Estimating the urban expansion and heterogeneity of a metropolitan region: a case of Kolkata metropolitan area

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Urban planners study development patterns along with the rate and type of urban expansion to formulate policies and schemes for planned and integrated future development of the cities. This study aimed to explore the dynamics of urban sprawl in the metropolitan region of Kolkata by using Gini–Simpson's diversity index. It was used on the generated decadal maps to understand the degree of spatial concentration or dispersion of the built areas. It revealed that the urban sprawl was increasing in the outskirts of the Kolkata metropolitan area (KMA) with gradual dispersion and increased heterogeneity. A better understanding of the spatial and temporal dynamics of the city's growth, provided by this study, forms the basis for better planning and effective spatial organization of urban activities for the future development of KMA.

Keywords: Built-up index, impervious surface area, spatial metrics, urban expansion, urban sprawl.

URBANIZATION has been defined as transforming non-built-up areas into built areas or rural areas into urban areas over time[1]. Globally, half of the population lives in urban areas, and the population living in urban areas increased to 55% in 2018; if the same trend is followed, the population will reach 68% in 2050 (ref. 2). India and China lead the urban development in Asia due to increased population and urban expansion[3]. Presently, the population of India is less than one-third of the total population, but by 2050, it will be one-half of the total population[3]. So, it becomes imperative to conduct further research on urban growth and development in developing countries, especially in India, for sustainable future development.

The impact of urban expansion is studied mainly for developing countries worldwide. There are literature that discusses the urban growth and sprawl in developing countries like India, China and African countries[4]. The majority of the research on urban sprawl is conducted either in the municipal boundary or city limits[4,5]. Few studies discuss the change in land-use land-cover (LULC) and urban sprawl in a regional context[6,7]. In India, urban sprawl is studied in city limits and not from a regional perspective[8]. Moreover, the methodology for detecting sprawl revolves around Shannon entropy and landscape metrics[9]. Out of these, the maximum number of research uses the traditional method of Arc GIS plugin of patch density to calculate the landscape metrics, and the calculation of Shannon entropy is done statistically for the given cities[10].

This research explores the gap in existing literature for calculating urban sprawl, considering both spatial and statistical approaches. The modified spectral index was used to make the impervious surface area map to detect the presence of sprawl. The modified impervious surface built index and the Simpson diversity index, were never used before to detect urban sprawl using the Landsat 9 imagery. Kolkata metropolitan area (KMA) was selected as the case for the study to understand the impact of urban expansion and growth from a regional perspective.

Some literature that discusses the sprawl of Kolkata, either talks about the municipal boundary of Kolkata city or it emphasizes the urban agglomeration of Kolkata, highlighting both the rural and urban areas around Kolkata[11,12]. So, for this research, the regional context of Kolkata is taken as the case study. Spectral index-derived impervious surface and the land-surface temperature are generally used to detect the sprawl. In this research, the spectral index is found on the Landsat 9 and Landsat 8 images by modified methods to get a novel approach to the detection of sprawl.

Advancements in remote sensing and GIS technology helped improve the overall accuracy of the data and helped in acquiring less expensive satellite images[13]. Remote sensing and GIS tools, along with spatial metrics, can be used to measure the pattern and dynamics of urban expansion and help better understand and visualize the data[12].

India's urban population growth rate is 2.1%, greater than the world's urban growth rate of 1.6% (ref. 14). Growth in urban population and economic development in recent years resulted in unplanned urban developments in different parts of India, specifically in West Bengal. KMA experienced the most urban expansion due to better living conditions and job opportunities[15]. Several studies have talked about the urban expansion of the city of Kolkata[11], but only a few studies have highlighted the dynamics and patterns of urban developments of KMA. KMA is the core of West Bengal, connecting different districts and serving as a

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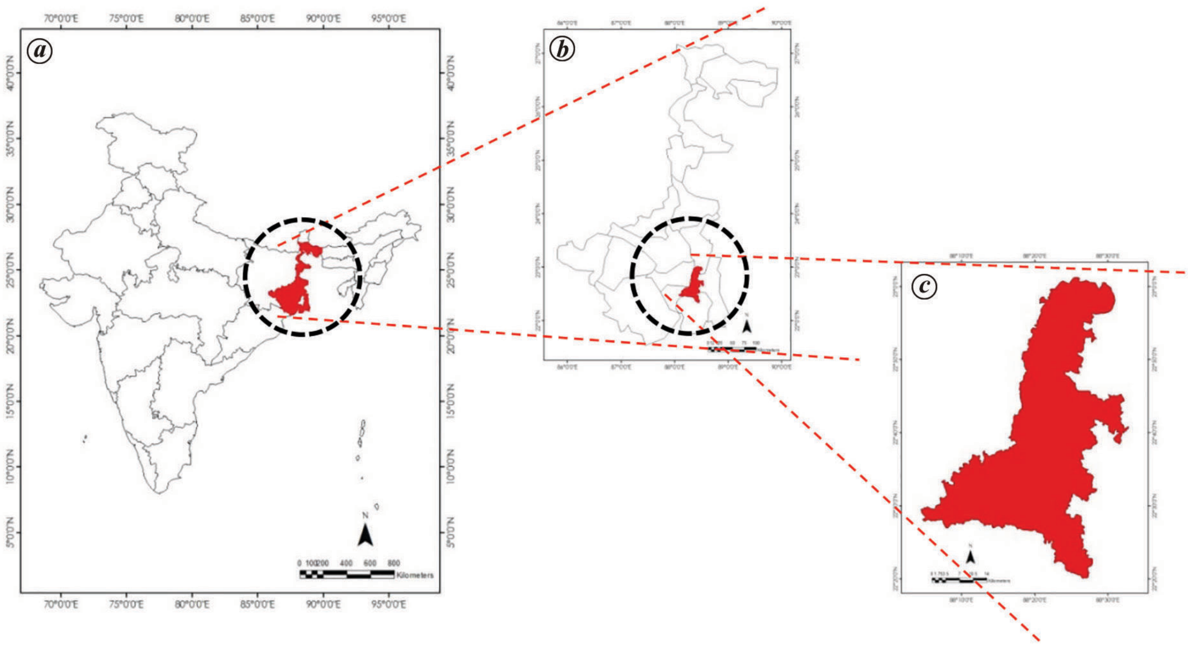

Figure 1. Location map of the study area.

rural–urban link. The perspective plan of KMDA is up to 2025. So, it is essential to understand the dynamics of the development of KMA to develop policies and schemes to sustain the city's future development.

So, the main objectives of the study were: (i) to detect the existence of any urban sprawl in KMA by analysing the change in the urban expansion, and (ii) to confirm the finding of sprawl by the new modified technique of spectral index-derived impervious surface area. This study helped analyse the change in spatial dynamics of KMA and the detection of urban sprawl in the periphery of KMA. It provided a base for proposing schemes and policies for the sustainable future urban development of KMA.

Materials and methods

Description of the study area

Kolkata metropolitan region (KMR), also known as Kolkata metropolitan area (KMA), was previously known as Calcutta metropolitan area. KMA is the urban agglomeration of the city of Kolkata in the state of West Bengal, India (Figure 1). After Delhi and Mumbai, it is the third most populated metropolitan area with a population of 14,112,536 and a population density of 7500/km^2, according to Census 2011 data. KMA lies between 23°3′0″–22°20′0″N and 88°3′0″–88°33′0″E, and the altitude ranges from 1.5 to 9 m. According to data from the 2011 Census, KMA comprises 4 municipal corporations and 37 municipalities. The KMA districts are Kolkata, North 24 Parganas, South 24 Parganas, Nadia, Howrah and Hooghly. In this study, the boundary of KMA is taken from the official website of Kolkata Municipal Corporation.

Data sources

OLI-TIRS for 2013 and 2023 was used to produce the built-impervious surface maps. The Landsat images of the year 2022 and 2023 were downloaded from the official website of the United States Geological Survey (USGS). In the search criteria tab of the USGS website Kolkata, was selected along with dates and cloud cover. For every image acquired, the cloud cover was kept below 5% in the USGS filter parameter, and the dates of the images were selected based on this parameter. The date of the image acquired for the years 2013 and 2023 was 19 April 2013 (path 138, row 44) and 7 April 2023 (path 138, row 44).

In the dataset tab of the USGS website, Landsat 8-9 OLI/TIRS C2 L2 was selected under Landsat Collection 2 Level-2. The images were imported into Arc Map 10.8, and the BUI was calculated using the raster calculator. The datum taken was WGS84, and the map projection was UTM. The secondary data was collected from the Kolkata Municipal Corporations. Arc Map 10.8, and MS Excel 2022, were used for the analysis part. Table 1 shows the dataset information.

Methodology

Experimented spectral index derived impervious surface area

The spectral index is one of the methods used to detect urban growth and sprawl[6]. The spectral index is a computational model used for feature extraction with the help of multi-spectral images. It is calculated by finding out the mathematical ratio between the spectral bands.

Table 1. Dataset information

Data collected	Purpose	Processing	Year	Description	Source	Data format
Landsat 8 imagery	BUI map and Simpson's diversity index	Raster calculation in Arc GIS	2013	USGS Landsat 8 OLI/TIRS Collection 2	USGS	Tiff
Landsat 9 imagery	BUI map and Simpson's diversity index	Raster calculation in Arc GIS	2023	USGS Landsat 9 OLI/TIRS Collection 2	USGS	Tiff
KMA boundary	To define boundary of KMA	Shape file editor in Arc GIS	2023	JPEG map of KMA was georeferenced and shape file was made using polygon tool of Arc GIS	KMDA	Shp

BUI, Built up index; KMA, Kolkata metropolitan area; USGS, United States Geology Survey, KMDA, Kolkata Metropolitan Development Authority.

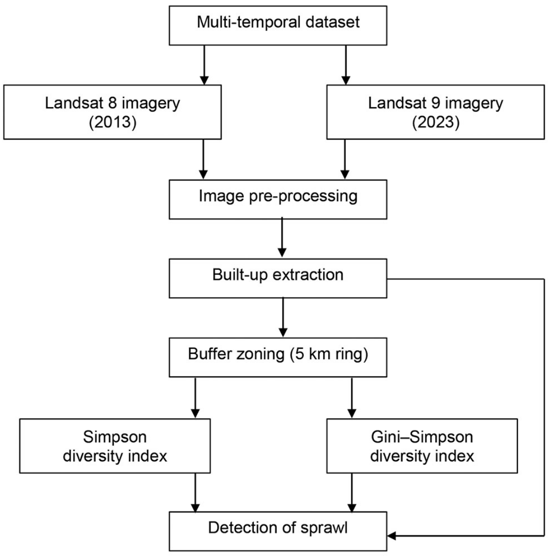

Figure 2. Methodology chart of the study.

Spectral index, also known as spectral ratio or band ratio, helps in transforming the multispectral image to extract some particular feature for the analysis. Some analysis requires only a single spectral of the multispectral images. So, to extract these single spectral images, the spectral index is used. In this study the formula for calculating the spectral index-derived impervious layer known as built up index (BUI) was taken as:

$$\text{BUI} = \frac{2*[(\text{Red}*\text{SWIR2}) - (\text{SWIR1}*\text{SWIR})]}{[(\text{Red}+\text{SWIR1})*(\text{SWIR1}+\text{SWIR2})]}.$$

The above formula is the experimented spectral index, which has been derived by making the comparative analysis of the different spectral index formulas[16–19]. The formula was applied on the Landsat 8 images[20]. However in this study, the above formula was applied both on the Landsat 8 and Landsat 9 images for the first time.

Simpson's diversity index

The BUI derived from the spectral analysis of the Landsat 8 and Landsat 9 images were used for the Simpson's diversity index. From the BUI, the built area was calculated for the year 2013 (Landsat 8) and 2023 (Landsat 9) for each 5 km incremental zone or the rings of KMA. For each ring, Gini–Simpson's diversity index was calculated.

Gini–Simpson's diversity index is based on the probability that if any two elements are randomly chosen, they will belong to the same category. This is another way of measuring diversity, where the value ranges from 0 to 1 (ref. 21). The lower value indicates a lack of diversity, and the higher value indicates an increase in diversity or the presence of sprawl. It is calculated by:

$$\text{Gini–Simpson index} = (1 - D)$$

$$\text{Simpson index } (D) = \left(\frac{\sum n_i(n_i - 1)}{N(N-1)}\right).$$

The parameters of the Simpson index are modified for this research. For this research, N is the summation of the total land use classification used in the analysis (green areas, built areas, and other areas), n_i is the area of the individual land use classification, i.e. the area of green areas, built areas and other areas. Gini–Simpson index is calculated for all the nine zones of KMA. The methodology chart is shown in Figure 2.

Results and discussion

Analysis of spectral index derived impervious layer (BUI) and Simpson's index

The spectral index analysis was done in Arc GIS. The atmospheric and radiometric correction of the Landsat 8 and Landsat 9 images were also done in Arc GIS of the respective bands. The impervious layer was calculated using the BUI formula. Figure 3 shows the impervious layer of the year 2013 and 2023. The area of the three land uses, i.e. water, built-up and non-built of the individual zones or rings, were taken from these spectral index-derived impervious layers. Tables 2 and 3 show the Gini–Simpson diversity analysis. From Table 2, it can be seen that for the year 2013, the Gini–Simpson index increased from zone one to zone nine, i.e. from the centre of KMA to its periphery.

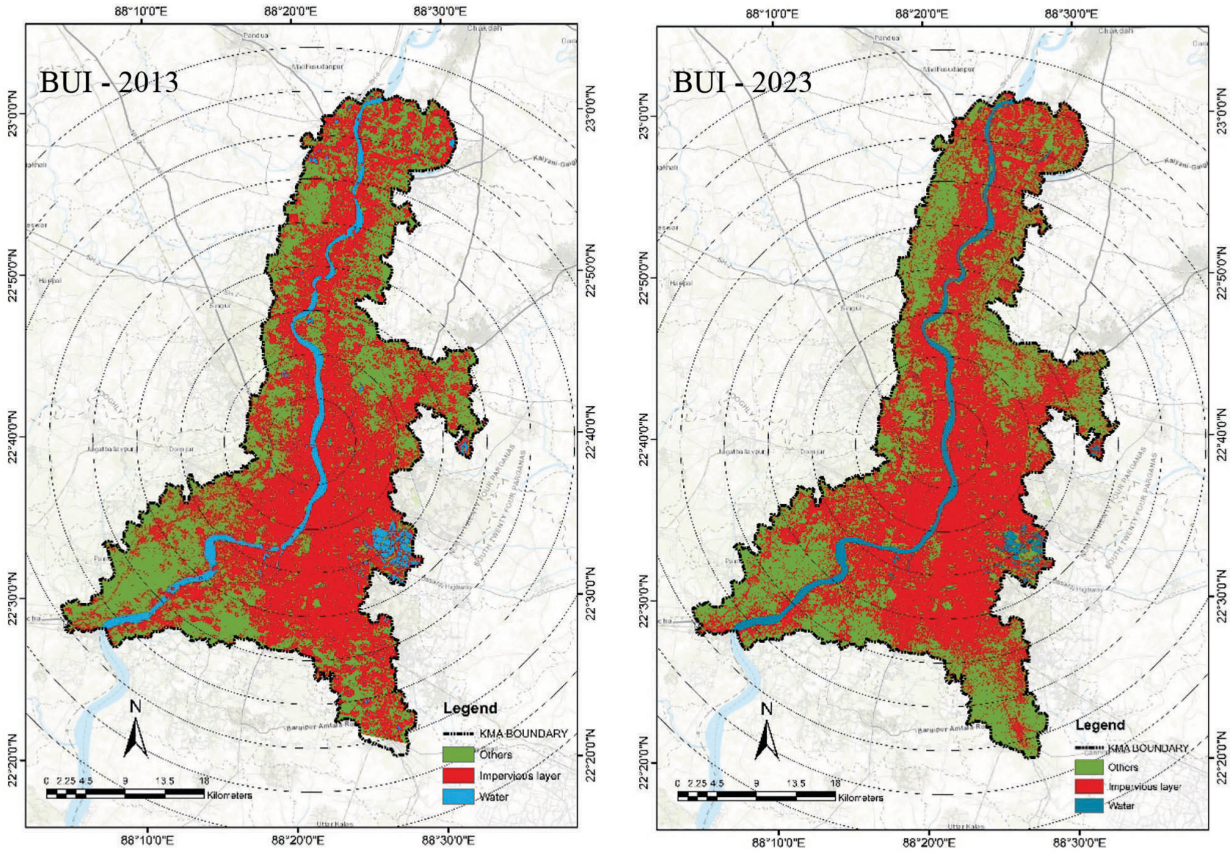

Figure 3. Spectral index derived impervious layer (BUI) for 2013 and 2023.

Table 2. Simpson diversity index and Gini–Simpson diversity index for 2013

Zone	Buffer (km)	Green areas (m^2)	Built-up (m^2)	Water (m^2)	Simpson diversity index	Gini–Simpson diversity index
2013 Landsat 8 images						
1	5	15,205,177	55,258,732	7,907,807	0.545	0.46
2	10	69,524,736	201,733,812	17,075,781	0.552	0.44
3	15	161,932,300	345,847,445	34,349,331	0.501	0.49
4	20	261,758,371	489,820,432	52,714,073	0.482	0.51
5	25	377,040,568	596,312,856	59,861,693	0.470	0.53
6	30	445,236,950	676,022,055	67,575,215	0.467	0.53
7	35	541,300,229	705,945,577	73,707,838	0.457	0.54
8	40	568,225,363	740,226,962	77,849,894	0.457	0.54
9	45	570,594,564	742,953,893	78,001,242	0.457	0.54

Table 2 shows that the value increases from 0.46 to 0.54 from the centre to the periphery, indicating the presence of sprawl. Some studies support this result. The core of Kolkata is compact due to historical growth in the past, so the major sprawl in the present time is occurring in the periphery of KMA[22]. In Table 3, a similar reading can be seen. The diversity index increased from 0.44 in the centre to 0.54 in the periphery, again indicating the presence of sprawl in the periphery of KMA. The increase in the population increased the demand for land, and as the core of KMA is compact, the development took place in the periphery of KMA, resulting in sprawl[23].

It can also be noted that the built-up of the different zones increased from 2013 to 2023. However, the Gini–Simpson index remained almost similar, which indicates that the sprawl is increasing at a constant rate in the periphery of KMA. The increase in the population, along with the housing demand, increased the real estate development like Eden City in Maheshtala, Rajawada Lake Bliss in Sonarpur, etc.[24]. These all led to urban sprawl in the periphery of KMA, which is highlighted by the results of the present study.

This study uses the Simpson diversity index on Landsat 9 images for the first time to detect sprawl. The results

Table 3. Simpson diversity index and Gini–Simpson diversity index for 2023

Zone	Buffer (km)	Green areas (m^2)	Built-up (m^2)	Water (m^2)	Simpson diversity index	Gini–Simpson diversity index
2023 Landsat 9 images						
1	5	14,634,322	56,258,732	7,478,662	0.5592752	0.44
2	10	68,705,633	210,729,552	8,899,144	0.59187593	0.41
3	15	150,088,613	361,625,593	30,414,870	0.52474536	0.48
4	20	256,402,301	502,204,631	45,685,944	0.49473683	0.51
5	25	365,413,972	604,690,352	63,110,793	0.4713302	0.53
6	30	435,236,950	687,022,055	66,575,215	0.47113149	0.53
7	35	538,882,727	716,164,252	65,906,665	0.46284655	0.54
8	40	563,322,377	753,533,674	69,446,168	0.46308263	0.54
9	45	565,491,102	748,944,911	77,113,686	0.45788078	0.54

from this Kolkata study align with the studies of sprawl done in Kolkata using other methods. A study on urban sprawl was done using the urban sprawl matrix technique, where the results highlighted that the municipalities and municipal corporations surrounding Kolkata's main core experienced the major sprawl from 1990 to 2005 (ref. 22). Similarly, Shannon Entropy and Pearson's Chi square method were used to understand the degree of sprawl in the periphery of KMA, and the result of the study confirmed the high degree of sprawl in the periphery of KMA[25]. Another study used change detection analysis, Shannon's Entropy, landscape metrics, and concentrated zone approach to detect the sprawl in KMA, and the results confirmed that KMA is experiencing typical urban sprawl in the form of leapfrog and fragmented development in the periphery as compared to the compact development in the core of KMA[26].

Conclusion

A better understanding of the spatial and temporal dynamics of KMA forms a basis for better planning for its sustainable development. An increasing trend in land consumption has also been observed in the last two decades, pointing to an overall low-density urban development in KMA. So, government authorities and planners need to make policies and schemes that support the future vertical development of urban areas. Moreover, policies should also be made to encourage compact city development by implementing denser residential areas and aggregated development of the existing built-up areas. This would help control the urban sprawl and provide basic facilities and infrastructure to the people at a minimum cost. Rapid urban development is summed up with increased population and economic development in the last two decades, and KMA is expected to gain more momentum in the coming decades. So it is necessary to formulate policies and schemes and keep in mind the future urban expansion and the increase in population; this land use planning and policies should be implemented to encourage sustainable urban development and balanced socio-economic growth. This study also highlighted the importance of remote sensing in urban planning and how remote sensing can be integrated with GIS and several tools to provide data on the LULC change at a regional level.

The results from this study provide basic information about the dynamics of urban development, the detection of sprawl, and the heterogeneity of KMA. This study will form a base for formulating policies and schemes to encourage sustainable urban development of KMA and other regional areas. The tools and techniques used in this study can be used to detect sprawl in other metropolitan areas of India. The techniques used in this study can only be applied at a regional level scale. If this technique is applied to a smaller scale than regional level, such as municipal corporations and municipalities the accuracy of the results may not be that good. The resolution of Landsat images is 30 m, so this technique cannot be applied to smaller areas. As the technique used in this study does not use context-specific parameters for the detection of sprawl, these techniques and tools can be used to detect sprawl in other areas at a regional level.

Conflict of interest: No potential conflict of interest was reported by the authors.

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