ABSTRACT VOLUME

UGC Sponsored State Level Seminar

on

GEOGRAPHICAL APPRAISAL OF THE CITY OF JOY'S ENVIRONMENTAL WELLBEING

17-18th January, 2012

Organised by

DEPARTMENT OF GEOGRAPHY

SARSUNA COLLEGE

In collaboration with

KOLKATA MUNICIPAL CORPORATION

And

COMPUTER AIDED DESIGN CENTRE

Department of Computer Science and Engineering

Jadavpur University

URBAN GROWTH OF KOLKATA FROM 1980 TO 2040: A REMOTE SENSING PERSPECTIVE

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This paper is aimed to analyse and simulate the urban growth and sprawl for the city of Kolkata, India. In this paper, four temporal satellite images of ten-yearly intervals (1980, 1990, 2000, and 2010) have been classified to determine the urban extent and built-up growth of Kolkata. These digitally classified imageries then have been used for the analysis and simulation. The analysis has been performed in consideration of multi-temporal natural boundaries of the city. The study has found that the city of Kolkata was always sprawling. However the sprawling rate is becoming lower with the declining rate of urban growth. Finally, the urban spatial patterns of Kolkata have also been modelled for the years 2020, 2030, and 2040. A simple cellular automaton model has been developed to simulate the future urban pattern from the classified imageries in consideration of the urban growth rate of the last decade (2000?2010).

The paper may aid in to help local authorities in general to establish and evaluate development goals in terms of establishing social and other infrastructure equipments considering the threats of urban growth and sprawl in achieving sustainable development.

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Keywords: urban growth; urban sprawl; Kolkata; remote sensing

1 Introduction

The spatial configuration and the dynamics of urban growth are important topics of analysis in the contemporary urban studies. Several studies have addressed these issues which have dealt with diverse range of themes (e.g., Acioly and Davidson 1996; Wang *et al.* 2003; Páez and Scott 2004; Zhu *et al.* 2006; Hedblom and Soderstrom 2008; Geymen and Baz 2008).

Urban sprawl, as a concept, although suffers from difficulties in definition (Johnson 2001; Barnes *et al.* 2001; Wilson *et al.* 2003; Roca *et al.* 2004; Sudhira and Ramachandra 2007; Angel *et al.* 2007; Bhatta 2010), a general consensus is that urban sprawl is characterized by unplanned and uneven pattern of growth, driven by multitude of processes and leading to inefficient resource utilization. The direct implication of such sprawl is change in land-use and land-cover of the region as sprawl induces the increase in built-up and paved area (Sudhira and Ramachandra 2007).

Understanding the urban patterns, dynamic processes, and their relationships is a primary objective in the urban research agenda with a wide consensus among scientists, resource managers, and planners; because future development and management of urban areas require detailed information about ongoing processes and patterns. Simulating the future urban pattern is equally important to understand the conditions likely to be faced in future. Remote sensing, although challenged by the spatial and spectral heterogeneity of urban environments (Jensen and Cowen 1999; Herold *et al.* 2004) seems to be an appropriate source of urban data to support such studies (Donnay *et al.* 2001). It is irrefutable that *earth observation* is a modern science, which studies the earth's changing environment, through remote sensing tools such as satellite imagery and aerial photographs (EEA 2002). A report published by NASA highlighted the fact that the advances in satellite-based land surface mapping are contributing to the creation of considerably more detailed urban maps, offering planners a much deeper understanding of the dynamics of urban growth and sprawl, as well as associated matters relating to territorial management (NASA 2001). In the recent years, remote sensing data and geographic information system (GIS) techniques are widely being used for mapping (to understand the urban pattern), monitoring (to understand the urban process), measuring (to analyse), and modelling (to simulate) the urban growth, land-use/land-cover change, and sprawl.

This paper is aimed to map, monitor, measure, and model the urban growth of Kolkata from remote sensing data. Although in the last two years some papers have analysed the urban growth of Kolkata from remote sensing data (Bhatta 2009a, 2009b; Bhatta *et al.* 2010a), the current study differs from them. This paper considers a much larger area than the earlier papers and it simulates the future urban pattern of Kolkata for the next 30 years.

2 Study Area

The city of *Kolkata* (formerly *Calcutta*) is more than 300 years old and it served as the capital of India during the British governance until 1911. Kolkata is the capital of the Indian state of West Bengal; and is the main business, commercial, and financial hub of eastern India and the north-eastern states. It is located in the eastern India at 22°33′N 88°20′E on the east bank of *River Hooghly* (in Ganges Delta) at an elevation ranging from 1.5 to 9 m (SRTM image, NASA, February 2000).

The civic administration of Kolkata is executed by several government agencies, and consists of overlapping structural divisions. There are several administrative definitions of the city, e.g., *Kolkata District*, *Kolkata Municipal Corporation* (KMC), and *Kolkata Metropolitan Area* (KMA). The word ‘city’, in relation to Kolkata, is not an official term; however when used, it normally refers to the KMA area. The KMA is the urban agglomeration of the city of Kolkata. It consists of many urban municipalities as well as rural areas. The current extent of KMA is 1851.41 km². It is the largest urban agglomeration in eastern India, and second largest in India with a population of 13.2 million as per 2001 census. This area contains more than 50% of the total population of West Bengal.

This study considers an area much larger than the KMA. The extent was defined on the basis of the boundary of Kolkata Metropolitan Development Authority (KMDA)—a statutory body responsible for the development of KMA area. The KMDA boundary was drawn roughly and then a buffer was created outside so that the area of the buffer becomes double (roughly) than the KMDA area. This buffer was considered as the extent of the study area.

3 Data and Methodology

The following multi-temporal optical remote sensing imageries have been used to extract built-up areas of Kolkata:

- Landsat Multispectral Scanner (MSS) image (path 148, rows 44 and 45) from 16 January 1980;
- Landsat Thematic Mapper (TM) image (path 138, row 44) from 14 November 1990;
- Landsat Enhanced Thematic Mapper Plus (ETM+) image (path 138, row 44) from 17 November 2000;
- Indian Remote Sensing (IRS) Resourcesat-1 Linear Imaging Self-scanning Sensor (LISS) III image (path 108, row 56) from 03 February 2010.

Ten number of ground control points (GCP), surveyed with Global Positioning System (GPS) receiver, have been used to make the satellite imageries geographically referenced.

Satellite imageries have been obtained as standard product, that means, geometrically and radiometrically corrected. However, owing to several standards and references used by the image supplying agencies, the overlay of the images generally does not match with considerable accuracy. To solve this problem, the LISS-III image has been geographically referenced with evenly distributed 10 numbers of GCPs within the study area. Then, other satellite images have been co-registered so that the overlay matches with sub-pixel accuracy (maximum root mean square error≈ 0.41). Nearest -neighbour resampling has been used to transform the imageries so that the original pixel value retains. First order polynomial transformation equations (ERDAS 2008) have been used to georeference/register the imageries.

Remote sensing imageries then have been digitally classified to extract built-up and other impervious surfaces (also referred to as *urban class*). Worth mentioning that impervious surfaces (such as built-up) are promoted as useful environmental indicators (Arnold and Gibbons 1996; Barnes *et al.* 2000; Schueler 1994), and one environmental condition that impervious surfaces clearly indicate is urbanization (Barnes *et al.* 2001). If the study is concerned only with urban growth—that is, only the classes of urban and non-urban use are under consideration, a simple binary classification of remotely sensed data is enough (Torrens and Alberti 2000; Barnes *et al.* 2001; Epstein *et al.* 2002). The classification was performed by using the non-parametric feature space classifier in supervised approach (Bhatta 2011).

The *rule-based rationality evaluation* (Liu and Zhou 2004) has been performed for the assessment of accuracy of the classified imagery. It has shown an overall classification accuracy of 88.62%. An overall classification accuracy of 85% is commonly considered sufficient for a remote sensing data product (Anderson *et al.* 1976). Therefore, it can be said that the accuracy assessment has resulted in sufficient confidence to proceed with the classified imageries.

4 Results and Analysis

Digital classification of satellite images into built-up (with other impervious) and non built-up areas, for four temporal dates (1980, 1990, 2000, and 2010), has resulted in the creation of abstracted and highly-simplified visual images of the study area as shown in Figure 1, which are important evidences of urban extents and growth patterns. By examining the classified images, the growth patterns of the city in different areas, the infill of the open spaces between already built-up areas, the extents of urban area, etc. can be identified intuitively. However, to describe these different patterns intelligently, to understand how they change over time, or to explain the variations among these patterns statistically, we need to select quantitative measures that summarize one or another of their properties.

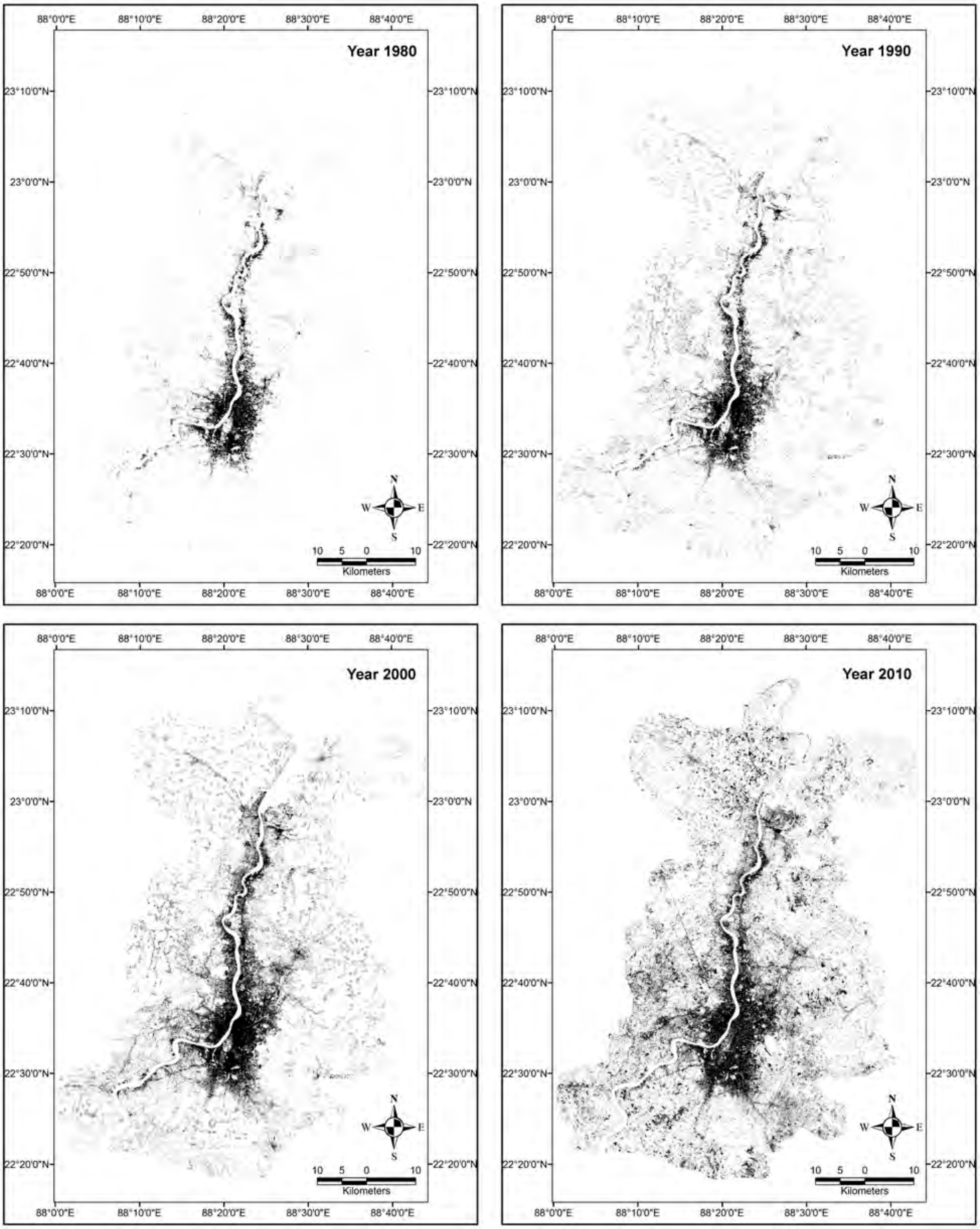

Figure 1 Classified images from different dates showing built-up areas in black

Cities have administrative boundaries associated with them in the sense that city governments have jurisdiction over certain well-defined administrative areas. But the area contained within the jurisdictional boundary of a city has little to do with the metropolitan area of the city. In some cases, this area is very small in comparison with the size of the metropolitan area. The Kolkata metropolitan area, for example, contains 38 independent municipalities and 3 municipal corporations. In other cases, say in Beijing, the jurisdictional boundary of the municipality contains an area that is much larger than the built-up area of the city. The official area of the municipality is therefore not a very precise measure, neither of the built-up area of the city nor of what we intuitively grasp to be the city (Angel *et al.* 2005). Furthermore, the extent of a city is a dynamic phenomenon; it changes over time; the jurisdictional boundary of the city cannot be changed frequently owing to administrative complexities. However, delineating the natural boundary or extent of a city is a real difficult task; because urban to rural transact generally shows a gradient. There are several approaches to determine the natural extent of a city or town (Bhatta 2010).

In this research, in consideration of physical or morphological criteria, a simple approach has been adopted to determine the extent of the city. A circular neighbourhood search from the urban core, for each date under analysis, has been conducted on the classified images to derive the contiguous urban area; and this boundary has been considered as the physical extent of the city (reported earlier in Bhatta (2009b)). The neighbourhood search determines which pixels will be considered contiguous to the *seed* (selected) pixel. Any neighbouring pixel that meets all selection criteria (in this case—belonging to built-up class) is accepted and thus, itself, becomes a seed pixel (ERDAS 2008). This has resulted in a contiguous area for each date under analysis. These contiguous areas can be considered as temporal boundaries or extents of the city—referred to as 'city-extents'. Discontinuous or scattered built-up pixels, outside of these city-extents, have not been included since they are generally considered as isolated developments—not connected with the core urban area. However, non-urban islands within the contiguous built-up pixels have been included, because the intention was to demarcate the extent (boundary) of the city, not to find out the contiguous built-up pixels. Encouragement of urban growth within this extent will force *infill* growth that is generally considered as remedies to sprawl (Wilson *et al.* 2003). This approach can eliminate the problems associated with determining the urban boundary in a rural to urban gradient.

In case of analysing the intra-city variations of urban growth and sprawl, it is necessary to subdivide the extent of the city. There are different approaches to subdivide the natural city extents. A popular approach is to divide the area into circular or pie sections or in both (Kumar *et al.* 2007; Bhatta *et al.* 2010a). The main problem of this approach is its blindness to the actual shape of the city; for example, if the city is very long and narrow in shape the circular subdivision includes several rural (or other) areas in the analysis. Another better approach may be to construct buffers (positive or negative) by using the natural boundary of the city. However, for multi-temporal analysis, we shall have multiple natural boundaries for multiple dates. Which boundary should be considered to construct the buffer is unclear. Therefore, we need a different approach for subdivision which can avoid the stated problems.

This paper proposes a new approach to subdivide the natural extent of the city. It considers the multi-temporal natural extents of the city for the subdivision of study area. The city-extent of 1980 has been considered as *Zone 1*, the difference area between the city-extents of 1980 and 1990 has been considered as *Zone 2*, difference between 1990 and 2000 has been considered as *Zone 3*, and the difference between 2000 and 2010 has been regarded as *Zone 4*. Figure 2 represents these zones spatially. Advantages of this zoning concept includes: (1) it is not influenced by the spatial resolutions at a high degree, (2) it considers the natural growth of the city in zoning process rather than any artificial or hypothetical shapes, and (3) it does not include large rural (or other) areas within it. Sometimes, a large area may be left blank and the built-up may jump that area as because it is unsuitable for development or protected from development purposefully. Administrative, or circular/pie, or buffer subdivisions will consider these areas in the analysis and the area will artificially indicate a sprawl. The subdivision approach adopted in this paper can avoid such type of large areas. Figure 2 clearly shows that River Hooghly and East-Kolkata wetlands have been excluded.

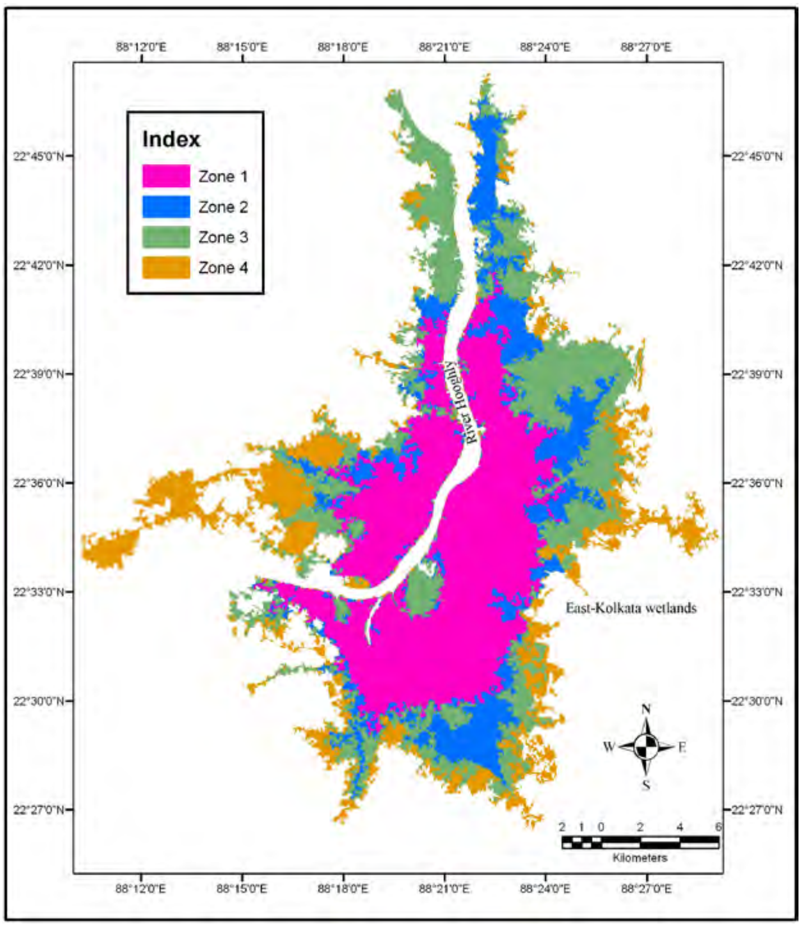

Figure 2 Zoning concept of the study area in consideration of natural city-extents

Built-up areas in each natural extent of the city and in each subdivided zone for each temporal image have been calculated by clipping the classified images with the respective vector, and then multiplying the number of pixels in each zone by the pixel size (presented in Table 1 and Table 3). Table 1 shows the area index for each natural city-extent. Area index is the ratio of patch size and built-up area within the patch (McGarigal and Marks 1995; McGarigal *et al.* 2002); hence, 'patch' is the city-extent. This index is a relative measure of porosity, for which we may have a lowest value of 1 that indicates lowest level of porosity. Hence, 'porosity' is the non built-up areas within the built-up. This index can provide us with the information of relative porosity—whether it is increasing or decreasing with the change of time. The results show that the city is becoming more porous. Increasing porosity is an indication of increasing urban sprawl.

Table 1 Area of city-extent and built-up area within the city extent, percentage of built-up, and area index

Year	Area of city-extent (in ha)	Built-up area (in ha)	Percentage of built-up	Area index (area of city-extent / built-up area)
1980	13002.92	9744.78	74.94	1.33
1990	18658.05	13830.30	74.13	1.35
2000	28813.03	21083.79	73.17	1.37
2010	36668.1	26258.30	71.61	1.40

A simple approach of determining the urban sprawl is—if the growth rate of the city-extent exceeds the built-up growth rate, it is an indication of sprawl. Positive values in their differences (*city-extent growth rate* minus *built-up growth rate*) indicate sprawl and negative values indicate compactness. The degree of sprawl and compactness can also be identified by their magnitudes. Actually, this index indirectly reveals the porosity within the city-extent. Higher built-up growth with a lower growth of city-extent is surely a compact development, and vice versa. Table 2 shows the results obtained from this index, in which positive values show sprawl and negative values show compactness. The degree of sprawl and compactness can also be identified by their magnitudes. The results show that the city is becoming sprawled.

Table 2 Trend of urban growth during 1980–2010

Time span	City-extent		Built-up area		City-extent growth rate minus built-up growth rate ($G_{CE} - G_B$)
	Growth (in ha)	Rate of growth (G_{CE}) (in %)	Growth (in ha)	Rate of growth (G_B) (in %)	
1980–1990	5655.13	43.49	4085.52	41.93	1.56
1990–2000	10154.98	54.43	7253.49	52.45	1.98
2000–2010	7855.07	27.26	5174.51	24.54	2.72

This index is better than the area index because it can identify the sprawl in black-and-white characterization. Further, this index is also useful to analyse the growth rates of city-extent and built-up areas within the city-extents. Therefore, it can be used for the analysis of both—urban growth and sprawl. As observed in Table 2, the growth rates in both of the instances were increasing during 1980–2000. However, in the time span 2000–2010, they have registered approximate 50% growth rates than that of the previous decade. Interestingly, the city became more porous despite of low growth rates in city-extent and built-up area. This clearly proves that a low built-up growth rate does not always guarantee a compact development.

However, the major limitation of the demonstrated indices is the consideration of the entire city in the analysis. They do not consider the variations of the built-up areas in different parts of the city. The entropy method can overcome this limitation. The entropy method is the most widely used metric for urban sprawl analysis. The review of literature found that the entropy method is the most reliable metric among the available sprawl measurement indices (Bhatta *et al.* 2010b). Shannon's entropy (H) can be used to measure the degree of spatial concentration or dispersion of a geographical variable (x_i) among zones (Theil 1967; Thomas 1981). Entropy is calculated by:

$$H_n = \sum_{i=1}^{n} P_i \log_e\left(\frac{1}{P_i}\right) \qquad 1$$

where, P_i is the proportion of a phenomenon occurring in the ith zone $(P_i = \frac{x_i}{\sum_{i=1}^{n} x_i})$, x_i is the observed value of the phenomenon in the ith zone, and n is the total number of zones. The value of entropy ranges from 0 to $\log_e(n)$. A value of 0 indicates that the distribution of built-up areas is very compact, while values closer to $\log_e(n)$ reveal that the distribution of built-up areas is dispersed. Higher values of entropy indicate the occurrence of sprawl. Half-way mark of $\log_e(n)$ is generally considered as threshold. If the entropy value crosses this threshold the city is considered as sprawled.

Relative entropy can be used to scale the entropy value into a value that ranges from 0 to 1. As Thomas (1981) demonstrated, relative entropy $(H^{'})$ for n number of zones can be calculated as:

$$H_n^{'} = \frac{H_n}{\log_e(n)} \qquad 2$$

In this instance 0.5 is considered as threshold. Values higher than this generally considered as sprawl.

However, the preceding approach cannot analyse the sprawl as a process. Yeh and Li (2001) argue that because entropy can be used to measure the distribution of a geographical phenomenon, the measurement of the difference of entropies (or relative entropies) between time t_1 and t_2 can be used to indicate the magnitude of change in urban sprawl as follows:

$$\Delta H_n = H_n(t_2) - H_n(t_1) \qquad 3$$

$$\Delta H_n^{'} = H_n^{'}(t_2) - H_n^{'}(t_1)$$ 4

Table 3 presents the built-up areas within each zone (refer Figure 2) and for each date. If we calculate the entropy from Table 3, we can get the entropy values for the four temporal dates as shown in Table 4. The results show that the city of Kolkata was always sprawled; because, the entropy values are always higher than the half-way mark of $\log_e(n)$. Relative entropy values are also always higher than the threshold of 0.50. This finding supports the results from other indices demonstrated in this paper.

Table 3 Built-up areas in different zones and different dates (in ha)

Year	Zone 1	Zone 2	Zone 3	Zone 4	Total
1980	9744.78	2059.72	1550.56	334.94	13690.00
1990	10148.41	3681.89	2536.13	771.07	17137.50
2000	10796.63	4825.07	5462.09	1719.81	22803.60
2010	11116.19	5001.51	5731.49	4409.11	26258.30

Table 4 Shannon's entropy for different temporal dates

Year	Entropy (H_n)	Relative entropy $(H_n^{'})$	$\log_e(n)$	$\log_e(n)$ / 2
1980	0.86	0.62	1.39	0.69
1990	1.06	0.77		
2000	1.22	0.88		
2010	1.31	0.95		

The change in entropy, between time t_1 and t_2, can be used to identify whether land development is becoming more dispersed (sprawled). Table 5 shows the values of change in entropy (ΔH_n) and change in relative entropy ($\Delta H_n^{'}$). As one can see, both are decreasing with time. Therefore it can be said that the degree of sprawling rate is decreasing with time. However, decrease in sprawling rate should not be interpreted as 'compact'. If the difference in entropy (ΔH_n) or relative entropy ($\Delta H_n^{'}$) value for a specific time span becomes negative, then only it can be said that the city is becoming compact. The word 'compact' in this sense is not relative; rather, it is an absolute characterization of urban growth.

Table 5 Differences in entropies between two successive dates under analysis

Time span	ΔH_n	$\Delta H_n^{'}$
1980–1990	0.20	0.14
1990–2000	0.16	0.11
2000–2010	0.09	0.07

5 Simulating the Future Urban Pattern

The past and present urban status of Kolkata can be well understood from the previous analysis. However, to understand the future we need to simulate the urban pattern of the city. There are several approaches to simulate the future urban patterns (Bhatta 2010); among them, the cellular automaton (CA) is most practiced. A CA is a discrete system in which space is divided into regular spatial cells, and time progresses in discrete steps. Each cell in the system has one of a finite number of states. The state of each cell is updated according to local rules, that is, the state of a cell at a given time depends on its own state and the states of its neighbours at the previous time step (Liu 2009). Urban growth resembles the behaviour of a CA in many aspects. The space of an urban area can be regarded as a combination of a number of cells, each cell taking a finite set of possible states representing the extents of its urban development. The state of each cell evolves in discrete time steps according to some local transition rules. Transition rules may vary at a wide range, because urban growth is the result of a variety of factors, these being physical, socioeconomic, and institutional. The simplest and most widely used rule is: a non-urban cell becomes urban if the neighbours of that non-urban cell are urban. All of the neighbours may not be urban in every case. Therefore it requires defining a threshold, for example, if 5 cells are urban among 8 neighbouring pixels, the candidate pixel will be converted to urban.

In this paper, we have developed a simple CA model to simulate the future urban pattern of Kolkata by using 5 × 5 neighbourhood. Cell states (urban=1, non urban=0) of all neighbouring cells have been summed up for each non-urban cell. If the value crosses the defined threshold value, it is converted into urban pixel. Figure 3 shows this concept with a threshold of 3.

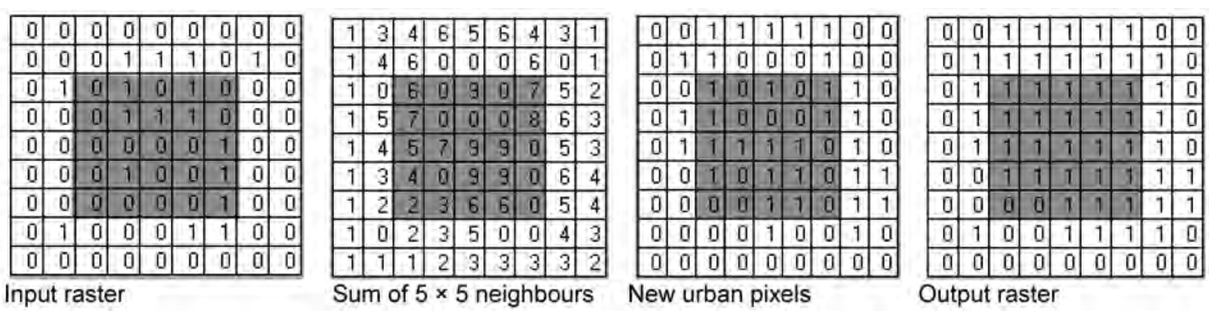

Figure 3 The concept of CA model to simulate the future urban pattern

To simulate the future urban growth, it was necessary to calculate the urban growth of past and present. Table 6 presents the urban growth rates of past decades for the entire study area considered in this paper. The table shows that urban growth rate is declining with the change of time. Now if we assume that the trend of last decade (2000–2010) will be continued in the future, 49.29% built-up growth will be registered. Thus we can determine the total built-up areas for the years 2020, 2030, and 2040. The aforementioned CA model was iteratively applied on the classified image of year 2010 with changing threshold to determine the urban growth pattern until it hits the determined built-up areas of year 2020. This has resulted in the urban map of the city

(Figure 4) for the year 2020. Similarly, the CA model was applied on the map of year 2020 to simulate the urban pattern of 2030, and 2030 map to simulate the map of year 2040 (Figure 4). These maps can provide us some idea about the future urban patterns, if the city is allowed to expand freely without any restriction.

Table 6 Built-up area and its growth rate for the past, present, and future

Year	Built-up area (in ha)	Growth rate (in %)
1980	18991.70	
1990	32538.00	71.33
2000	54008.90	65.99
2010	80628.80	49.29
2020	120369.11	49.29
2030	179696.63	49.29
2040	268265.48	49.29

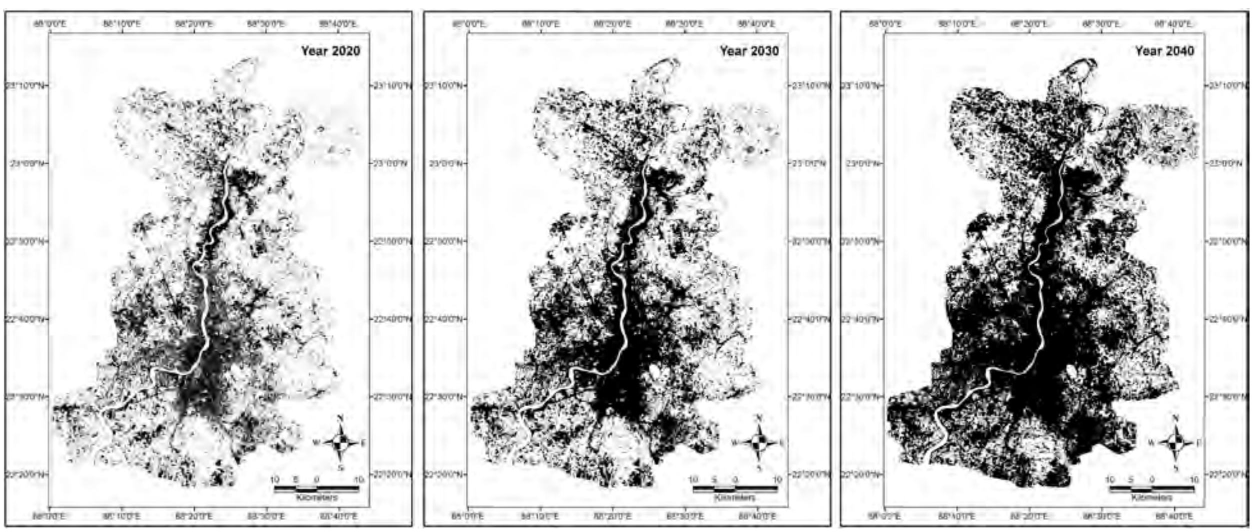

Figure 4 Simulated future urban pattern of the city of Kolkata

6 Conclusions

The analysis shows a clear indication of urban sprawl in the city of Kolkata. However, it has also been noticed that the degree of sprawling rate is declining with the declining rate of urban growth. There is an urgent need of restricting the sprawl of the city in view of the environmental and ecological sustainability.

The paper has tested several feasible models for the measurement of sprawl in the city of Kolkata. These models, based on remote sensing data, have proved to be useful for the identification of urban growth pattern and their general tendencies. These models are less demanding in terms of data, computation, and expertise. They are simple and empirically devised, and not constrained by the straitjacket of rigid theory devices.

The results and analysis in this paper have attempted to draw the attention of the magnitude and pattern of urban growth of Kolkata for the last three decades as well as for future three decades. These may be very helpful in terms of guiding future planning and policy-making for the development of the city.

The key issue facing decision makers at the local, national and international levels—is not whether the urban growth or sprawl will take place, but rather what is likely to be the scale of urban growth or sprawl and what needs to be done to adequately prepare for it. Ideally, the growth that takes place around urban areas should be channelled in an orderly manner that will produce an economically efficient, socially and personally satisfying living environment. In practice, ideal growth can hardly be achieved owing to many practical reasons and difficulties including inefficiency and lack of timely funding of development projects, inefficient management systems, weak legal support, and several other factors. However, there are many approaches, known as *growth control policies*, which can be seen towards achieving a sustainable urban growth. The current paper presents only the analysis and simulation of urban growth for the city of Kolkata. What the measures should be taken, in order to mitigate the problems associated with undesirable urban growth in Kolkata, is an important issue of research. Further analytical research may shed some light on this issue in the near future.

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