWMPFD index. The correspondence between the categorized values of AWMPFD index in classes like very high to high, high to moderate, moderate to low and low to very low and the typical zonal distribution of urban spatial pattern can clearly be revealed from the perceptual maps (figure. 8 a-d) derived from multiple correspondence analysis (MCA). MCA is one of the potential tools to find the optimum ordering of variables for a given set of characteristics (Weller et al, 1990). Homogeneity between row and column elements in terms of categorised AWMPFD index values and typical zonal distribution of urban spatial pattern specifies the correspondence between them. Such homogeneity could be addressed by the maximum cross tabulated responses between each row and column elements (table. 9.a-d). Besides, the resultant perceptual maps are also distinctly describing the correspondence between the row and column elements through their characteristic association. In perceptual maps the close spacing between the elements depict the correspondence among them and vice versa. In this present study, for each period close spacing of low to very low level of AWMPFD with urban primary and secondary core, medium to high level of AWMPFD with sub urban fringe and scattered settlement as well depicted the characteristic associations viz correspondence between urban spatial patterns and urban patch fragmentation.

However, the temporal dynamics of typical urban spatial pattern is also noteworthy. A consistent growth was evident in zone of urban primary core, secondary core and sub-urban fringe area within the 30 years of span (table. 10) of the study. The zone of urban primary core has increased from 71.62 sq.km in 1990 to 104.51 sq.km in 2000 (at the growth rate of 3.85%), from 2000 to 2010 that has increased to 213.15 sq.km (at the growth rate of 7.39%) and to 435.48 sq.km in 2020 (at the growth rate of 7.41%). The zone of urban secondary core alike the primary core has also increased from 129.44 sq.km in 1990 to 198.80 sq.km in 2000 (at the growth rate of 4.38%). But in 2010 the growth rate has slowed down. It has increased to 222.53 sq.km at the growth rate of 1.13% and again it has increased to 439.41 sq.km in 2020 at regained growth rate as 7.04%. However, for the zone of sub-urban fringe areas, the growth rate was considerably slow like from 1990 to 2000 that was 0.51%, from 2000 to 2010 that was 0.08% and from 2010 to 2020 that was 1.15%. On the other hand, there was a distint decreasing in the zone of scattered settlement. From 1990 to 2020, the area has decreased from 1262.35 sq.km to 417.38 sq.km (at the growth rate of -3.35%).

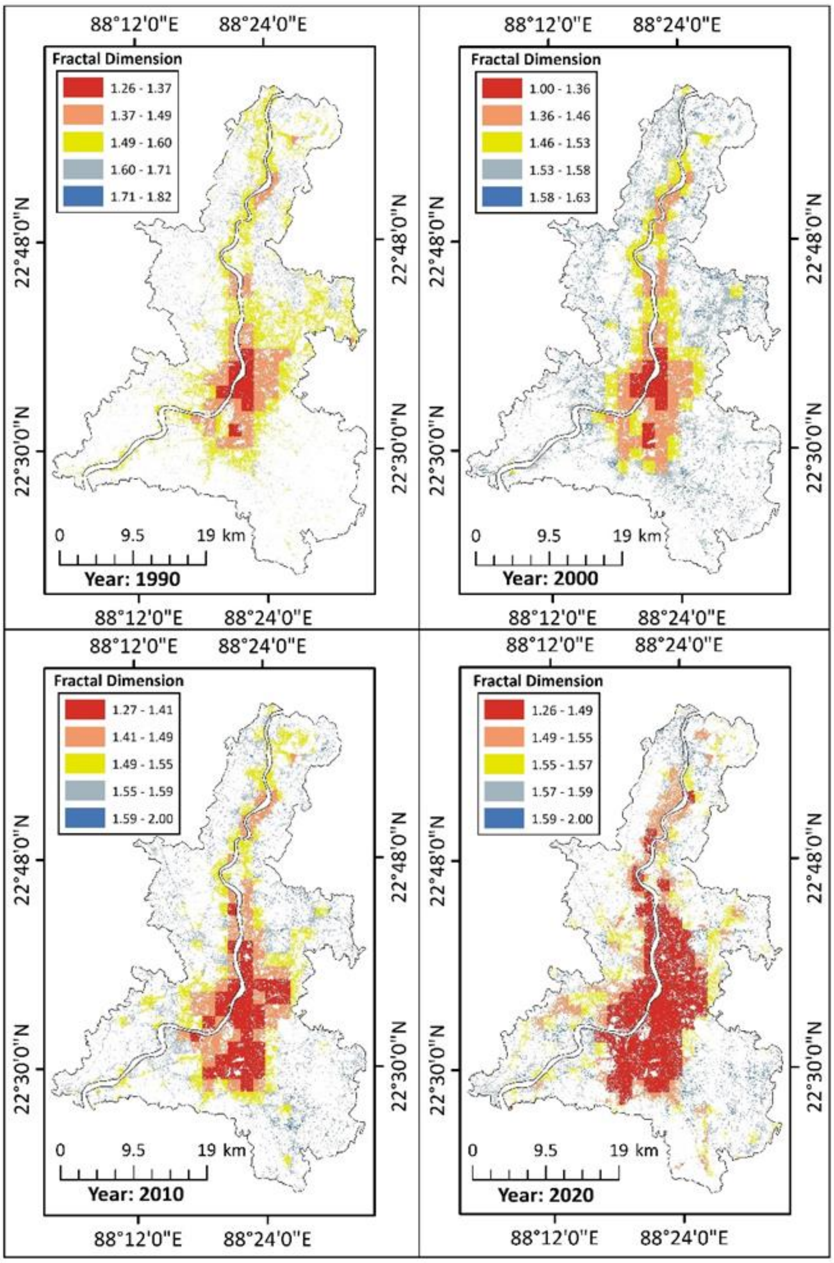

Figure 6. Thematic presentation of AWMFPD to show the urban patch fragmentation on temporal manner where clustering of patches is seen at the centre and fragmentation are seen towards the periphery

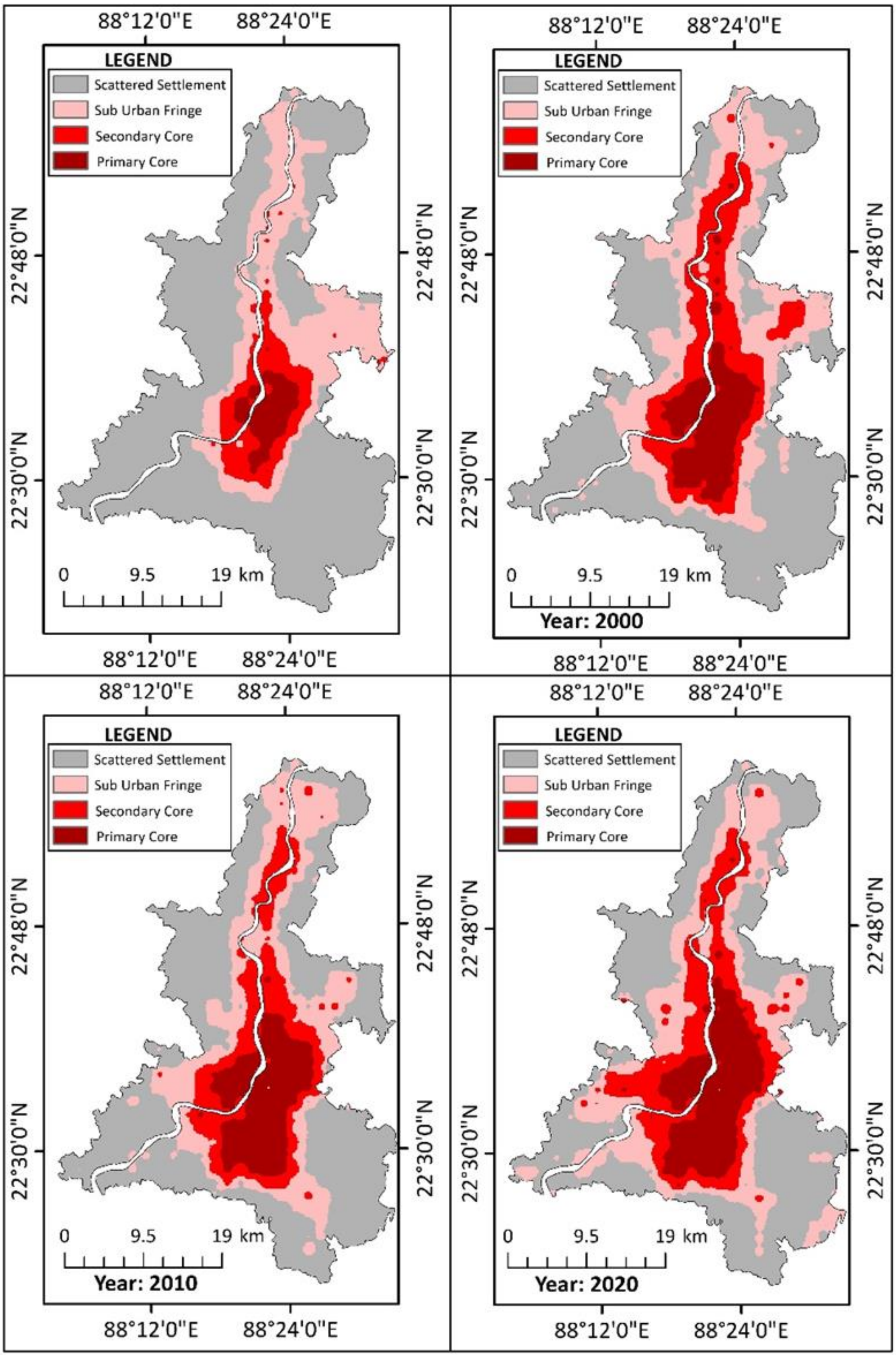

Figure 7. Temporal nature of urban spatial pattern

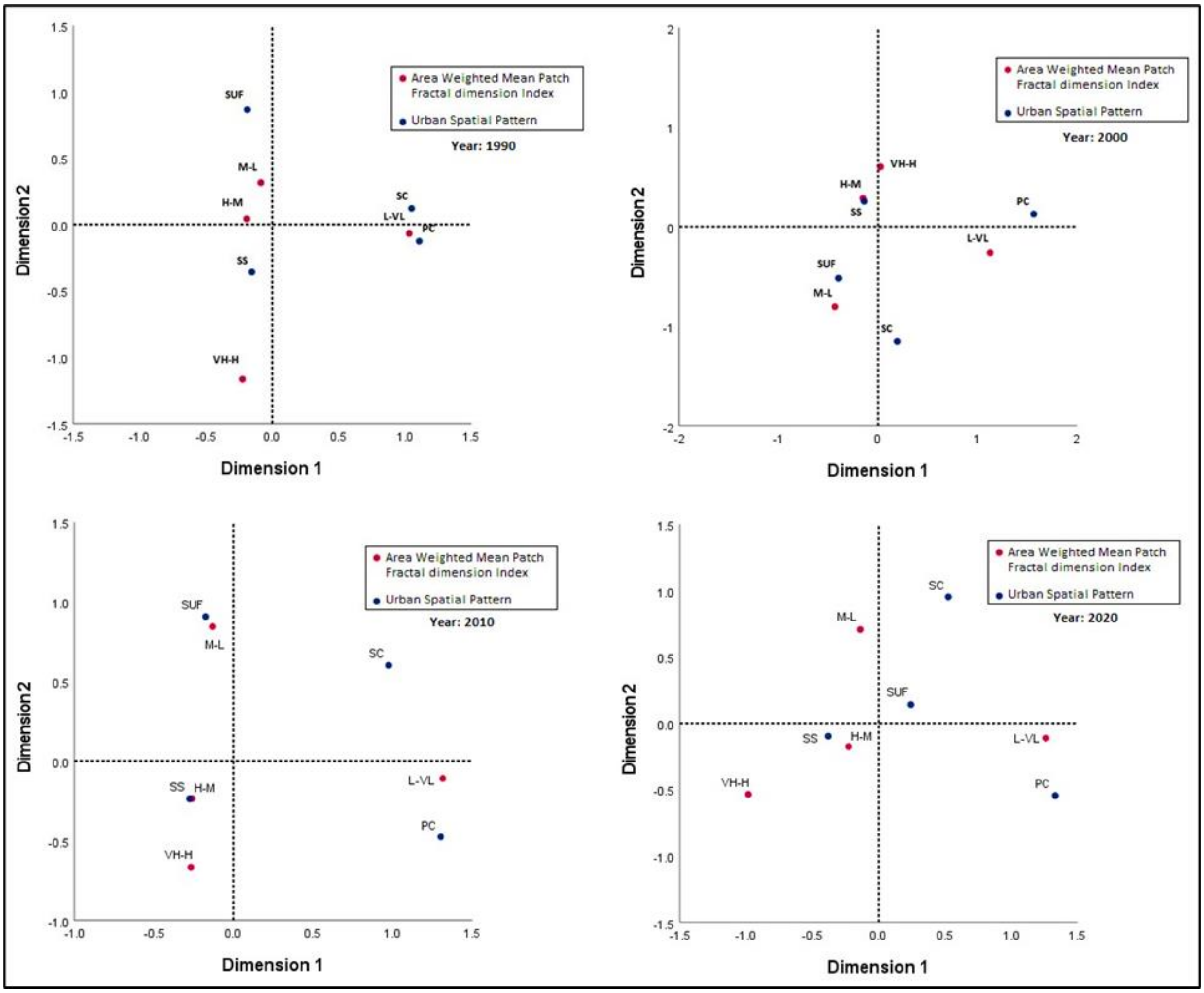

Figure 8. Depiction of correspondence between AWMPFD and urban spatial pattern using Multiple Correspondence Analysis

Table. 10. Temporal areal dynamics of typical urban spatial pattern

Description	1990	2000	2010	2020
	Area in sq. km			
Primary Core	71.62	104.51	213.15	435.48
Secondary Core	129.44	198.80	222.54	439.41
Sub-urban Fringe	377.58	397.20	400.33	448.72
Scattered settlement	1162.35	1040.49	904.99	417.39

5. DISCUSSION:

The planning and development of the Kolkata Metropolitan Area (KMDA), which includes Kolkata city and the surrounding suburban areas, is under the jurisdiction of the Kolkata Metropolitan Development Authority (KMDA). From 1990 to 2020, the KMDA has been involved in major changes brought about by infrastructural expansion, population shifts, and economic reforms. Within this 30 year of spans, typically three phases of urban growth could be indicated like from 1990 to 2000: the initial expansion stage, from 2000 to 2010: rapid sub urbanization phase and from 2010 to 2020: the consolidation and modernization phase. Urban growth was primarily concentrated in the city core and nearby areas like Salt Lake (Bidhannagar) during the first phase (1990–2000), with some early developments in areas like Rajarhat (Mukherjee, 2006). Suburban areas like South 24 Parganas, Howrah, and Rajarhat had substantial business and residential development between 2000 and 2010. According to Das and Datta (2002), the New Town project became a significant metropolitan center. Significant development occurred in outlying places including Baruipur, Sonarpur, and Kalyani during the last phase (2010-2020). With high-rise residential and commercial buildings, vertical growth was also prioritized (Roy, 2019).

Between 1990 and 2020, the Kolkata Metropolitan Development Authority (KMDA) region had substantial urban changes that were typified by polycentric expansion, a pattern in which several hubs of infrastructural, residential, and economic development appear within a metropolitan area. This layout supported a more sustainable and balanced urban landscape by reducing demand on the conventional urban core.

Urban growth in the KMDA's northeastern (Bidhannagar, Barasat, and Madhyamgram) and southeastern (Rajpur-Sonarpur and Baruipur) regions accelerated due to significant shifts in the state's industrial and economic policies in 2000 (Shaw & Satish, 2007). Major metropolitan cities and urban areas in India experienced substantial urbanization as a result of the economic liberalization of 1991 (Mondal, Das, & Dolui, 2015). In the northwestern (Dankuni) and southwestern (Sankrail-Abada) zones, the development of key industrial hubs further spurred this expansion (Vision 2025, KMDA). Notably, the current rate of urban expansion in the KMDA is significantly higher in settlements (census towns and villages) under rural administration compared to those under urban governance. This highlights the ongoing trend of informal urbanization, where unregulated development is encouraged in peri-urban areas managed by rural institutions (Roy, 2005; 2011; 2016).

The economic liberalization of India accelerated transition of Kolkata from an industrial to a more diversified economy in the early 1990s. A basis for polycentric growth was established during this time, with an emphasis on the development of satellite townships and improving communication within the metropolitan area. Salt Lake City (Bidhannagar), which was first founded in the 1960s, kept growing until a major change occurred with the emergence of Sector V as an IT hub. This drew professionals and tech businesses, establishing a new economic hub beyond the conventional city center (Chakrabarti et al., 2014). Furthermore, the Eastern Metropolitan Bypass, an important infrastructural project, enhanced connection between Kolkata's eastern and southern edges, enabling the growth of the city's residential and commercial sectors (Mukherjee, 2006).

Rapid suburbanization and the emergence of new urban centers were the outcomes of significant economic growth and well-executed urban planning in the first ten years of the twenty-first century. Thought of as a contemporary satellite town, New Town, Rajarhat quickly became a well-known urban center with large investments in IT parks, residential complexes, and commercial centers, signifying the urban development of Kolkata (Das & Datta, 2002). By generating an efficient economic node outside of the city center, Sector V in Salt Lake maintained its position as a significant IT hub and brought in a large number of technology companies and professionals, which in turn contributed to the larger polycentric pattern (Sengupta, 2008). Suburban areas witnessed substantial residential and commercial development, especially in Howrah and South 24 Parganas, which are located south of the Hooghly River. This development was supported by better connectivity made possible by bridges such as Vidyasagar Setu (Roy, 2019).

By 2020, the Kolkata metropolitan area had many development centers, signifying the effective implementation of the polycentric growth model. New Town, Rajarhat was designated a Smart City, emphasizing sustainable development and technology integration, thereby enhancing its status as a leading urban center with smart infrastructure efforts that improve economic productivity and quality of life (Bose, 2018). The extension of the Kolkata Metro network, particularly the East-West Metro Corridor between Howrah and Salt Lake, has greatly facilitated polycentric growth by enhancing connectivity and permitting the movement of individuals and goods (Chatterjee, 2018). Over the decade, suburban regions such as Baruipur, Sonarpur, and Kalyani experienced both horizontal expansion and vertical development, exemplified by the erection of high-rise residential and commercial edifices in areas like New Town and along the Eastern Metropolitan Bypass (Chattopadhyay, 2011; Dasgupta, 2019).

Despite the various advantages of polycentric growth, including equitable economic development and reduced congestion in the urban core, it also presented certain disadvantages. Rapid urbanization has precipitated environmental challenges such as the degradation of wetlands and natural habitats (Dutta, 2010). Traffic congestion and inadequate public services resulted from infrastructure development frequently trailing the rapid growth (Sarkar, 2012). Disparities in access to infrastructure and services among various metropolitan areas exemplify the persistent nature of socioeconomic inequality. (Mitra, 2015).

The KMDA region underwent substantial transformation from 1990 to 2020, marked by polycentric urban development. This growth pattern mitigated pressure on Kolkata's historic core by creating numerous growth centers, supported by strategic planning, infrastructure development, and economic diversification. Although the polycentric method has numerous benefits, it is essential to advocate for equitable and sustainable urban growth by continually tackling social, infrastructural, and environmental issues.

The study provides important insights into the differences in intra-urban growth patterns compared to theoretical expectations, highlighting the variations between the inner and outer zones of the Kolkata Urban Agglomeration (KUA). The growth dynamics in these areas are varied and exhibit distinct characteristics that challenge conventional urban growth theories. The core areas typically experience densification and redevelopment, whereas the outer regions observe significant suburbanization and expansion of urban infrastructure.

The research predominantly use landscape metrics to objectively evaluate the geographical characteristics and intricacies of urban growth. The metrics demonstrate that coalescence, the merging of smaller urban areas into larger, contiguous ones, has been the primary driver driving urban expansion in KMDA. This process indicates a transition from a dispersed urban growth pattern, known as diffusion, to a more cohesive and integrated urban framework.

The increase in patch shape complexity, measured by the Area-Weighted Mean Fractal Dimension (AWMFD), underscores this alteration. As urban regions converge, their borders become progressively irregular and complex, reflecting the integration of diverse land uses and infrastructure elements. The shift from diffusion to coalescence has been noted in both the center areas and the growing edges of the agglomeration, indicating a widespread change in the urban growth pattern during the research period (Dietzel, Herold et al., 2005; Dietzel, Oguz et al., 2005).

The urbanized and mixed-use regions of the Kolkata Metropolitan Area (KMDA) have experienced continuous growth, resulting in a decline of undeveloped land (Mithun, 2020; Mithun et al., 2016). This extension has revealed substantial discrepancies between KMDA-urban and KMDA-rural areas. The developed and mixed-use areas of KMDA-rural have experienced significant expansion due to accelerated periphery growth. Conversely, KMDA-urban has experienced an expansion of built-up areas alongside a reduction in mixed-built-up areas, indicating that mixed-built-up land is being transformed into exclusively built-up land.

The most typical type of land cover has continued to be built-up land, followed by mixed-built-up areas. While non-built-up land is mostly being converted to mixed-built-up areas in KMDA-rural, mixed-built-up areas in KMDA-urban are mostly transitioning to built-up areas. This brings prominence to a paradox in urban growth: although urban sprawl transforms undeveloped land into mixed-use areas, infill, expansion, and edge growth processes are turning already-existing mixed-use regions into entirely urban built-up areas (Mithun, 2020; Mithun et al., 2016).

The typical spatial pattern of growth in the KMDA can be categorized into several zones: the urban primary core, urban secondary core, suburban fringe, and scattered settlements. The urban primary core includes central Kolkata, where growth is characterized by high-density development, infill projects, and redevelopment of existing structures. Areas like Esplanade, Dalhousie, and Park Street represent this core, exhibiting significant vertical growth and infrastructure modernization. The urban secondary core consists of emerging urban centers within the metropolitan area that function as significant economic and administrative hubs. Salt Lake (Bidhannagar) and Sector V serve as prime examples, with Salt Lake evolving into a major IT and commercial hub and Sector V becoming a critical IT corridor.

The suburban fringe encompasses regions that shift from rural to urban land use, propelled by suburbanization and emerging residential developments. Areas such as Rajarhat New Town illustrate this trend, characterized by swift infrastructure advancement and the emergence of new residential developments that have altered the environment. Dispersed towns demonstrate fragmented urban development and are often situated at the outskirts of metropolitan areas. Areas such as parts of Howrah and South 24 Parganas demonstrate uneven growth marked by varying densities and land uses.

Understanding these trends is crucial for urban planning, as it highlights the dynamic and complex nature of urban development in KMDA. The results imply that continuous urbanization is causing high-density developed zones to expand beyond formerly moderate and low-density areas. The rapidly expanding urban center is extending the urban edge into the neighboring rural region. The urban environment evolves as low-density areas advance and retreat from the growing city. The urban-rural border, especially amid rapidly expanding urban agglomerations, is more aptly regarded as a dynamic frontier than a static zone.

(Bosch et al., 2020; Dong et al., 2019). The shift from diffusion to coalescence, the differing growth dynamics of inner and outer zones, and the transformation of mixed-use regions into developed land underscore the necessity for strategic and sustainable urban development plans. These insights can mitigate the problems of fast urbanization, including environmental degradation, infrastructure pressure, and social inequality, so guaranteeing a balanced and equitable growth trajectory for the metropolitan region.

The dominance of edge expansion, together with the fluctuating growth and decline between infilling and outlying modes, aligns with the theoretical foundations of the three-growth mode framework for overall agglomeration. Nonetheless, discrepancies were present among the six sub-territories, along with their external and internal boundaries. In Phase I, infilling in the outside sections was negligible, and peripheral expansion in the inner portions was limited. In Phase II, edge expansion dominated the outer regions, restricting outlying growth, while infill type-1 prevailed in the inner areas, reducing edge expansion. Throughout the study, infilling increased in the inner sub-territories at the expense of outlying development and edge expansion, indicating conflicting processes. However, in Phase II, significant infilling occurred only in two sub-territories of the outer regions. These results show variations from the predicted paths of urban growth, indicating that widely accepted models of urban growth (Bosch et al., 2020; Dahal et al., 2017; Li, Li, Wu et al., 2013) need to be re-examined. These growth patterns and trajectories are further accentuated by the subdivisions found within the city's larger spatial extents.

In order to examine growth dynamics, this research used a directional method, breaking the Kolkata Metropolitan Area (KMDA) up into eight directional sectors: north, north-east, east, south-east, south, south-west, west, north-west, and north. This approach is more successful at handling the complexities of KMDA than standard zoning solutions, which concentrate on administrative divisions like wards or municipalities (Punia et al., 2012; Sudhira et al., 2004). The study described typical patterns of urban development as well as specific growth trajectories and rates. Notable disparities exist between the urban center and rural periphery in big metropolitan systems like KMDA with regard to economic frameworks, infrastructure, urban amenities, local government, and population growth, all of which have an impact on urban planning. (Mithun et al., 2016). Different factors impact urban expansion in the core and the periphery, necessitating specialized planning and policy approaches. Zoning analysis, which takes into account the administrative, socioeconomic, and demographic aspects of KMDA, is therefore a useful instrument for studying urban growth and may be skillfully applied to the creation of policies and plans for urban areas.

To complete, the sprawl in patterns of urban form observed in this study especially edge expansion or low density urban sprawl haves with grave consequences for environmental sustainability in the campus of Kolkata Metropolitan Area. A significant decrease in ecological buffers that regulate urban microclimates and water retention has resulted in converting agricultural land, wetlands and peri-urban green spaces in built-up areas. This conversion has resulted in greater surface runoff, less groundwater recharge, and greater susceptibility to flooding especially in the low-lying southwestern areas. Furthermore, the fragmentation of green patches and elimination of vegetative cover have adversely affected local biodiversity and air quality. As urban centers expand out, reliance on wheeled propulsion increases, adding emissions and poor air quality into this sundry equation. The findings emphasize the need to integrate ecological considerations in urban planning frameworks such as greenbelt preservation, compact growth strategies and sustainable drainage systems to reduce the environmental costs associated with urban land expansion.

Overall in summary, this study demonstrates the complex, multi-directional manner of urban growth in the Kolkata Metropolitan Development Area over three decades, with a significant predominance of edge expansion and a clear shift in growth direction towards the south-west. The integration of spatial metrics using AUER, UEII, LEI, AWMPFD, and MCA provides detailed insights into the magnitude and pattern of urban sprawl [13]. These findings also have practical implications for urban governance. It is in the understanding of this spatial bias towards expansion that planners can target infrastructure that align with high-growth zones particularly in the south-western periphery. In addition, detecting edge-dominated growth patterns indicates the need to implement stronger landuse regulation and more aggressive infill development strategies to limit sprawl. The study reinforces the need for regional planning to align with both transportation infrastructure and socio-economic dy-namics, in order to achieve more balanced and sustainable urban development.

CONCLUSION:

The land use of the Kolkata Metropolitan territory (KMDA) has changed significantly, especially with the rise in built-up and mixed-use zones and the decline in non-built-up territory. There are considerable differences in these developments across the urban and rural areas of KMDA. Built-up and mixed-use projects have increased in rural areas due to rapid peripheral expansion, but in metropolitan settings, mixed-use land is progressively being converted into fully developed zones, reflecting dynamics of edge growth, urban sprawl, and infill(Mithun, 2020; Mithun et al., 2016).

The study employs a spatial pattern-based approach to examine the relevance of traditional urbanization theories to KMDA's growth patterns. It reveals that the dense urban core has extended outward, affecting both already urbanized zones and previously undeveloped open spaces. The peripheral areas, in particular, are the most dynamic, showing significant variations in urban growth metrics across different spatial scales.

At the metropolitan level, there is a discernible transition from diffusion to coalescence. Inner-city areas primarily exhibit coalescent growth, while outer zones show mixed patterns of diffusion and coalescence, varying in intensity across distinct sub-territorial units. These multi-scale analyses are essential for understanding intra-urban differences and for formulating spatial policies that cater to diverse growth patterns.

The study's zoning technique proves to be a robust method for examining urban growth dynamics, with potential applicability to other developing metropolises. It highlights rapid growth, especially in KMDA's peripheral areas, underscoring the need for sustainable residential development supported by adequate infrastructure, particularly in the west, southwest, south, southeast, and east directions. Future urban planning should focus on compact growth strategies to curb sprawl, with regular assessments to ensure growth targets align with urban planning goals, thereby promoting sustainable development.

To effectively manage urban sprawl, the study recommends implementing target-based growth strategies at both local and metropolitan levels, with periodic evaluations to ensure that actual growth matches planned objectives. Integrating these strategies into urban planning could encourage more compact urban growth and prevent unplanned expansion. Further research across various urban areas and city sizes could enhance urban growth theories and inform policies for sustainable urbanization, with a focus on dynamic spatial territories and intra-urban growth patterns to mitigate environmental impacts (Mithun, 2020; Mithun et al., 2016).

Policy Implications:

The results of this study could be a good reference for urban policymakers and planners. This edge growth and urban sprawl towards the south-west requires forward-thinking zoning regulations to impose control on the inordinate amount of peripheral development. Authorities can encourage infill development in our cities, for example, to use land more efficiently and ease pressures on infrastructure. The high-growth identified zones may be prioritized for preventative planning of infrastructure, e.g. networks for transport, drainage and green space. Moreover, to incorporate spatial indices, for instance, LEI and AWMPFD into regular urban monitoring assists evidence-based planning decisions so that urbanization could be regulated in a suitable amount in accordance with environmental conditions.

Limitations

Although this study is comprehensive, some limitations should be recognized:

Classification Uncertainties:

Landsat based urban land cover classification may contain erroneous elements because of medium spatial resolution (30m) and similarity of building and bare soil spectral signature. Although accuracy assessments were carried out with Google Earth and other ancillary data, there may be some misclassification, especially in mixed land-use areas.

Temporal Resolution of Data:

Urban growth was evaluated at decade intervals (1990, 2000, 2010, and 2020). Intermediate variability and short-to mid-term land use transitions may not be captured, missing out important things like sudden switches from large policy acts or infrastructure projects.

Model Assumptions:

These four spatial indices (AUER, UEII, LEI, AWMPFD, and MCA) are based on random assumptions on landscape structure and urban behavior. These models are commonly used in the study area, but the interpretations were spatially selective, and may not accurately represent all areas for all zones of the KMDA.

Absence of Socioeconomic and Policy Variables:

This study analyzed the spatial metrics and remote sensing data. But even though some policy and infrastructure input is provided indirectly, integration of demographic, economic and policy datasets into the dataset would enhance insights into urban dynamics.

Biases Potential In Ground Reference Data:

Use of Google Earth and limited ground-truthing to assess accuracy may induce bias, especially for earlier years (1990, 2000) with sparse or inconsistent historical high-resolution imagery.

Future studies can overcome these restrictions by using higher spatial resolution satellite data (as Sentinel-2 or PlanetScope), broader temporal scales, and harmonized socio-environmental databases for a comprehensive urban analysis approach.

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