ANALYSING URBAN SPRAWL OF THE MUMBAI METROPOLITAN REGION USING REMOTE SENSING AND SOCIOECONOMIC DATA

Samarth Y. Bhatia[1]*. Gopal R. Patil[1], and Krishna Mohan Buddhiraju[2]

[1] Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai 400076, Maharashtra, India – *samarthbhatia121212@gmail.com, gpatil@iitb.ac.in

[2] Center of Studies in Resources Engineering, Indian Institute of Technology Bombay, Mumbai 400076, Maharashtra, India – bkmohan@iitb.ac.in

KEYWORDS: Urban Growth, Urban Sprawl, Metropolitan Region, Population, Mumbai.

ABSTRACT:

Urban growth in developing countries like India is happening more than twice as fast as the population increase. Such rapid urban growth has resulted in urban sprawl characterized by low-density scattered development. Urban planners require a timely updated dataset and suitable tools to monitor the urban sprawl and ensure sustainable development. The present study uses Landsat data from 1999, 2009 and 2019 and socioeconomic data to study the urban sprawl characteristic of the Mumbai Metropolitan Region (MMR) over two decades. The analyses show that MMR's built-up areas have expanded from 400 sq. km in 1999 to 761 sq. km in 2019, implying a 90% growth in the past two decades. While most municipal corporations have more than 60% of land covered by built-up areas, municipal councils are less saturated, with <30% built-up covers. With saturated land spaces within municipal corporations, higher growth rates are observed in the municipal councils. Also, the urban growth rates in these municipal councils outpace the population growth rate. The urban sprawl indices computed also suggest a continuous compact development within the municipal corporations while a continued sprawling within these fast-developing municipal councils. Mira Bhayandar is the most compact, while Bhiwandi Special Notified Area is the most sprawled urban area in MMR. The analyses show a clear indication of urban sprawl characteristics of the MMR. Many of these municipal councils are in the initial stages of development and lack appropriate governance to tackle rapid urbanization. Suitable policy measures that result in balanced urban growth can help ensure sustainable development.

1. INTRODUCTION

Urbanisation is an aspatial phenomenon which results in an increase in urban population. It is often associated with a change in lifestyle resulting from changes in social behaviour arising from the population shift from rural to predominantly urban (Bhatta et al., 2010). The world is facing large-scale rapid urbanization, which is alarming. Large rural-urban migration is happening mainly in search of better employment opportunities, healthcare facilities, education and improved quality of life (Kantakumar et al., 2016; Shukla & Jain, 2019). In today's integrated and increasingly associated world, more than half of the world's population lives in urban areas. As per the United Nations (2019) report, the population in urban areas is likely to increase to more than two-thirds by 2050. The increase implies that cities worldwide must accommodate an additional two and a half billion population, requiring the existing infrastructure to be scaled by 2050. It is also estimated that about 90% of the other population will be packed in developing countries, with India, China and Nigeria accounting for about 37% of the additional population of 2.5 billion (United Nations, 2019). Although urbanization process started in a delayed fashion in most of the developing world, the rate of urbanization is much faster than the developed countries (Getu & Bhat, 2021).

Urbanization leads to urban growth, which refers to the continuous physical expansion of urban cores along important highways and roads connecting city centres (Hamidi & Ewing, 2014). In fact, in these developing countries, urban growth is occurring more than twice as fast as the increase in population (Angel et al., 2011). Such rapid growth of urban extents, especially in developing countries like India, leads to a continuous and haphazard outgrowth of urban footprint resulting in urban sprawl. Although the accurate definition of urban sprawl is often debated, the sprawl is characterized by scattered, low-density development resulting in inefficient use of the available resource (Bhatta et al., 2010). Policies promoting polycentric developments, improved transportation network connectivity, low transportation cost, and increased affordability of private car ownership are a few reasons that promote urban sprawl (Talkhabi et al., 2022). Urban sprawl increases land use per capita, which comes at the expense of ecologically essential landscapes like forests, wetlands, and waterbodies. The sprawl has also been associated with various other problems, such as the degradation of farmlands, danger to food security, and traffic congestion resulting in a reduced quality of life.

While urban sprawling is a global phenomenon, its complexity and dynamics are exceptional in India. In recent decades several Indian cities are experiencing rapid and unplanned urban expansion. Since 1950, the population of India increased threefold to 1.35 billion in 2018, while its urban population has doubled to 34%. India is expected to contribute the most to the global urban population by adding more than 400 million urban dwellers by 2050 (United Nations, 2019). Among the other cities, megacities will play an essential role in the urbanization journey of India. The present work is carried out for the Mumbai Metropolitan Region (MMR), one of the largest urban agglomerations in India. It aims to understand the spatiotemporal urban growth patterns of the rapidly expanding MMR. The specific objectives are (1) To quantify the urban growth of MMR using remote sensing data. (2) To determine urban sprawl characteristics of MMR using the land use extracted through satellite data along with the socioeconomic data.

*Corresponding Author

2. LITERATURE REVIEW

The effective planning of urban areas requires timely updated information about urban sprawl, its extent, and patterns. Lack of updated information leads to enhanced negative impacts, resulting in a lack of basic infrastructure facilities in sprawling areas (Kantakumar et al., 2016). The rapid pace of urban expansion that India and other developing countries face necessitates using modern tools like space technologies that can provide the data required by planners to manage the sprawl proactively. Remote sensing (RS) and Geographic Information System (GIS) serves as powerful and cost-effective alternative to conventional land survey techniques for accurate monitoring of urban sprawl (Dewan & Yamaguchi, 2009). RS provides a retrospective coverage of land use information, while GIS helps map urban growth and its analysis. Several RS and GIS-based techniques have been developed to determine the urban growth structures and their spatial patterns and understand the sprawling characteristics of various cities worldwide. One of the techniques used for measuring urban sprawl is the spatial metrics, also called the landscape metrics (Mcgarigal, 2015). The spatial metrics like the number of patches, largest patch index, percentage land, and patch density have been used in studies by Mohamed & Worku (2020), Weng (2007) and Li et al. (2017). In addition to these spatial metrics, studies by Getu & Bhat (2021), Hasan et al. (2020) have also used fractal dimensions like Area Weighted Mean Fractal Dimension and Mean Fractal Dimension to understand the spatial organization of urban areas.

Similarly, Angel et al. (2007) proposed a metric for measuring key attributes of urban sprawl. The urban sprawl metrics proposed by Angel et al. (2007) are based on urban density and has been successfully used by Sharma & Joshi (2013), Kantakumar et al. (2016) and Sahana et al. (2018) to study different aspects of urban sprawl like, the scattered development, development along urban fringes and ribbon development. A few studies have also used the Landscape Expansion Index (LEI) to identify the three growth modes: infill, edge expansion and leapfrog (Shi et al., 2012). As per the study by Xu et al. (2020), an increase in infill improves land use efficiency, while edge expansion and leapfrog development reduce the density. Many studies, like the ones by Sun & Zhao (2018), have used the three growth modes and their relative proportions to identify the spatial patterns of urban growth. Another approach widely used to measure urban sprawl is the Shannon Entropy (Bhatta, 2009; Yeh & Li, 2001). The entropy-based index helps in understanding the degree of dispersion or concentration of urban areas.

The rapid expansion of various Indian cities has led to nationwide studies to understand land use land cover changes, monitor urban growth, and analyse urban sprawl—Shukla & Jain (2019) study Lucknow city's urbanisation using the three growth modes. Lal et al. (2017) use spatial metrics like class area, percentage land, number of patches, edge density and mean patch size to quantify the urban sprawl of Dhanbad urban agglomeration. The urban sprawl in Tiruchirappalli is studied by Rastogi & Jain (2018) using Shannon Entropy. On the other hand, Sahana et al. (2018) use urban sprawl metrics to analyse urban spatial patterns of Kolkata urban agglomeration. A few studies have also carried out comparative analyses of various Indian cities. Taubenböck et al. (2009) compares the growth in 12 urban agglomerations in India using landscape metrics like the number of patches, landscape shape index, patch density and edge density. Similarly, Chakraborty et al. (2022) computed the urban growth statistics of 33 megacities worldwide, including five cities in India, using the LEI.

Much research on urban sprawl and growth dynamics has been carried out worldwide, but a detailed analysis of urban sprawl in developing countries like India is still limited. Among the urban sprawl studies in India, none has been carried out considering the entire metropolitan region of Mumbai. The MMR presents a unique metropolitan region in India with different governing authorities like municipal corporations, municipal councils, census towns, villages and special notified areas. Furthermore, most studies for other cities in India and developing cities are at coarser agglomeration levels. The present study is focused on understanding the urban sprawl of the Mumbai Metropolitan Region (MMR) at the urban local body level. Such a sub-agglomeration level analysis can help administrators and planners continuously monitor urban sprawl and ensure sustainable development. Also, instead of using sprawl measures like spatial metrics, which neglect the socioeconomic characteristics, the present study combines the urban extents and socioeconomic variables to comprehensively understand the urban sprawl at the urban local body (ULB) level.

3. STUDY AREA AND DATA

3.1 Study Area

The Mumbai Metropolitan Region is a coastal metropolis located on the western coast of the Indian subcontinent between 18°33´-19°31´ N and 72°45´-72°28´ E. Figure 1 shows the location of MMR. The region is between the Tansa River on the north, the Patalganga River on the south, the Arabian Sea on the west, and the Sahyadri foothills on the northeast. With a population of 22.8 million and a geographic area of about 4253 sq. km, MMR is the sixth-largest metropolitan region in the world (MMRDA, 2019). The MMR comprises eight municipal corporations, nine municipal councils, 35 census towns and 994 census villages (MMRDA, 2016). Out of the total population residing in MMR, about 88% live in municipal corporations and councils, making the population in MMR predominantly urban. Greater Mumbai, with a population of 12 million, forms the parent city and acts as a growth engine of the region. However, Greater Mumbai's population share has declined from 76% in 1971 to 54% in 2011, indicating the growth of other regions within MMR.

The average population density of MMR is 5361 persons per sq. km. The population of MMR is concentrated mainly in dense municipal corporations. Ulhasnagar has the highest population density among the municipal corporations, followed by Greater Mumbai and Bhiwandi. The average household size of urban MMR is 4.39.

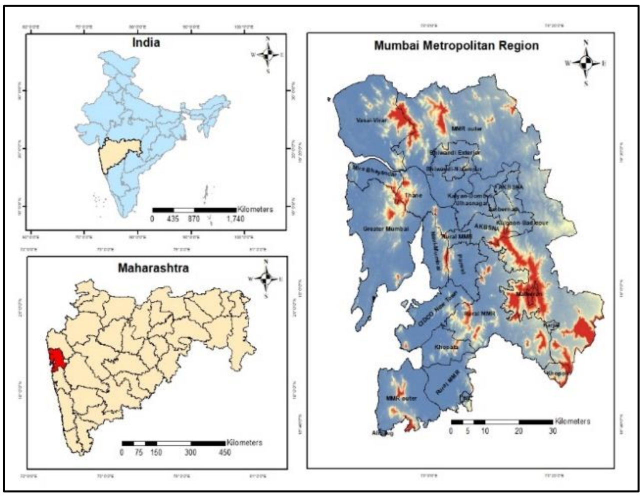


Figure 1 Study Area

3.2 Data

The study uses two datasets, (1) Landsat satellite Data and (2) Socioeconomic data. The Landsat Thematic Mapper (TM) sensor of 1999 and 2009 and the Operational Land Imager (OLI) sensor of 2019 are procured from US Geological Survey. The images selected for each year are of April-May months of nearby dates. It helps in minimizing the seasonal variation while comparing the multitemporal dataset. Also, care is taken that there is a negligible cloud cover in the downloaded images. Three tiles of satellite images for each year are used to prepare the scene of the entire study area. The downloaded tiles for each year are mosaicked using Erdas Imagine (2015) software package. The boundary shapefile of MMR is used to mask out the study area. The processed data set has been used to map the urban areas of MMR for two decades.

The second data set used is the socioeconomic data of the study region. It includes population, population density, and household size. All these measures are used along with the urban growth data to analyse the sprawling characteristics of MMR at suitable administrative levels. The socioeconomic data is extracted from the 2011 Census of India (*Census*, 2011) and various regional reports like the Regional Development Plan 2016-2036 (MMRDA, 2016) and Comprehensive Transportation Studies 2019 (MMRDA, 2019).

4. METHODOLOGY

The present study uses the Landsat satellite data from 1999, 2009 and 2019 and socioeconomic data like population and household size to understand the sprawling characteristics of MMR. Figure 2 shows the methodology flowchart followed in the present study.

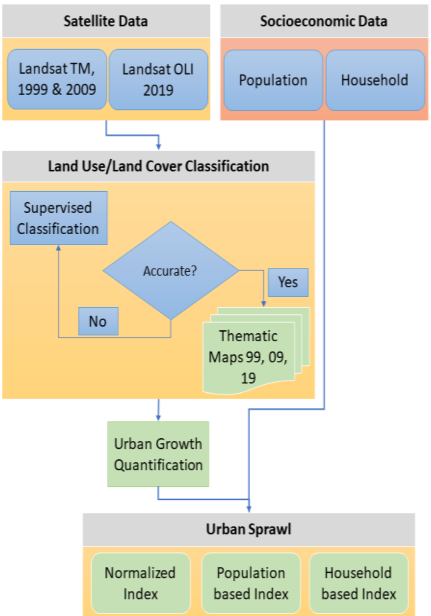


Figure 2 Methodology Flow Chart

4.1 Land Use Land Cover Classification and Accuracy Assessment

The study identifies five dominant land use/land cover classes with the help of regional reports like Mumbai Metropolitan Regional Plan 2016-2036 (MMRDA, 2016). Five LULC classes selected are: Built-up, Vegetation, Waterbody, Wetland and Other land.

Among the various classification algorithms, the maximum likelihood (ML) supervised classification algorithm is one of the most widely used methods for urban applications (Dewan & Yamaguchi, 2009). The present study implements the ML algorithm using the Erdas Imagine (2015) software package. The ML method assumes that a pixel has an equal probability of belonging to all the classes. About 200 to 250 training samples (identified using Google Earth), each comprising 3 to 5 pixels, are selected for each of the selected classes. The spatial signatures for each class derived through the training samples are used to generate the classified maps.

The classified images are assessed for accuracy before being used for urban sprawl analysis. It is done by comparing the classified maps with the Google Earth Imagery of the respective year. Two accuracy measures are derived through the error matrix, as suggested by Congalton (1991). One hundred fifty random samples for each class are taken to compare the actual and classified maps. The first measure used is the overall accuracy, defined as the ratio of correctly classified pixels to the total pixels taken to assess the accuracy. The second measure is the Kappa coefficient which accounts for all the elements of the error matrix rather than considering the diagonal elements only. Once the accuracy of classified maps is ascertained the maps are analysed further.

4.2 Urban Growth Quantification

The classified LULC maps are reclassified to a two-class problem with built-up and non-built-up areas. Thus, the built-up areas are extracted for three time periods are analysed for each urban local body (ULB) to understand the urban growth patterns in MMR. Two measures of urban growth are adopted in the present study. The first measure is the percentage of land covered by built-up area in each ULB. The multi-temporal analysis of the percentage of built-up cover can serve as a straightaway measure of urban growth. In simple words, the areas with a higher proportion of land covered by built-up areas can be considered more developed than those with a lesser proportion. For determining the percentage of land covered by built-up areas, the built-up area of each ULB is compared with the total available land area within the respective ULB. The percentage of land covered by built-up is calculated for each ULB and each study year. It helps determine the degree of built-up saturation and, thereby, the growth prospectus of each ULB.

The second measure of urban growth is the comparison of growth rates of built-up areas and population for each ULB. The growth rate of built-up areas and population are in general related. As the population increases, it results in the built-up expansion. It may also serve as a primitive measure of urban sprawl. If the growth rate of urban areas exceeds the population growth rate, it can indicate that the area is sprawling. Urban growth is analysed for MMR using these two indicators.

4.3 Sprawl Index

The study uses an integrated approach that combines GIS, classified land use data and socioeconomic data like the population and household density to study the urban sprawl characteristics of MMR. The study uses three different measures of urban sprawl. The first measure of the sprawl is computed as the normalized sprawl index. The normalized sprawl index is based on space available per capita. The higher the per-capita space available, the lesser the density, the greater the degree of sprawl, and vice-versa. The index is based on the hypothesis that

https://doi.org/10.5194/isprs-archives-XLVIII-M-3-2023-35-2023

if the built-up area growth exceeds the population growth, sprawl will occur (Bhatta, 2009; El Garouani et al., 2017). In the present study, the population of each ULB is computed by adding the population of census wards lying in that zone. Further, since the administrative classification and boundaries in MMR have changed significantly, significant efforts have been put into computing the population distribution at the ULB level as per the latest administrative setup. Equation 1 is used for the computation of the normalized sprawl index.

$$U_{N,i} = \frac{B_i/P_i}{\sum_i B_i/P_i} \quad (1)$$

Bi is the built-up area of the ULB, P_i is its population, and $U_{N,i}$ is the normalized urban sprawl index. The normalized urban sprawl index ranges from 0 to 1, with higher values indicating greater urban sprawl. The measure is suitable for comparing the urban sprawl of various ULBs at one point.

However, with the simple measure of sprawl using equation 1, Bhatta et al. (2010) argues that it is difficult to judge whether the change in population within the considered administrative unit is a cause or effect of the increase in the urban area. Hence, Ji et al. (2006) suggest that using population as a proportion of built-up areas may not be suitable as the sole measure of urban sprawl. A better way would be to consider the population and built-up area distribution of a ULB relative to that of the metropolitan region. Thus, the second index, the population-based urban sprawl index, is computed based on the proportion of the population and the proportion of built-up using Equation 2.

$$U_{p,i} = \frac{B_i \sum_i P_i - P_i \sum_i B_i}{\sum_i P_i \times \sum_i B_i} \quad (2)$$

Where $U_{P,i}$ is the population-based sprawl index. The proportion of population and built-up areas are calculated by taking a ratio of the respective zone's population and built-up areas to the total population and built-up of MMR. The population proportion is then subtracted from the proportion of built-up to obtain the population-based urban sprawl index. The value of $U_{P,i}$ ranges from -1 to +1. A value of -1 indicates overcrowding, +1 indicates sprawling and 0 indicates a balanced condition.

The third measure uses the number of households as a proxy for the population to compute the household-based sprawl index. In many cases, an increase or decrease in household sizes is a better indicator of urban sprawl because it directly indicates the space required for construction. The built-up areas usually increase with an increase in the number of households. However, to consider the ULB level variations, the present study uses the proportion of households computed as the ratio of households in the i^{th} Zone to the total number of households in MMR. The household-based urban sprawl index can be computed using Equation 3.

$$U_{HH,i} = \frac{B_i \sum_i HH_i - HH_i \sum_i B_i}{\sum_i B_i \times \sum_i HH_i} \quad (3)$$

$U_{HH,i}$ is the urban sprawl index based on household size, and HH_i is the number of households in zone i. Like the population-based sprawl index, the household-based sprawl index also ranges from -1 to +1 with higher positive values indicating higher per-capita land consumption.

5. RESULTS AND DISCUSSION

5.1 Urban Growth Analysis

Figure 3 shows the spatial distribution of built-up areas in various ULBs in MMR for 1999, 2009 and 2019, and Table 1 shows the urban growth statistics. The built-up area increased from 400 sq. km in 1999 to 556 sq. km in 2009 and 761 sq. km in 2019. Thus, the region experienced a rapid urban expansion of about 90% in the past twenty years. The spatial distribution statistics at the ULB level suggest that all ULBs classified as municipal corporations showed a reduced growth rate over time except Vasai Virar, which grew by 105% between 2009-2019, much faster than the previous decades. Most municipal councils also grew faster between 2009 and 2019.

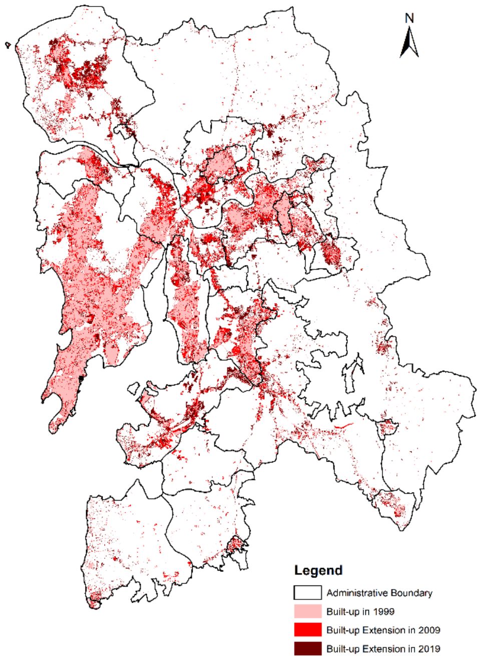


Figure 3 Built-up Area Expansion

Figure 4 compares the percentage of land covered by built-up areas each year. The total land under built-up cover increased from 1999 to 2019 in all the ULBs. The matrix shows that municipal corporations have a high proportion of land covered by built-up areas. Ulhasnagar is the most saturated ULB, with 95% of the land covered by built-up areas indicating no space for future expansion. Among other municipal corporations, Greater Mumbai, Navi Mumbai, and Bhiwandi have more than 50% of available land covered by built-up areas. On the other hand, developing municipal corporations like Vasai-Virar shows sufficient land available for further development, with just 18% of the ULB land covered by built-up areas.

The analysis of the municipal councils, most of which have started developing recently, shows that except for Alibag, Pen and Ambernath, all other municipal councils have less than 30% of the land covered by built-up areas. Similarly, all the special planning areas have less than 20% of land covered by built-up areas. The low proportions of land covered by built-up areas in these fast-developing ULBs indicate the future scope of urban expansion due to sufficient space. The comparison of the increase in built-up coverages suggests that while the municipal corporation showed a steady growth rate, the municipal councils expanded rapidly, especially in the last decade (2009-2019). The rapid growth rate in municipal councils can be attributed to the planning policies that aim at a polycentric development.

https://doi.org/10.5194/isprs-archives-XLVIII-M-3-2023-35-2023

ULB	Built-up Areas (km^2)			Change (%)	
	1999	2009	2019	1999-2009	2009-2019
Municipal Corporations					
GB	196.6	237.1	261.9	20.6	10.5
MB	9.5	14.8	20.1	55.9	35.9
VV	17.5	31.6	65.0	81.0	105.7
Thane	23.9	40.2	51.3	68.3	27.6
NM	36.2	46.9	56.1	29.6	19.6
KD	22.5	35.6	48.6	58.2	36.6
BN	11.7	14.8	16.9	26.3	14.4
Ulhasnagar	10.4	11.6	12.3	11.4	6.4
Municipal Councils					
Panvel	31.9	50.2	84.6	57.2	68.5
Ambernath	6.5	9.2	14.5	41.2	58.7
Badlapur	2.7	4.7	9.7	75.9	105.4
Alibag	0.6	0.8	1.2	48.7	39.6
Pen	0.7	1.3	2.4	79.2	91.9
Khopoli	2.6	2.2	4.9	-14.8	117.7
Karjat	0.6	0.9	1.9	44.9	115.7
Matheran	0.028	0.034	0.091	22.5	169.1
Special Notified Areas					
BSNA	8.2	20.6	31.0	150.4	50.8
AKBSNA	1.3	2.3	7.5	80.3	224.0
Khopate	0.5	1.7	2.5	225.0	46.0

*__GB__: Grater Bombay, **MB**: Mira Bhayandar, **VV**: Vasai Virar, **NM**: Navi Mumbai, **KD**: Kalyan Dombivli, **BN**: Bhiwandi Nizampur, **BSNA**: Bhiwandi Special Notified Area, **AKBSNA**: Ambernath Kulgaon Badlapur Special Notified Area

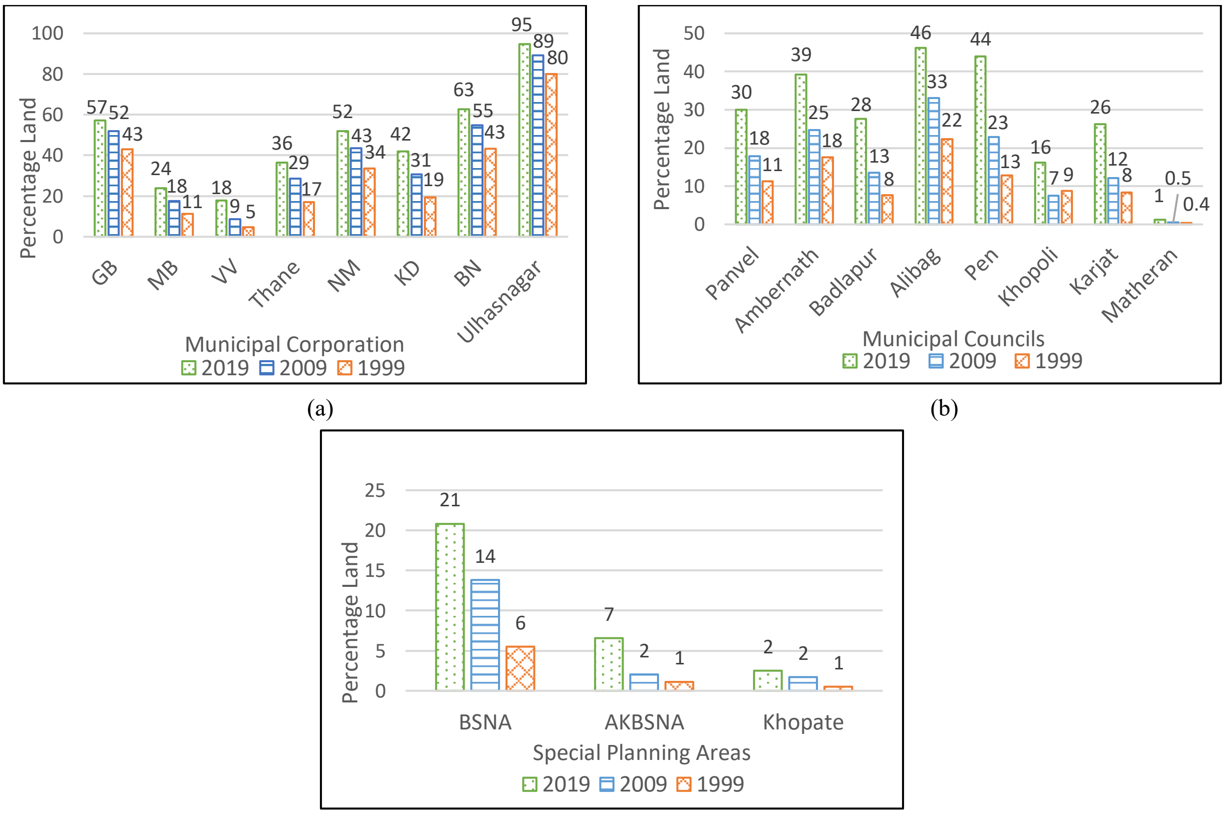
Table 1 Built-up Area Distribution in Various ULBs

Figure 5 compares the growth rate of the built-up area and population. Although it is a known fact that built-up expansion occurs because of an increase in population, comparing the urban growth rate and population helps get the essence of urban sprawl. The comparison suggests that the growth rates of population and built-up areas are comparable for all the ULBs except the special planning areas in the first decade (1999-2009). During this period, the MMR witnessed a balanced development. However, in the three special planning areas, BSNA, AKBSNA and Khopate, the built-up area expanded much faster than the population. The urban area expansion rates are 80%, 150% and 225% for AKBSNA, BSNA and Khopate, respectively.

In the second period (2009-2019), all the ULBs designated as municipal corporations except the fast-growing Vasai Virar continued to grow balanced. The growth rate of built-up areas in Vasai Virar is almost three times the population growth rate. Also, urban areas' growth rate is at least three to five times the population growth rate for all municipal councils. The disparity between the urban and population growth rates indicates the rapid construction activities in these fast-growing municipal councils. It must be noted that these municipal councils are comparatively less equipped to handle such a rapid pace of urban expansion that may result in haphazard development.

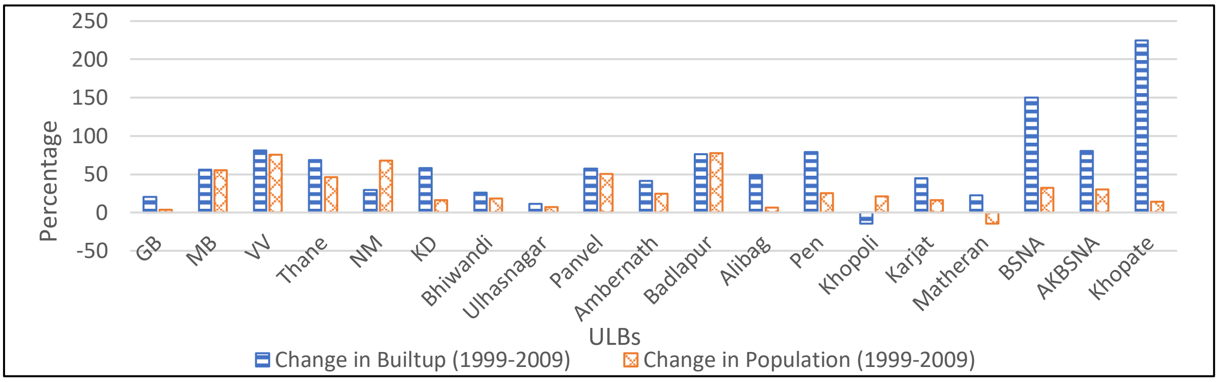
5.2 Urban Sprawl Analysis

Table 2 shows the computed urban sprawl metrics. The first index is the normalized sprawl index *($U_{N,i}$)*, taken as the ratio of population and built-up. The normalized sprawl index is used to compare the sprawl degree among various ULBs. In 1999 Khopate was the most compact ULB; however, from 2009 onwards, Mira Bhayandar showed the most compact structure. Among the sprawling ULBs, the Panvel municipal council was the most sprawled in 1999, while BSNA shows the most sprawled character in 2009 and 2019.

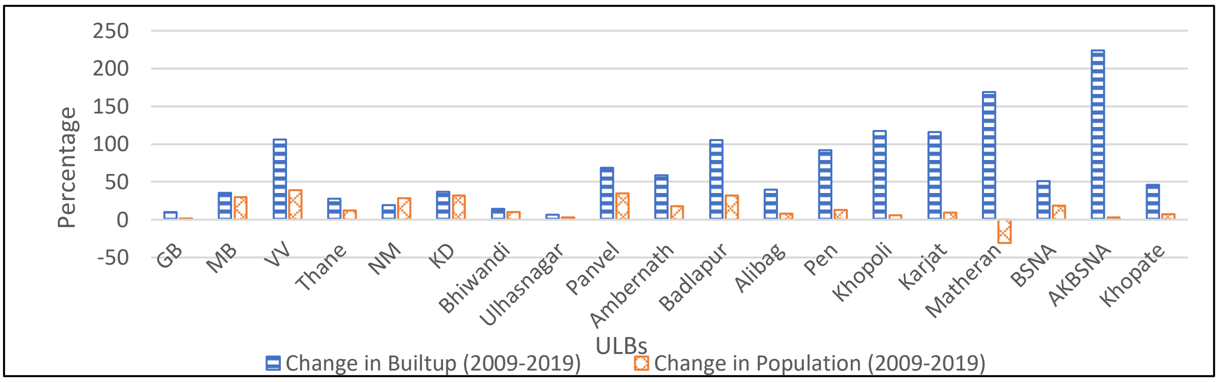


(a) (b) (c)

Figure 4 Percentage of Land Covered by Built-up



(a)



(b)

Figure 5 Growth Rate of Built-up Area vs. Growth Rate of Population

Urban Local Body	Normalized Sprawl Index ($U_{N,i}$)			Population-based Sprawl Index ($U_{P,i}$)			HH-based Sprawl Index ($U_{HH,i}$)	
	1999	2009	2019	1999	2009	2019	1999	2009
Municipal Corporations								
Greater Mumbai	0.031	0.031	0.023	-0.136	-0.127	-0.151	-0.089	-0.072
Mira Bhayandar	0.035	0.030	0.022	-0.003	-0.009	-0.015	-0.003	-0.007
Vasai Virar	0.048	0.042	0.043	0.008	0.003	0.023	0.008	0.007
Thane	0.036	0.035	0.028	-0.006	-0.009	-0.012	-0.005	-0.004
Navi Mumbai	0.103	0.068	0.044	0.058	0.037	0.021	0.065	0.045
Kalyan Dombivli	0.040	0.046	0.033	0.000	0.010	0.001	0.000	0.014
Bhiwandi Nizampur	0.037	0.034	0.025	-0.002	-0.005	-0.008	0.005	0.003
Ulhasnagar	0.042	0.037	0.027	0.001	-0.001	-0.004	0.004	0.002
Municipal Councils								
Panvel + Uran + Rest of CIDCO	0.138	0.123	0.108	0.059	0.065	0.085	NA	NA
Ambernath	0.061	0.058	0.055	0.006	0.006	0.008	0.007	0.008
Kulgaon-Badlapur	0.052	0.044	0.048	0.002	0.001	0.004	0.002	0.001
Alibag	0.055	0.065	0.059	0.000	0.001	0.001	0.000	0.001
Pen	0.045	0.054	0.064	0.000	0.001	0.002	0.000	0.001
Khopoli	0.085	0.051	0.073	0.004	0.001	0.004	0.004	0.001
Karjat	0.046	0.049	0.067	0.000	0.000	0.001	0.000	0.001
Matheran	0.010	0.013	0.034	0.000	0.000	0.000	0.000	0.000
Special Notified Areas								
Bhiwandi Special Notified Area (BSNA SPA)	0.085	0.136	0.122	0.011	0.028	0.033	NA	NA
Ambernath Kulgaon Badlapur Special Notified Area (AKBSNA SPA)	0.030	0.035	0.078	-0.001	-0.001	0.006	NA	NA
Khopate (KHOPTA SPA)	0.021	0.050	0.048	-0.001	0.001	0.001	NA	NA

Table 2 Urban Sprawl Indices Computed

https://doi.org/10.5194/isprs-archives-XLVIII-M-3-2023-35-2023 |

The second index calculation takes the difference between the proportion of built-up and population as given by equation 2. Table 2 shows the population-based sprawl index $(U_{P,i})$ computed for various ULBs. It shows an overcrowding condition in Greater Mumbai, Mira Bhayandar, Thane, and Bhiwandi for all three years. The municipal corporation of Ulhasnagar transitioned to the overcrowding category from the sprawling category in 2009. Kalyan Dombivli municipal corporation showed a balanced development in 1999 but later transitioned to a sprawling category. Similarly, AKBSNA and Khopata, the special planning areas, initially developed compactly; they transitioned to sprawling categories in 2019 and 2009, respectively. All other ULBs showed a sprawling arrangement for all the years.

The third index is the household-based sprawl index $(U_{HH,i})$ computed for 1999 and 2009, as shown in Table 2. Based on the household size, Greater Mumbai, Thane, and Mira Bhayandar municipal corporations show overcrowding. Except for these three corporations, all other ULBs show a sprawling character. The comparison of urban sprawl indices suggests that for all the ULBs except Bhiwandi and Ulhasnagar, the household-based and population-based sprawl indexes give the same results. Bhiwandi was sprawling in 1999 and 2009 with respect to the number of households; however, it is found to be compact compared to the population. Similarly, for Ulhasnagar, while the household-based index suggests sprawling in 2009, the population-based index suggests a compact development.

The sprawl measures generally suggest a compact characteristic in municipal corporations. However, Vasai Virar, Navi Mumbai and Kalyan Dombivli are the three municipal corporations showing continuous sprawling. Apart from these three municipal corporations, all municipal councils also show a continuous sprawling. The continuous sprawling of these ULBs can be associated with high urban growth rates. The sprawling results in higher per capita land consumption and higher resource utilization. The situation calls for immediate attention by the concerned authorities to put policies in place to promote more balanced development.

6. CONCLUSION

Continuous monitoring and analysis of urban growth dynamics is a precursor for planners to manage urban sprawl and ensure sustainable development. The study is carried out to analyse the urban sprawl characteristics of the Mumbai Metropolitan Region, one of India's fastest-growing urban agglomerations, between 1999 and 2019. It showcases that satellite remote sensing-based data combined with socioeconomic data like population and household size can be a valuable and cost-effective substitute for conventional land survey techniques. The thematic maps obtained through the classification of Landsat satellite data are first used to study the urban expansion of MMR at the urban local body level. Later the satellite images and the socioeconomic data are used to study the urban sprawl characteristics using three sprawl indices.

The analysis reveals that the MMR underwent a rapid urban expansion in the past two decades, with the built-up areas expanding from 400 sq. km in 1999 to over 761 sq. km in 2019, an increase of about 90%. The ULB level analysis suggests that while the municipal corporations show a stable growth rate, the urban growth rates of municipal councils still in the developing stage show a significantly high growth rate. Among the municipal corporations, only the Vasai Virar municipal corporation shows a high growth rate of about 105% between 2009 and 2019. The high growth rates can be associated with higher availability of vacant spaces for development. While Ulhasnagar shows more than 95% of land covered by built-up, most other municipal corporations show more than 60%. Vasai Virar municipal corporation and most other municipal councils show that only about 30% of the areas are covered by built-up, indicating sufficient spaces for future development. The sprawl indicators also suggest that while most municipal corporations show a compact development, the municipal council continues to sprawl. Among all ULBs, Mira Bhayandar shows the most compact development, while BSNA, a special planning area, shows the most sprawled development.

The study highlights the large-scale sprawling in the developing regions of MMR. Thus, the question that the decision makers face is not if the rapid urban expansion will occur but rather what scale of urban sprawl can be and how they can prepare to tackle the situation and ensure sustainable development. The development authorities should recommend suitable policies that balance the sprawling and densification of urban areas to ensure balanced development. The indices used in the present study can serve as an essential measure for city planners to take proactive measures and ensure holistic development.

REFERENCES

Angel, S., Civco, D., & Parent, J. (2007). Urban sprawl metrics : An analysis of global urban expansion using GIS. *ASPRS 2007 Annual Conference, Tampa, Florida*, *7*(11).

Angel, S., Parent, J., Civco, D. L., Blei, A., & Potere, D. (2011). The dimensions of global urban expansion: Estimates and projections for all countries, 2000-2050. *Progress in Planning*, *75*(2), 53–107. https://doi.org/10.1016/j.progress.2011.04.001

Bhatta, B. (2009). Analysis of urban growth pattern using remote sensing and GIS: A case study of Kolkata, India. *International Journal of Remote Sensing*, *30*(18), 4733–4746. https://doi.org/10.1080/01431160802651967

Bhatta, B., Saraswati, S., & Bandyopadhyay, D. (2010). Urban sprawl measurement from remote sensing data. *Applied Geography*, *30*(4), 731–740. https://doi.org/10.1016/j.apgeog.2010.02.002

Census. (2011). Office of Registrar General and Census Comissioner, Ministry of Home Afairs Government of India. https://censusindia.gov.in/

Chakraborty, S., Dadashpoor, H., Novotný, J., Maity, I., Follmann, A., Patel, P. P., Roy, U., & Pramanik, S. (2022). In pursuit of sustainability – Spatio-temporal pathways of urban growth patterns in the world’s largest megacities. *Cities*, *131*(August), 103919. https://doi.org/10.1016/j.cities.2022.103919

Congalton, R. G. (1991). A review of assessing the accuracy of classifications of remotely sensed data. *Remote Sensing of Environment*, *37*(1), 35–46. https://doi.org/10.1016/0034-4257(91)90048-B

Dewan, A. M., & Yamaguchi, Y. (2009). Land use and land cover change in Greater Dhaka, Bangladesh: Using remote sensing to promote sustainable urbanization. *Applied Geography*, *29*(3), 390–401. https://doi.org/10.1016/j.apgeog.2008.12.005

El Garouani, A., Mulla, D. J., El Garouani, S., & Knight, J. (2017). Analysis of urban growth and sprawl from remote sensing data: Case of Fez, Morocco. *International Journal of Sustainable Built Environment*, *6*(1), 160–169. https://doi.org/10.1016/j.ijsbe.2017.02.003

Getu, K., & Bhat, H. G. (2021). Analysis of spatio-temporal dynamics of urban sprawl and growth pattern using geospatial technologies and landscape metrics in Bahir Dar, Northwest Ethiopia. *Land Use Policy*, *109*(August), 105676. https://doi.org/10.1016/j.landusepol.2021.105676

Hamidi, S., & Ewing, R. (2014). A longitudinal study of changes in urban sprawl between 2000 and 2010 in the United States. *Landscape and Urban Planning*, *128*, 72–82. https://doi.org/10.1016/j.landurbplan.2014.04.021

Hasan, S., Shi, W., Zhu, X., Abbas, S., & Khan, H. U. A. (2020). Future simulation of land use changes in rapidly urbanizing South China based on land change modeler and remote sensing data. *Sustainability (Switzerland)*, *12*(11), 4–6. https://doi.org/10.3390/su12114350

Ji, W., Ma, J., Twibell, R. W., & Underhill, K. (2006). Characterizing urban sprawl using multi-stage remote sensing images and landscape metrics. *Computers, Environment and Urban Systems*, *30*(6), 861–879. https://doi.org/10.1016/j.compenvurbsys.2005.09.002

Kantakumar, L. N., Kumar, S., & Schneider, K. (2016). Spatiotemporal urban expansion in Pune metropolis, India using remote sensing. *Habitat International*, *51*, 11–22. https://doi.org/10.1016/j.habitatint.2015.10.007

Lal, K., Kumar, D., & Kumar, A. (2017). Spatio-temporal landscape modeling of urban growth patterns in Dhanbad Urban Agglomeration, India using geoinformatics techniques. *Egyptian Journal of Remote Sensing and Space Science*, *20*(1), 91–102. https://doi.org/10.1016/j.ejrs.2017.01.003

Li, C., Zhao, J., & Xu, Y. (2017). Examining spatiotemporally varying effects of urban expansion and the underlying driving factors. *Sustainable Cities and Society*, *28*, 307–320. https://doi.org/10.1016/j.scs.2016.10.005

Mcgarigal, K. (2015). Fragstats help. In *University of Massachusetts: Amherst, MA, USA* (Issue April). University of Massachusetts: Amherst, MA, USA. https://doi.org/10.1016/S0022-3913(12)00047-9

MMRDA. (2016). *Draft Mumbai Metropolitan Regional Plan Report, 2016-36*. https://doi.org/https://mmrda.maharashtra.gov.in/regional-plan

MMRDA. (2019). *Comprehensive Transportation Study for Mumbai Metropolitan Region (MMR)*.

Mohamed, A., & Worku, H. (2020). Simulating urban land use and cover dynamics using cellular automata and Markov chain approach in Addis Ababa and the surrounding. *Urban Climate*, *31*(October 2019). https://doi.org/10.1016/j.uclim.2019.100545

Rastogi, K., & Jain, G. V. (2018). Urban Sprawl Analysis Using Shannon'S Entropy and Fractal Analysis: a Case Study on Tiruchirappalli City, India. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLII–5*(November), 761–766. https://doi.org/10.5194/isprs-archives-xlii-5-761-2018

Sahana, M., Hong, H., & Sajjad, H. (2018). Analyzing urban spatial patterns and trend of urban growth using urban sprawl matrix: A study on Kolkata urban agglomeration, India. *Science of the Total Environment*, *628–629*, 1557–1566. https://doi.org/10.1016/j.scitotenv.2018.02.170

Sharma, R., & Joshi, P. K. (2013). Monitoring Urban Landscape Dynamics Over Delhi (India) Using Remote Sensing (1998-2011) Inputs. *Journal of the Indian Society of Remote Sensing*, *41*(3), 641–650. https://doi.org/10.1007/s12524-012-0248-x

Shi, Y., Sun, X., Zhu, X., Li, Y., & Mei, L. (2012). Characterizing growth types and analyzing growth density distribution in response to urban growth patterns in peri-urban areas of Lianyungang City. *Landscape and Urban Planning*, *105*(4), 425–433. https://doi.org/10.1016/j.landurbplan.2012.01.017

Shukla, A., & Jain, K. (2019). Modeling Urban Growth Trajectories and Spatiotemporal Pattern: A Case Study of Lucknow City, India. *Journal of the Indian Society of Remote Sensing*, *47*(1), 139–152. https://doi.org/10.1007/s12524-018-0880-1

Sun, Y., & Zhao, S. (2018). Spatiotemporal dynamics of urban expansion in 13 cities across the Jing-Jin-Ji Urban Agglomeration from 1978 to 2015. *Ecological Indicators*, *87*(December 2017), 302–313. https://doi.org/10.1016/j.ecolind.2017.12.038

Talkhabi, H., Ghalehteimouri, K. J., Mehranjani, M. S., Zanganeh, A., & Karami, T. (2022). Spatial and temporal population change in the Tehran Metropolitan Region and its consequences on urban decline and sprawl. *Ecological Informatics*, *70*(March), 101731. https://doi.org/10.1016/j.ecoinf.2022.101731

Taubenböck, H., Wegmann, M., Roth, A., Mehl, H., & Dech, S. (2009). Urbanization in India - Spatiotemporal analysis using remote sensing data. *Computers, Environment and Urban Systems*, *33*(3), 179–188. https://doi.org/10.1016/j.compenvurbsys.2008.09.003

United Nations. (2019). *World Urbanization Prospects: The 2018 Revision*. https://doi.org/10.4054/demres.2005.12.9

Weng, Y. C. (2007). Spatiotemporal changes of landscape pattern in response to urbanization. *Landscape and Urban Planning*, *81*(4), 341–353. https://doi.org/10.1016/j.landurbplan.2007.01.009

Xu, G., Zhou, Z., Jiao, L., & Zhao, R. (2020). Compact Urban Form and Expansion Pattern Slow Down the Decline in Urban Densities: A Global Perspective. *Land Use Policy*, *94*(January 2019), 104563. https://doi.org/10.1016/j.landusepol.2020.104563

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