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REVIEW PAPER

A systematic review of urban sprawl studies in India: a geospatial data perspective

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Abstract

This paper reviews articles published in the English language and using geospatial data in analysing the state of urban sprawl in India. India is not far behind in the unparalleled global phenomenon of urbanization, with it adding the highest number of urban dwellers by 2050. We review a total of 153 articles involving the use of remote sensing data for studying urban sprawl in India since it was first reported in the 1980s to the present. We find an exponentially increasing trend of urban sprawl studies since the year 2010 attributing to 72% of the total publications. This review helped in finding preferences as regards the most frequently studied city, platforms/sensors used, journals and the most active group carrying out urban sprawl studies. We then group the studies decade wise and report the major findings. Earlier studies mainly focused on the post-classification comparison of multi-temporal data. With the advancement of geospatial technology along with the ease of availability of satellite data, there has been a significant spurge in the number and quality of urban sprawl studies in the recent decades and involves advanced methods like spatial metrics, artificial neural network, object-based classification, and different kinds of modelling for future prediction of sprawl. Our findings suggest that sprawl research has evolved significantly over the years. With the availability of a large number of studies and copious amounts of data, the governmental agencies and large organizations should actively formulate a national-level database and incorporate these studies in various urban planning decisions.

Keywords Urban sprawl · Urbanization · Urban growth · India · Remote sensing and GIS

Introduction

Urbanization is a global phenomenon. More than one half of the world population (55% as of 2018) lives now in urban areas, and virtually, all countries of the world are becoming increasingly urbanized (United Nations 2018a). The current world population of 7.6 billion is expected to reach 8.6 billion in 2030 (United Nations 2017) out of which 5 billion will be urban population. Much of this urbanization will unfold in Africa and Asia, bringing substantial social, economic and environmental transformations (UNFPA, (United Nations Population Fund) 2016). Together, India, China and Nigeria will account for 35% of the projected growth of the world's urban population between 2018 and 2050 (United Nations 2018b). And the appalling fact related to urbanization is that over 60% of the land which has been projected to become urban by 2030 is yet to be built! (CBD Secretariat of the Convention on Biological Diversity 2012; World Economic Forum (WEF) 2016).

The term "sprawl" was coined by Earle Draper in 1937 in the USA (Black 1996). Urban sprawl is a complex and multifaceted phenomenon because there is no consensus about either its definition or measurement within the existing literature (Harvey and Clark 1965; Galster et al. 2001; Johnson 2001; Clifton et al. 2008; Wilson and Chakraborty 2013; Liu et al. 2018). Harvey and Clark (1965) stated that urban sprawl is often discussed without any associated definition at all. Torrens (2008) attempted to tabulate varying characterizations of sprawl in urban studies literature. There is so much confusion as related to its definition that Galster et al. (2001) reported—"the literature on urban sprawl confuses causes, consequences and conditions". To strengthen this argument further, Torrens (2008) reported that existing studies yield contrary results of urban sprawl for the same cities in many cases.

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The terms urban growth and urban sprawl are now used almost synonymously, and edge cities have become the dominant urban form (Glaeser and Kahn 2004).

Out of the numerous definitions of sprawl available in the literature, a few have been presented here to show the ambiguity and versatility in definitions. Ermer et al. (1994) defined sprawl as “a process of the spilling-over of settlement areas and excessive use of the open landscape by unsystematic, mostly weakly condensed extensions of settlement areas in the fringes of urban agglomerations.” Sierra Club (1999) identified sprawl as “low-density development beyond the edge of service and employment, which separates where people live from where they shop, work, recreate and educate—thus requiring cars to move between zones.” ARL and VLP (1999) state that sprawl is to be understood as the disturbance or destruction of the landscape and ecosystems by spill-over development of settlements outside of closed built-up areas. Jaeger et al. (2010) defined it as “a phenomenon that can be visually perceived in the landscape. The more heavily permeated a landscape by buildings, the more sprawled the landscape. Urban sprawl, therefore, denotes the extent of the area that is built up and its dispersion in the landscape. The more area built over and the more dispersed the buildings, the higher the degree of urban sprawl.”

Therefore, it is clear that sprawl means different things to different people and thus depends on the perspective of who presents the definition (Brueckner 2000; Barnes et al. 2001). We attempt to define urban sprawl as heterogeneous, low-density areas having essentially urban characteristics located at the fringes of already well-established urban centres. These areas are dynamic and are usually surrounded by or adjacent to vacant, undeveloped or agricultural lands and could be detected using satellite images. They have a negative impact on the surrounding natural environment and are most commonly associated with air pollution and traffic congestion amongst other factors.

A few issues related to increasing urbanization are increased residency in slums and informal settlements; challenges in providing public services to such a large population and an upsurge in exclusions, inequality, insecurities and international migration (United Nations 2016). On the environmental front, an imminent result of urban sprawl is a high degree of land consumption and fragmentation of natural and anthropogenic features (Maktav et al. 2005). Climate and the local environment are being affected due to changes in urban patterns (Deosthali 2000; McCarthy et al. 2010). World Cities Report (United Nations 2016) states, “Urbanization brings about fundamental changes in production and consumption patterns, which when associated with dysfunctional urban forms and structure of cities, contribute to higher levels of energy consumption and greenhouse gas emissions”. Almost all the meteorological parameters are also being modified as a result of urbanization (Sundersingh 1990). Some of the environmental impacts include repercussions on hydrological cycle (Wakode et al. 2014); degradation of ecosystems due to air and water pollution, scarcity or excess of water (flooding) in highly dense urban areas as more and more land is becoming impervious leading to less recharge, changes in river and groundwater regimes (Rogers 1994; Grimm et al. 2008; Farooq and Ahmad 2008; Strohschön et al. 2013; Goel and Guttikunda 2015), formation of urban heat islands (Sundersingh 1990; Deosthali 2000); rampant land use changes especially the conversion of agricultural lands to non-agricultural land uses (Fazal 2000, 2001; Pandey and Seto 2015) and impact on water resources (Wagner et al. 2016; Butsch et al. 2017); loss of ecologically sensitive habitats (Ramachandra and Kumar 2009; Butsch et al. 2017); excessive solid waste generation and problems related to its disposal (Rahman et al. 2009); changes in social fabric, impacts on health and quality of life, increasing environmental costs due to rising quantities and qualities of urban waste (Butsch et al. 2017).

In this unparalleled phenomenon of urbanization, India is not far behind. It has been projected that India will have added 416 mn urban dwellers by 2050—the highest amongst all the countries (Fig. 1) (United Nations 2018b). If we study the case of the national capital Delhi, we observe that in the 1950’s, the population of Delhi was 1.7 mn which increased to 26.5 mn in 2018 and is projected to reach 36 mn by 2030 (United Nations 2014). The built-up area is expected to increase by 26% by 2024 as compared with the year 2014 (Tripathy and Kumar 2019).

Land use/land cover changes, being dynamic, need to be mapped at specific intervals (Iyer et al. 2007). It is essential for urban planners to understand the trend of development on the urban periphery and subsequently to regulate it (Sokhi et al. 1989). Also, identification of the urban sprawl patterns and monitoring and analyses of spatial and temporal changes would help immensely in the planning for proper infrastructure facilities (Verma et al. 2009). Up until the late 60s and early 70s, land use studies have been based on conventional surveys which are very expensive and time-consuming. However, in recent times, remote sensing coupled with GIS has anchored its place in urban sprawl studies because of its synoptic coverage, repeatability and cost-effectiveness.

Research gaps and objectives

Previous reviews on urbanization or urban sprawl focused on characteristics, causes and effects of sprawl (Ewing 1994); urban economics (Brueckner Jan 2001); the influence of urban form on travel (Crane 2000); quantitative analysis of urban form (Clifton et al. 2008); climate impacts of urban land use trends (Seto and Shepherd 2009); and impacts of logistics sprawl on urban environment (Aljohani and Thompson 2016). Urbanization reviews have been conducted at global

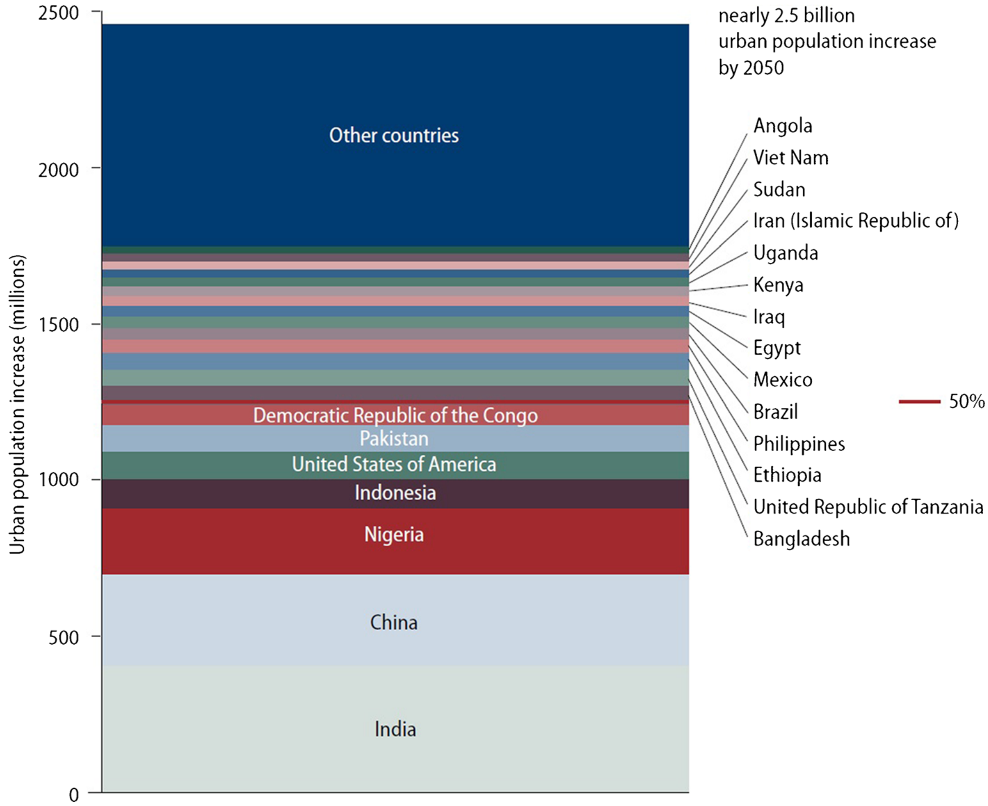

Fig. 1 Contribution to the increase in urban population by country, 2014 to 2050. *Source*: United Nations 2018b

(Wang et al. 2012); continental, e.g. Asia (Costa et al. 1989); Latin America (Gilbert et al. 1982); and national levels, e.g., China (Chao-lin 2008); Colombia (Samad et al. 2012) and USA (Barrington-leigh and Millard-Ball 2015) to name a few. A few reviews include satellite data focused on the potential applications of remote sensing in urban settings (Patino and Duque 2013), discussion of sprawl measurement techniques along with their merits and demerits (Bhatta et al. 2010a) and review of cellular automata (CA) models (Aburas et al. 2016) and geospatial-based urban growth models and modelling initiatives (Musa et al. 2017). In the Indian context, two reviews related to urbanization date back to the mid-1980s which focused on trends in the growth of urban population and the projections of the growth to the end of the twentieth century either based on the World Development Report 1984 (Nath 1986) or Census data (Mohan 1985). But none of the studies reviewed concerning the geospatial point of view. A methodical review on the use of remote sensing and GIS in mapping, monitoring and modelling urban sprawl in the Indian context was found lacking.

Thus, this paper aims to provide a systematic review of urban sprawl studies carried out using geospatial techniques spanning from the early 1980s onwards in India. Our article serves as a resource for researchers, who wish to engage the literature in their domain and consider their interdependence with related fields. The rest of the article has been organized as follows: "Methodology" describes the approach adopted to select the literature while "Review of literature" describes the general observations from the selected literature and later detailed review of individual studies organized by the decade starting from the year 1980. In "Trends and changes" and "Challenges and opportunities", we discuss the trends and changes over the decades as well as the challenges and opportunities in relation to urban sprawl studies. In conclusion ("Conclusion"), we summarize the findings and finally present the limitations and future prospects of the study in "Research limitations" and "Future prospects", respectively.

Methodology

This section represents the characteristics of research output, the criteria used to select the literature and how it was processed. We reviewed research articles from peer-reviewed journals published in the English language only. The search was based primarily using the ISI Web of Science and Google Scholar databases and included research articles dating back to the early 1980s. The keywords used to collect the literature were: "urban growth India OR urbanization India and remote sensing" and "urban sprawl remote sensing India". The search yielded > 28,000 publications, and screening the publications as per our objectives resulted in 153 publications which were ultimately downloaded and considered for this study. All the information related to the source journal, study area (city), publication year and satellite/sensor data used was prepared (see Appendix, Table 4), and the outcomes have been presented in various forms in the manuscript. The journals for which we could not establish academic reliability were not considered.

Review of literature

General observations

India has been predominantly an agrarian and rural economy since the prehistoric times. However, with unprecedented growth in population, India is becoming one of the fastest urbanizing countries. Its rural population is increasingly migrating towards the cities, and by 2050, the percentage of the urban population will exceed the rural population (United Nations 2018b; Fig. 2). As per the UN, a megacity is defined as a city with a population of 10 million or above. Currently, India has five megacities namely New Delhi (26.5 mn), Mumbai (21.4 mn), Kolkata (15 mn), Bengaluru (10.5 mn) and Chennai (10.2 mn). In its World Cities Report 2016, the UN has predicted that two more cities—Hyderabad (12.8 mn) and Ahmedabad (10.5 mn)—will become megacities by the year 2030 (Fig. 3).

While reviewing, we observed that the most common type of studies for urban sprawl includes a post-classification comparison of multi-temporal data. In earlier studies, the classification was done mainly using visual interpretation on aerial photographs and satellite data, but with the advent of advanced satellite sensors, more sophisticated techniques for classification like supervised, object-oriented etc. originated. The results predominantly aimed at quantifying the magnitude, location and type of urban change. However, recently, specific models (for example, urban trajectory, SLEUTH, Geomod) have been developed to ascertain how the changes have occurred and how these could be projected to know the extent of the future urban sprawl. The decade-wise review has been given in "Decadal reviews".

Time period with maximum studies

As is evident from the pie chart below (Fig. 4), there has been a spurt in the studies using remote sensing and GIS to study urban sprawl patterns in the decade from 2010 to 2019 (June). This may be attributed to the ease of availability of data and models along with the need for such studies due to the problems faced in urban zones. The trend shows not only the advancement of technology but also its popularity amongst

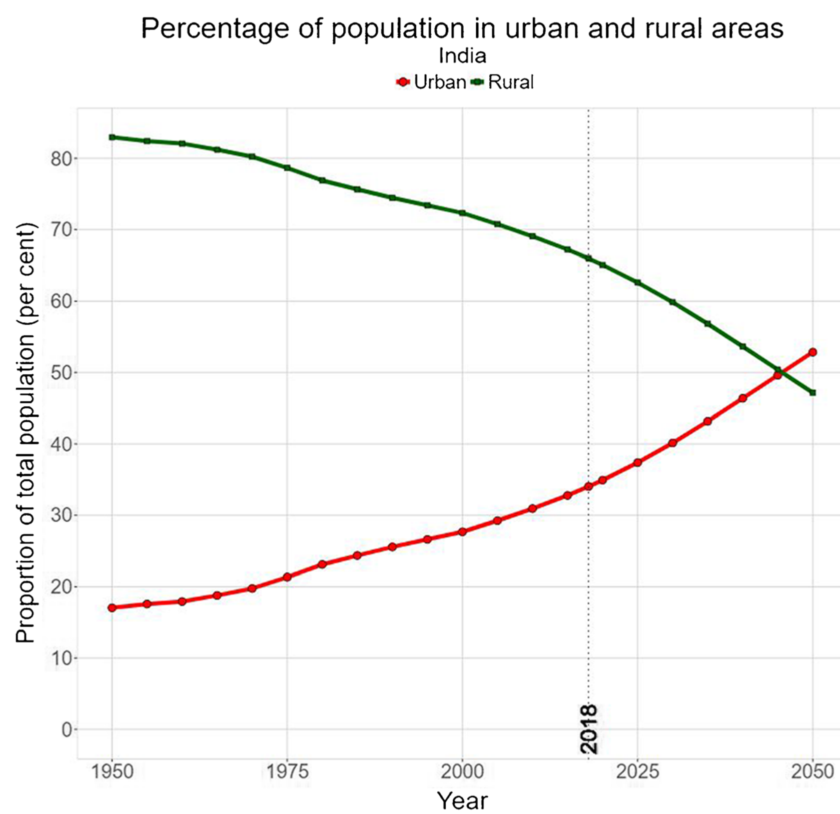

Fig. 2 Percentage of the urban and rural population in India, 1950 to 2050. *Source*: United Nations 2018b

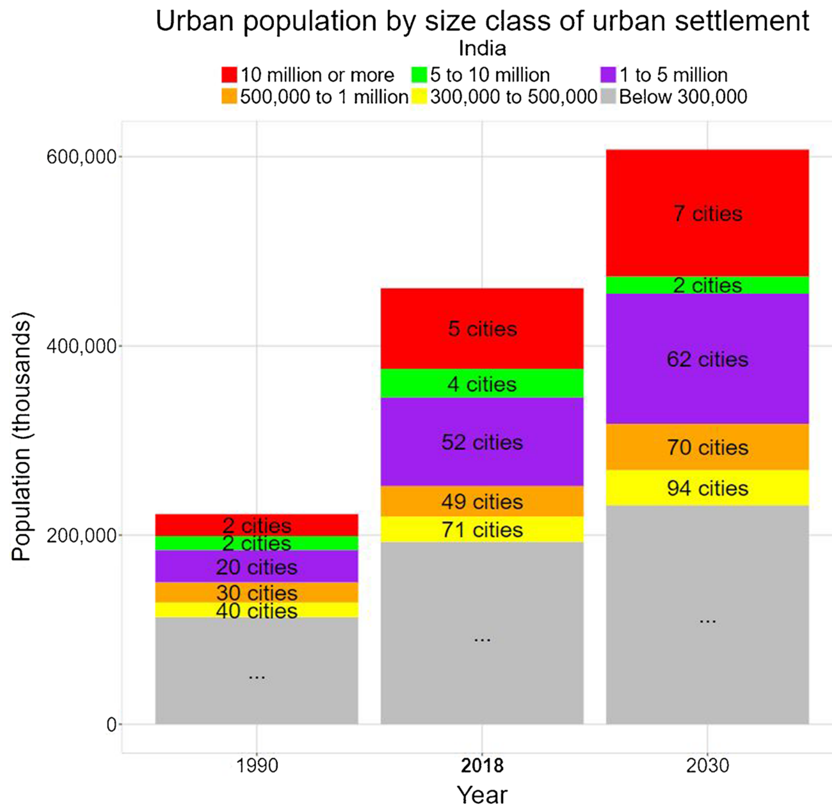

Fig. 3 Urban population by size class of urban settlement and number of cities, 1990, 2018, 2030 in India. NOTE: The grey area is a residual category that includes all urban settlements with a population of fewer than 300,000 inhabitants. *Source*: United Nations 2018b

the scientific community to study a complex phenomenon such as urban sprawl.

Geographical trend

There has been a sizable geographic bias in the cities being studied for urban sprawl using the satellite data. Karnataka is the most predominantly studied state with 15% of the studies, followed by Delhi (14%) and Maharashtra (13%). Thirty-eight cities have only one study attributed to them, out of which, 93% have been undertaken just in the last decade (2010–2019 (June)).

Satellite sensors

Aerial photography has been used for urban analysis since the 1950s (Patino and Duque 2013), and satellite data has been available since 1972, but it was not very actively used in India until 1999 as only seven studies were published till that time. One of the reasons may be the prohibitive cost of the satellite

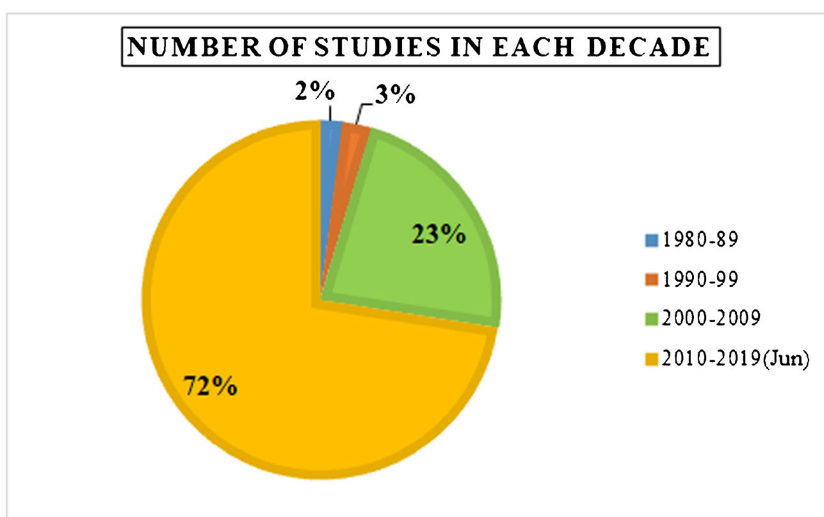

Fig. 4 Percent of studies in each decade. Note that the final year (2019) has data only till June

data at that time. But with the launch of Indian Remote Sensing Programme which provided relatively cheaper data, and later free availability of Landsat data gave impetus to research studies using geospatial techniques. Landsat data is the most preferred data source as it has been used in more than 65% of the studies reviewed here (Table 1). The main advantage of using Landsat data is that it has an extended temporal coverage (1972–present).

Top journals

Until 2013, Journal of the Indian Society of Remote Sensing (JISRS) was the most favoured for publication by the Indian Scientific community, but recently, with the increased use of remote sensing data by researchers, introduction of several new journals and less article processing times, the articles being published in JISRS have been decreasing. Still, it has the largest share amongst the papers reviewed for this study. Table 2 summarizes the most productive journals, along with the total number of publications, h-index and 2018 impact factor.

Key research group

Twenty-nine studies (19%) out of the total 153 have been conducted by Dr. T. V. Ramachandra from Indian Institute of Science Bangalore, and his team. The studied cities are of Bangalore (12), Delhi (2), Udupi-Mangalore highway (2), Belgaum (1), Chennai (1), Kolkata (1), Mumbai (1), Hyderabad (1), Gulbarga (1), Mysore (1), Pune (1), Ahmedabad (1), Bangalore-Mysore highway (1), Chennai-Bangalore and Mumbai-Pune highway (1), four metropolitan areas (1) and 7 tier-II cities (1). The rest of the studies have been carried out by different individual researchers.

Decadal reviews

1980–1989

This decade happens to initiate the use of remote sensing data in urban sprawl studies in India. Earlier such studies were conducted using census data (Bala and Krishan 1982). The studies during this decade included the preparation of base maps using visual interpretation techniques on topographic maps and false colour composites (FCC) of satellite data. One of the earliest studies was conducted on the national capital of Delhi (Gupta and Munshi 1985). The methods adapted to study urban change detection included visual interpretation and stereoscopy on guide maps of the years 1959, 1969 and 1978 and Landsat MSS data of 1977 and 1980. Another attempt to study the urban sprawl in Delhi was made by Sokhi et al. (1989). Landsat MSS, TM and toposheets were used to find the growth of urban areas from 1975 to 1988 using visual interpretation, and field surveys were conducted to fill any gaps in the prepared base maps and to check their accuracy. The authors reported a phenomenal areal urban growth of 127%, 45% and 18% for the periods 1975–1981, 1981–1985 and 1985–1987 respectively.

Table 1 Top five satellite remote sensing data used in urban sprawl studies in India

Satellite/sensor	Number of papers
Landsat	100
LISS III	34
LISS IV	18
Cartosat-1	10
LISS II	9

Pathan et al. (1989) attempted urban land use mapping and zoning of Bombay (now Mumbai) metropolitan region using SPOT and Landsat (MSS, TM) data from 1975 to 1987. A total of 31 land use maps—fifteen from SPOT and sixteen from Landsat data—were prepared using the elements of visual interpretation. They concluded that Landsat MSS data was useful for delineating urban built-up as one class while Landsat TM fared with differentiating the built-up land as recreational areas, open lands and major transportation networks. These data were used to prepare 1:50,000 scale maps. Since SPOT multispectral data has a finer resolution as compared with Landsat data; therefore, it was used to classify the study area into level II classes. The authors also devised a land suitability index based on comparing different land use qualities using which they attempted urban land use zoning of the study area on a scale of 1:250,000. This map provided information on the areas to be used for construction and regions to be conserved as green spaces in the study area.

1990–1999

The start of the Indian Remote Sensing (IRS) programme in 1988 gave impetus to the use of indigenous data in urban sprawl studies. This is evident as three (Pathan et al. 1991; Pathan et al. 1993; Taragi and Pundir 1997) out of the four investigations during this time frame used IRS LISS II data. Pathan et al. (1991) prepared urban sprawl maps of Ahmedabad using multi-temporal (1975–1990), multi-sensor (Landsat MSS, TM, SPOT MLA; IRS LISS II) data using visual and digital interpretation techniques such as supervised and unsupervised classification (though these were not successful in discriminating urban land uses at level II). The maps depicted that the city extended well outside the then municipal limits, and most of this growth was along the transportation network. Two other studies during this decade also used similar techniques of visual interpretation to map and monitor urban sprawl in the cities of Hisar (Jain et al. 1991) and Lucknow (Taragi and Pundir 1997). Both the studies reported a fast rate of urban sprawl along the major transport routes.

Table 2 Most productive journals in remote sensing-based urban sprawl studies in India

Journal	Total publications	h-index	2018 Impact Factor	Average time from submission to first decision (days)
JISRS	23	29	0.86	222
IJRS	7	151	2.49	n/a
EJRSSS	7	20	–	110
IJAEOG	6	76	4.84	17

JISRS Journal of the Indian Society of Remote Sensing, *IJRS* International Journal of Remote Sensing, *EJRSSS* The Egyptian Journal of Remote Sensing and Space Sciences, *IJAEOG* International Journal of Applied Earth Observation and Geoinformation, *n/a* Not Available

To fully demonstrate the potentials offered by the integration of remote sensing with GIS for urban and regional planning, an innovative study was carried out by Pathan et al. (1993) in Bombay (now Mumbai) from 1968 to 1989. Apart from preparing the urban sprawl maps, they predicted the extent of land required for urban development for the year 2001 by studying the population trends and establishing its relationship with sprawl. Further, the authors identified the areas suitable for urbanization based on land suitability analysis.

2000–2009

In this decade, most of the research was based on multi-temporal land use/land cover classification in different cities revealing the spatial distribution of the urban sprawl and sometimes predicting the future sprawl (Kamini et al. 2006; Rajeshwari 2006; Iyer et al. 2007; Rahman 2007; Farooq and Ahmad 2008; Jat et al. 2008a, 2008b; Schneider and Woodcock 2008; Taubenböck et al. 2008, 2009; Bhatta 2009a; Lilly Rose and Devadas 2009; Rahman et al. 2009). However, there was an emergence of more recent methods, for example, the use of neural network-based classification (Iyer and Mohan 2002); cellular automation, Markov and discrete choice models (Srinivasan 2005); site suitability analysis (Jain and Subbaiah (2007); object-oriented analysis (Niebergall et al. 2007; Taubenböck et al. 2007); entropy approach (Kumar et al. 2007; Jha et al. 2008; Jat et al. 2008a, 2008b; Lata et al. 2009); expert system classification (Wentz et al. 2008) and neural network-based urban growth modelling (Maithani 2009), optimization of multi-resolution data by image fusion and classification (Bharath et al. 2009), spatial metrics (Sudhira and Ramachandra 2007; Dasgupta et al. 2009) and modelling using ideal urban radial proximity (Bhatta 2009b) for studying urban sprawl.

Research in this decade also explored the use of multiple satellite remote sensing data (Landsat; IRS 1A, 1B, 1C, 1D, P6; Cartosat-1; Radarsat-1; IKONOS; ASTER; Quickbird) to study the relationship between urban sprawl and other environmental variables. A variety of topics were covered in these studies such as the impact of urban sprawl on heat and moisture islands (Deosthali 2000); urban expansion and loss of agricultural land and the need to preserve it (Fazal 2000, 2001); correlating the increase of built-up area in river catchment areas and flooding in cities (Kamini et al. 2006), urbanization and degradation of watershed health (Jat et al. 2009) and natural resources (Ramachandra and Kumar 2009). Sudhira et al. (2003a, 2003b) reported that urban sprawl either takes place radially around a well-established city or linearly along the highways. They studied urban sprawl along two highways, namely the Bangalore-Mysore highway (Sudhira et al. 2003a) and Mangalore-Udupi highway (Sudhira et al. 2003b, 2004). The findings along the Bangalore-Mysore highway pointed to a staggering 559% and 128% increase in the built-up area in Bangalore North/South taluks and Mysore-Srirangapatna region respectively from 1972 to 1998 with a high degree of dispersion. The degree of sprawl was also reported to be directly proportional to the distances from the cities (Sudhira et al. 2003a).

2010–June 2019

This decade saw an exponential increase in the use of remote sensing and GIS for studying urban sprawl. Apart from studying the metropolitan areas, the focus now shifted towards lesser-known smaller cities such as Karaikal, Malegaon, Raichur, Belgaum and Gulbarga, to name a few. Based on the articles published in this decade, we divided it into two main categories, namely urban sprawl (i) modelling and (ii) assessment. Table 3 synthesizes the findings of our review in this decade.

Trends and changes

- 1980–1989. This decade could be marked as a starting stage for urban land use studies using remote sensing in the Indian context. The studies were mainly conducted by government bodies like Survey of India, Space Applications Center and municipal authorities of respective areas.

Table 3 Summary of urban sprawl modelling and assessment studies in the decade 2010–2019 (June)

Category	Issue	Approach and methods	Author, year (city studied)
Modelling		Markov method	Maithani 2010 (Saharanpur); Dadhich and Hanaoka 2011 (Jaipur); Bharath et al. 2013 (Bangalore); Moghadam and Helbich 2013 (Mumbai); Deep and Saklani 2014 (Dehradun); Sivakumar 2014 (Pune); Mishra and Rai 2016 (Patna); Bharath et al. 2017 (Delhi, Mumbai, Chennai, Kolkata, Coimbatore)
		Markov model, Fuzzy-AHP, Cellular automata	Bharath et al. 2014 (Bangalore); Ramachandra et al. 2019 (Chennai-Mangalore, Mumbai-Pune highway)
		Random forest classification, Land change modeller, spatial metrics, Renyi's entropy	Padmanaban et al. 2017 (Chennai)
		Land Change Modeller, Markov cellular automata, Geomod	Ramachandra et al. 2013b (Bangalore)
	Spatiotemporal landscape modelling of urban growth patterns	Unsupervised classification, spatial metrics, FRAGSTATS	Lal et al. 2017 (Dhanbad)
	Spatiotemporal variability of urban growth factors	Regression modelling	Kuchay and Bhat 2014 (Srinagar); Moghadam and Helbich 2015 (Mumbai)
	Urban growth assessment and prediction	Cellular Automata, Logistic regression	Kumar et al. 2014 (Bangalore); Munshi et al. 2014 (Ahmedabad); Siddiqui et al. 2018 (Lucknow); Tripathy and Kumar 2019 (Delhi)
		SLEUTH model	Jat et al. 2017 (Ajmer)
		Object-oriented classification, Urban trajectory model	Shukla and Jain 2019 (Lucknow)
		Geomod model	Bharath et al. 2018 (Bangalore)
		Scenario-based urban growth simulation model (SUSM)	Kantakumar et al. 2019 (Pune)
	Modelling spatial growth pattern	Ordinary least squares model, Spatial regression model	Pandey et al. 2019 (Pune)
Assessment	Analysing heterogeneity in residential areas	Supervised classification, Simpson's Evenness Index	Baud et al. 2010 (Delhi)
	Effect of urbanization on land surface temperature and NDVI	NDVI, LST*	Saini and Tiwari 2017 (Dehradun)
	Emerging Urban Heat Island; urban growth dynamics	Supervised classification, NDVI, LST*	Ramachandra and Kumar 2010 (Bangalore); Lakra and Sharma 2019 (Ajmer)
	Extent and growth of urban sprawl	Feature Space classification, Shannon's entropy, Pearson's chi-square test	Bhatta et al. 2010b (Kolkata); Borana et al. 2013 (Jodhpur); Ghosh 2019 (Bhopal)
	Identification of urban slums; Urban growth monitoring	Texture-based classification	Kit et al. 2012 (Hyderabad); Raja et al. 2013 (Madurai)
	Impact of urbanization on diurnal temperature range	Mann-Kendall Trend, LST*	Mohan and Kandya 2015 (Delhi)
	Impact of Regional Factors on Pattern of Urbanization; urban footprint dynamics	Spatial metrics	Shetty et al. 2010 (Mumbai, New Delhi, Kolkata, Hyderabad); Jain et al. 2011 (Gurgaon); Settur et al. 2012 (Bangalore); Ramachandra et al. 2013a (Belgaum); Jain et al. 2014 (Jamnagar); Ramachandra et al. 2014a (Kolkata); Ramachandra et al. 2014b (Mumbai); Ramachandra et al. 2014c (Pune); Ramachandra et al. 2015 (Delhi); Bharath and Ramachandra 2016 (Chennai); Jain et al. 2016 (Delhi); Kantakumar et al. 2016 (Pune); Anees et al. 2018 (Kurukshetra)
	Land use dynamics and peri-urban growth characteristics	Visual interpretation, AHP* and GIS	Dutta 2013 (Lucknow)
	Mapping and monitoring of built-up areas	Human Settlement Index using DMSP-OLS*, NDVI*	Chowdhury and Maithani 2010; Chowdhury et al. 2012 (Indo-Gangetic Plains); Maithani et al. 2019 (Indo-Gangetic Plains)
	Monitoring urbanization, urban sprawl	Object-oriented classification	Taubenböck et al. 2012 (Delhi, Mumbai, Kolkata); Jain et al. 2013 (Delhi) Saini and Tiwari 2018 (Chandigarh)
	Monitoring urbanization dynamics	Support vector Machine	Pandey et al. 2013a (India)

Table 3 (continued)

Category	Issue	Approach and methods	Author, year (city studied)
	Monitoring urban landscape dynamics	Knowledge-based classification, ULAT*	Sharma and Joshi 2013 (Delhi)
		City Biodiversity Index, PCA*, visual interpretation, spatial metrics, Shannon's entropy	Sahani and Raghavaswamy 2018 (Khammam)
	Monitoring urban sprawl	Shannon's entropy model	Rahman et al. 2011a, b (Hyderabad-Secundrabad)
	Mapping urban sprawl	NDVI, Factor analysis, Shannon's entropy, Markov model	Dinda et al. 2019 (Midnapore)
	Spatiotemporal analysis of urban growth	Linear spectral unmixing	Dutta et al. 2015 (Dehradun)
		Object-oriented classification	Jain and Sharma 2018 (five cities of Gujarat)
	Spatial pattern of urban sprawl, impacts of population growth patterns and trends on urban sprawl	Supervised classification, Shannon's entropy	Mohan 2010 (Noida); Punia and Singh 2012 (Jaipur); Deka et al. 2012 (North-East India); Ranpise et al. 2016 (Pimpri-Chinchwad); Shaw and Das 2018 (English bazaar, Kolkata)
		Supervised classification, Shannon's entropy, Growth-metric/spatial metrics	Ramachandra et al. 2013c; (Hyderabad) Vani and Prasad 2019 (Vijaywada)
		Supervised classification, Shannon's entropy, PCA	Dhali et al. 2019 (North 24 Parganas)
	Spatiotemporal assessment of urban environmental conditions	Unsupervised classification	Kumar and Pandey 2013 (Ranchi); Poyil and Misra 2015 (Malegaon); Ahmad and Goparaju 2016 (Ranchi)
	Urban built-up area assessment	Contour density obtained from DEM*	Pandey et al. 2013b (Ranchi)
	Urban dynamics	Spatial metrics, NDVI, Shannon's entropy, density gradient analysis	Ramachandra et al. 2012 (Bangalore); Bharath et al. 2012 (Mysore); Ramachandra and Bharath 2013 (Gulbarga); Bharath and Ramachandra 2013 (7 tier II cities of Karnataka); Ramachandra et al. 2014d (Ahmedabad)
	Urban growth monitoring	NDVI, NDBI, BUI*	Badlani et al. 2017 (Gandhinagar); Jain et al. 2017 (Gurgaon)
	Urban growth zonation	Artificial Neural Network	Maithani et al. 2010 (Dehradun)
	Urban growth assessment	Satellite detected luminosity	Gibson et al. 2015 (India)
	Urban landscape characteristics	NDBI, MNDWI, SAVI, LST	Tiwari and Mishra 2019 (Bhopal)
		Supervised classification	Chandrasekar et al. 2010 (Tirunelveli); Kumar et al. 2010 (Varanasi); Mohan et al. 2011 (Delhi); Rahman et al. 2011a, b (Delhi); Basawaraja et al. 2011 (Raichur); Rahman et al. 2012 (Delhi); Sajjad and Iqbal 2012 (Kashmir); Singh and Kumar 2012 (Rohtak); Bhagyanagar et al. 2012 (Dakshin Kannada district Karnataka); Suribabu et al. 2012 (Tiruchirapalli); Mallupattu et al. 2013 (Tirupati); Wakode et al. 2014 (Hyderabad); Goldblatt et al. 2016 (India); Naqshbandi et al. 2016 (Kashmir); Mishra et al. 2018 (Bhubaneshwar); Saini and Tiwari 2019 (Chandigarh);
		Visual interpretation	Kumar et al. 2011a (Ranchi, Jamshedpur, Dhanbad); Kumar et al. 2011b (Ranchi); Mitra et al. 2011 (Kolkata); Sharma et al. 2012 (Bhagalpur); Manonmani et al. 2012 (Karaikal); Acharjee et al. 2013 (Assam); Mohapatra et al. 2014 (Gwalior); Bhat et al. 2017 (Dehradun); Dame et al. 2019 (Leh)
		Knowledge-based classification, LST*	Sharma et al. 2013 (Surat); Sharma et al. 2015 (Kolkata); Sharma and Joshi 2016 (National Capital Region)

AHP Analytical Hierarchical Process, *BUI* Built-up Index, *DEM* digital elevation model, *DMSP-OLS* Defense Meteorological Satellite Program/Operational Linescan System, *MNDWI* Modified Normalized Difference Water Index, *NDBI* Normalized Difference Built-up Index, *NDVI* Normalized Difference Vegetation Index, *PCA* principal component analysis, *SAVI* Soil-adjusted Vegetation Index, *LST* Land Surface Temperature, *ULAT* urban landscape

- 1990–1999. The use of remote sensing data for urban studies remained scarce, but this decade introduced IRS data at the global stage. Apart from visual analysis, this decade saw the use of digital analysis techniques like supervised classification for the works carried out. Studies also started identifying and predicting the directions of future growth and started giving recommendations as what would be the best areas to direct the growth so that no encroachments are done on agricultural land.
- 2000–2009. Because of their rapidly growing status, Indian cities started becoming a part of global urbanization studies. Primarily, the cities of Mumbai, Delhi, Kolkata, Bangalore and Ahmedabad hogged the international limelight. Further, due to the ease of availability, high spatial resolution and comparatively lower prices, the IRS data began to be used as rampantly as Landsat data. This decade also saw authors moving away from traditional sprawl studies and venturing into areas of modelling the urban sprawl for the future.
- 2010–June 2019. This decade saw an exponential increase in the use of remote sensing and GIS for studying urban sprawl with almost three times the publications than in the preceding decade. For mapping and monitoring urban landscape dynamics, newer methods like spatial metrics, artificial neural network, object-oriented classification, texture-based classification began to be used significantly. Similarly, the authors started using advanced concepts and models, for example, Geomod, Land change modeller, SLEUTH, ULAT, FRAGSTATS and SUSM for urban sprawl prediction.

Challenges and opportunities

The process of urban sprawl leads to a change in land use but does not follow a uniform pattern. Various methods have been reported for assessing the urban sprawl, but no single method can solve the problem of land use change due to urban sprawl. Different methods have their advantages and disadvantages over the other, and no single approach is optimal and universally applicable. However, the selection of an appropriate method is important for an accurate outcome (Berberoglu and Akin 2009; Sharma et al. 2012). To successfully formulate policies and strategies to mitigate the effects of urban sprawl, it is pertinent to prepare accurate sprawl maps. The magnitude, dynamics and pattern of sprawl may differ in different cities due to the presence of variable factors, such as availability of employment opportunities, educational, medical and other such facilities. These factors can lead to heterogeneity in the direction of pattern, type (leapfrog, radial, linear, etc.) and magnitude (high/low) of urban sprawl and depend upon the region and available resources.

Different studies show that supervised classification and visual image interpretation remain the most common techniques for urban sprawl analysis since the 1980s to date (Table 3). But with time, new methods and techniques should be adapted to continuously and accurately monitor the urban sprawl (Bhatta 2010). Accordingly, the scientists adopted newer methods for urban growth assessment such as Shannon's entropy and spatial metrics (first used in 2007 in India), and these have been relied heavily upon since then. Shannon's entropy is a commonly used technique which can accurately measure sprawling phenomenon in association with GIS-based database management systems (Seto and Fragkias 2005; Tewolde and Cabral 2011). It has been used either singly or in combination with additional parameters such as spatial metrics, statistical indices and models. Spatial metrics help bring out the spatial component in urban structure and dynamics of change and growth processes (Alberti and Waddell 2000; Barnsley and Barr 1997; Herold et al. 2002).

Studying dynamic simulation of urban growth is very much important to have an idea about the futuristic view of urban areas based on different driving variables, and this problem of urban sprawl and expansion can be reduced by proper planning, administration and strategy (Bhatta 2009a). Urban growth prediction is also essential for long-term planning and sustainable urban management (Dinda et al. 2009); consequently, several models were invented to accurately predict future sprawl. The most extensively used models are Markov model and CA-based models such as land change modeller, FRAGSTATS and SLEUTH.

Understanding the changes in the spatial pattern of land use and the expansion of the urban areas with time is paramount for better sustainable urban planning and land management. Inefficient planning leads to haphazard urban growth and vice-versa. However, there has been a glaring gap in the literature pertaining to the use of urban growth models in urban planning or evaluation of development plans.

In practice, different techniques are often compared to find the most useful or used in conjunction to get the best outcomes for urban sprawl studies for a specific application. In fact, combining two or more methods can improve the thematic detail and accuracy of remote sensing mapping products and facilitate their analysis for specific urban applications (Herold et al. 2005). For example, Padmanaban et al. (2017) combined application of GIS, remote sensing, urban change modelling, landscape metrics and entropy measures to efficiently assess and model urban sprawl for Chennai city. Similarly, Dinda et al. (2019) successfully used the Normalized Difference Built-up Index, Shannon's entropy and simulated urban growth by Markov Chain model in Midnapore town, India. Recently, Maithani et al. (2019) studied the urban settlement pattern and growth dynamics in Doon valley, Uttarakhand using supervised classification (LISS II, LISS III, Landsat TM data) and Human Settlement Index (DMSP-OLS nighttime; MODIS NDVI data). Later, they performed urban growth modelling using an artificial neural network (ANN)-based model demonstrating its importance over other models in terms of it being data-driven and reducing subjectivity in the urban modelling process. However, these models have limitations of their own. For example, the most common limitation of logistic regression, CA and Markov modelling is not giving weightage to human decision variables in the simulation. The non-factoring of personal preferences and government policies were and still are limitations to the integration of CA and Markov models in analysing and simulating urban growth (Arsanjani et al. 2013). Yagoub and Al Bizreh (2014) reported that in the CA-Markov model, the factors that drive the change in land use in the past are assumed to remain the same during the future. Since this is not so in the real world, it leads to errors during the simulation. Deep and Saklani (2014) reported that CA does not incorporate socio-economic factors, and proximity to existing land use as well as the geographic factors constrains the land use change. Therefore, out of different methods available in the literature, the most suitable may be adopted after carefully studying the parameters influencing urban growth in a particular region and weighing the limitations of the same.

Conclusion

This article documents and synthesizes sprawl literature in the Indian context from the past four decades. Our findings suggest that sprawl research has evolved significantly over the years. Based on the review of the literature, we could identify the two most common approaches adopted to study urban sprawl. The first approach requires the use of classification techniques from historical times to the present using aerial photographs, toposheets and satellite imagery. The classification is either pixel-based (supervised and unsupervised) or object/texture/knowledge-based. The urban areas are quantified for different years, and an analysis is made about how the urban areas have increased over the study period. The second approach requires measuring the urban pattern, shape and growth magnitude using spatial metrics like patch density, percentage of landscape, class area etc. Another aspect of urban sprawl studies is to simulate the future sprawl of an area based on its past growth. Many models have been developed to predict the future sprawl, for example, CA-based models (SLEUTH, Markov), logistic regression and neural networks for predicting the urban sprawl. The use of remote sensing and GIS has picked momentum in the recent decade of 2010–2019 (June) contributing to a total of 72% of the published literature in this decade. Emerging issues like climate change are increasingly used to frame urban planning research and to evaluate the impacts of sprawl. With the availability of a large number of studies and amount of data, the governmental agencies and large organizations should actively formulate a national-level database and incorporate these studies in various urban planning decisions.

Research limitations

This work has been carried out for urban sprawl studies conducted in Indian cities using remote sensing coupled with GIS. There may be studies which do not involve geospatial techniques (for example social, biodiversity, economic, health impact related studies). Such studies have not been included in this review.

Future prospects

- All the cities should be studied, and a database should be made available to all the state governments. The availability of such data for all the cities will make a robust database for the urban development authorities and give a framework for planners to develop their policies on.
- The use of urban growth models in urban planning or evaluation of development plans is still in its infancy stage. This area needs to be explored.
- There may be methods/models or satellite data that have not been used in India yet. Those may be used and checked if they provide better results.
- Interdisciplinary studies/researchers from other domains may use such data for studying ecological (species richness and distribution), epidemiological, climatological and similar impacts of rampant urban sprawl in future studies.

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Author contributions Varinder Saini determined the paper's focus, searched and reviewed the literature and drafted the article. Reet Kamal Tiwari provided valuable inputs on the analyses and discussions.

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Appendix

Table 4 Information related to the publication year, study area, source journal, satellite/sensor data used and authors in the review

Year	Study area	Journal/conference/workshop/website	Satellite/sensor	Authors
1985	Delhi	IJRS	Landsat MSS	Gupta and Munshi
1989	Delhi	JISRS	Landsat MSS and TM	Sokhi et al.
1989	Mumbai	JISRS	SPOT and Landsat MSS, TM	Pathan et al.
1991	Ahmedabad	JISRS	Landsat MSS, TM, SPOT, LISS II	Pathan et al.
1991	Hisar	JISRS	Aerial photographs, Landsat TM	Jain et al.
1993	Mumbai	IJRS	Landsat MSS, TM, LISS II	Pathan et al.
1997	Lucknow	JISRS	Landsat MSS, SPOT, LISS II, IRS-1B	Taragi and Pundir
2000	Pune	Atmos. Environ.	IRS 1D PAN+ LISS III	Deosthali
2000	Saharanpur	Environ. Urban.	IRS 1C	Fazal
2001	Saharanpur	Landsc. Urban Plann.	IRS 1C, 1D	Fazal
2002	Mumbai	IEEE Int. Geoscience and Remote Sensing Symposium	IRS 1A LISS II	Iyer and Mohan
2003	Bangalore-Mysore highway	JISRS	IRS LISS III	Sudhira et al.
2003	Mangalore-Udupi National Highway	Map India (C.)	IRS LISS III	Sudhira et al.
2004	Mangalore-Udupi National Highway	IJAEOG	IRS LISS III	Sudhira et al.
2005	Delhi	Transportation	IRS	Srinivasan
2006	Dehradun	J. Human Ecol.	IRS 1C, 1D, IKONOS	Rajeshwari
2006	Mumbai	JISRS	Landsat TM, Cartosat-1, Radarsat-1	Kamini et al.
2007	Bangalore	10th Int. Conf. on Computers in Urban Planning and Urban Management (C.)	Landsat TM, ETM+	Iyer et al.
2007	Bangalore and Hyderabad	Urban Popu. Dev. Environ. Dyn. Developing Countries (W.)	Landsat MSS, TM, ETM+	Sudhira and Ramachandra
2007	Delhi	Urban remote sensing joint event (C.)	Quickbird	Niebergall et al.
2007	Delhi	Book Chapter	Multi-source data	Rahman and Netzband
2007	Hyderabad	Urban remote sensing joint event (C.)	Quickbird, Landsat TM, ETM+	Taubenböck et al.
2007	Indore	JISRS	Not GIVEN. Data of the year 2000	Kumar et al.
2007	Roorkee	J. Appl. Sci.	IRS 1D PAN	Jain and Subbaiah
2008	Ajmer	IJRS	Landsat MSS, TM, ETM+, IRS LISS II, III	Jat et al.
2008	Ajmer	IJAEOG	Landsat MSS, TM, ETM+, IRS LISS III	Jat et al.
2008	Ahmedabad, Bangalore Lucknow	Urban Studies	Landsat TM	Schneider and Woodcock
2008	Aligarh	JISRS	Landsat TM, ETM+, IRS 1B LISS II	Farooq and Ahmad
2008	Delhi	IJRS	ASTER	Wentz et al.
2008	Haridwar	KSCE J. Civil Eng.	IRS	Jha et al.
2008	Mumbai, Delhi, Kolkata	Int. Archives Photogramm. Remote Sens. Spatial Inf. Sci. (C.)	Landsat MSS, TM, ETM+	Taubenböck et al.
2009	Ajmer	Urban Water J.	Landsat MSS, TM, ETM+, IRS LISS II, III	Jat et al.
2009	Bangalore	COSMAR (C.)	IKONOS, Landsat MSS, IRS LISS III	Bharath and Kumar
2009	Bangalore	Int. Conf. on Infrastructure, Sustainable Transportation and Urban Planning	Landsat MSS, TM, ETM+	Dasgupta et al.
2009	Bangalore	Book Chapter	Landsat MSS, TM, ETM+, IRS LISS III, MODIS, SRTM	Ramachnadra and Kumar
2009	Chennai	7th Int. Conf. on Climate Change (C.)	Landsat TM, ETM+	Lilly Rose and Devadas
2009	Delhi	Book Chapter	Landsat TM, IRS-P6, ASTER	Rahman et al.

Table 4 (continued)

Year	Study area	Journal/conference/workshop/website	Satellite/sensor	Authors
2009	Hyderabad	Geospatial World	IRS 1C LISS III + PAN	Lata et al.
2009	Kolkata	IJRS	Landsat MSS, TM, ETM+, Resourcesat-1 LISS III	Bhatta
2009	Kolkata	IJDE	Landsat MSS, TM, Resourcesat-1 LISS III	Bhatta
2009	Saharanpur	JISRS	IRS 1C PAN	Maithani
2009	12 cities of India	Compu. Environ. Urban Syst.	Landsat MSS, TM, ETM+	Taubenböck et al.
2010	Bangalore	Geospatial Resource Portal (O.)	Landsat MSS, Landsat TM, ETM+, IRS LISS III, MODIS	Ramachandra and Kumar
2010	Dehradun	Geocarto Int.	IRS 1C, 1D LISS III	Maithani et al.
2010	Delhi	IJAEOG	IKONOS	Baud et al.
2010	Delhi, Mumbai, Kolkata, Hyderabad	Conf. on Infrastructure, Sustainable Transportation and Urban Planning (C.)	Landsat TM, ETM+	Shetty et al.
2010	Indo-Gangetic plain	JISRS	DMSP-OLS, MODIS NDVI	Chowdhury and Maithani
2010	Kolkata	Appl. Geogr.	Landsat MSS, TM, IRS Resourcesat-1 LISS III	Bhatta et al.
2010	Noida	FIG Congress (C.)	IRS 1C, IRS-P6 LISS III	Mohan
2010	Saharanpur	JISRS	IRS-1C	Maithani
2010	Tirunelveli	Af. J. Basic Appl. Sci.	IRS 1D LISS III	Chandrasekar et al.
2010	Varanasi	Environ. Monit. Assess.	IRS LISS IV	Kumar et al.
2011	Delhi	J. Environ. Prot.	IRS LISS III	Mohan et al.
2011	Delhi	J. Geogr. Inf. Syst.	ASTER	Rahman et al.
2011	Gurgaon	JISRS	LISS III	Jain et al.
2011	Hyderabad-Secundrabad	IEEE JSTARS	IRS P6 LISS III	Rahman et al.
2011	Jaipur	J. Urban Tech.	Landsat ETM+	Dadhich and Hanaoka
2011	Kolkata	Int. J. Climatology	Landsat TM, ETM+	Mitra et al.
2011	Raichur	J Geogr. Reg. Plan.	IRS 1C, 1D- LISS II; IRS P6 LISS IV	Basawaraja et al.
2011	Ranchi, Dhanbad, Jamshedpur	IJRS	Landsat TM, ETM+, IRS P6- LISS IV	Kumar et al.
2011	Ranchi	JISRS	Landsat MSS, TM, IRS P6 LISS IV	Kumar et al.
2012	Bangalore	IJAEOG	Landsat TM, ETM+	Ramachandra et al.
2012	Bangalore	14th Annual Int. Conf on Geospatial Information Technology and Applications (C.)	Landsat MSS, TM, ETM+	Settur et al.
2012	Bhagalpur	J. Land Use Sci.	Landsat MSS, ETM+, IRS P6 LISS IV, Cartosat 1	Sharma et al.
2012	Dakshin Kannada district	J. Appl. Remote Sens.	IRS 1A, 1C LISS III	Bhagyanagar et al.
2012	Delhi	JISRS	ASTER	Rahman et al.
2012	Delhi, Mumbai, Kolkata	Remote Sens. Environ.	Landsat MSS, TM, ETM+, TerraSar-X	Taubenböck et al.
2012	Hyderabad	Appl. Geogr.	QucikBird	Kit et al.
2012	Indo-Gangetic plain	IJRS	DMSP-OLS	Chowdhury et al.
2012	Jaipur	JISRS	Landsat MSS, TM, ETM+, IRS P6 LISS III	Punia and Singh
2012	Karaikal	Geospatial Inf. Sci.	LISS IV, Cartosat 1	Manonmani et al
2012	Kashmir	Int. J. Urban Sci.	Landsat TM	Sajjad and Iqbal
2012	Mysore	NRSC User Interaction Meet (C.)	Landsat MSS, TM, ETM+, IRS-P6 LISS IV	Bharath et al.
2012	North-East India	Int. J. Geomat. Geosci.	Landsat TM	Deka et al.
2012	Rohtak	J. Geogr. Inf. Sci.	Cartosat 1 and LISS IV	Singh and Kumar
2012	Tiruchirapalli	JISRS	IRS 1A,B,C LISS 1, IRS P6 LISS III, IV; Cartosat 1	Suribabu et al.
2013	Assam	Int. J. Geomat. Geosci.	Landsat MSS, TM	Acharjee et al.

Table 4 (continued)

Year	Study area	Journal/conference/workshop/website	Satellite/sensor	Authors
2013	Bangalore	Int. Conf. on Advances in Computer Science (C.)	Landsat TM, ASTER DEM	Bharath et al.
2013	Bangalore	30th Annual In-House Symposium on Space Science and Technology (C.)	Landsat TM, ETM+	Ramachandra et al.
2013	Belgaum	SCIT J.	Landsat TM, IRS LISS III, IV	Ramachandra et al.
2013	Delhi	Environ. Urban. ASIA	Landsat, TerraSAR-X	Jain et al.
2013	Delhi	JISRS	Landsat TM, ETM+	Sharma and Joshi
2013	Gulbarga	Int. J. Geomat. Geosci.	Landsat TM, ETM+, IRS LISS III	Ramachandra and Bharath
2013	Hyderabad	Theor. Empir. Res. Urban Manage.	Landsat MSS, TM	Ramachandra et al.
2013	India	IJAEOG	DMSP-OLS, SPOT-VGT	Pandey et al.
2013	Jodhpur	Indian Cartographer	Landsat MSS, TM, ETM+	Borana et al.
2013	Lucknow	Environ. Urban. ASIA	IRS 1C LISS III, Google Earth image	Dutta
2013	Madurai	JISRS	IRS 1B, IRS-P6	Raja et al.
2013	Mumbai	Appl. Geogr.	Landsat MSS, TM, ETM+	Moghadam and Helbich
2013	Ranchi	Int. J. Urban Sci.	Landsat ETM+, IRS LISS IV, WorldView II	Kumar and Pandey
2013	Ranchi	JISRS	Cartosat 1	Pandey et al.
2013	Surat	Environ. Monit. Assess.	Landsat TM	Sharma et al.
2013	Tier-II cities Karnataka	IEEE Global Humanitarian Technology Conference: South Asia Satellite,	Landsat MSS, TM, ETM+, IRS-P6 LISS IV, Resourcesat-2 LISS IV	Bharath and Ramachandra
2013	Tirupati	The Scientific World Journal	IRS LISS III + PAN	Mallupattu et al.
2014	Ahmedabad	SPATIUM Int. Rev.	Landsat MSS, TM	Ramachandra et al.
2014	Ahmedabad	Cities	Cartosat −1, Landsat TM, ETM+	Munshi et al.
2014	Bangalore	IEEE Int. Geoscience and Remote Sensing Symposium	Landsat TM, ETM+, ASTER DEM	Bharath et al.
2014	Bangalore	Boletín Geológico y Minero	Landsat MSS, TM, IRS LISS III	Kumar et al.
2014	Dehradun	EJRSSS	IRS LISS IV	Deep and Saklani
2014	Gwalior	Geogr. J.	Landsat MSS, TM, ETM+, OLI	Mohapatra et al.
2014	Hyderabad	Arab. J. Geosci.	Landsat TM, ETM+	Wakode et al.
2014	Jamnagar	Int. Archives Photogramm. Remote Sens. Spatial Inf. Sci.	CORONA, IRS 1D PAN + LISS III, IRS P6 LISS IV, Resourcesat 2 LISS IV	Jain et al.
2014	Kolkata	JISRS	Landsat MSS, TM, ETM+	Ramachandra et al.
2014	Mumbai	J. Urban Reg. Anal.	Landsat MSS, TM, ETM+	Ramachandra et al.
2014	Pune	TeMA-Journal of Land Use, Mobility and Environment	Landsat MSS, TM, ETM+, OLI	Ramachandra et al.
2014	Pune	Int. Archives Photogramm. Remote Sens. Spatial Inf. Sci.	Landsat TM, ETM+	Sivakumar
2014	Srinagar	Trans. Institute of Indian Geographers	IRS P5, P6	Kuchay et al.
2015	Dehradun	Remote Sens. Appli: Soc. Environ.	Landsat TM, ETM+	Dutta et al.
2015	Delhi	Sci. Total Environ.	MODIS	Mohan and Kandya
2015	Delhi	J. Environ. Manage.	Landsat MSS, TM, ETM+	Ramachandra et al.
2015	India	Food Policy	DMSP-OLS	Gibson et al.
2015	Kolkata	Environ. Monit. Assess.	Landsat TM, ETM+	Sharma et al.
2015	Malegaon	Int. J. Sust. Built Environ.	Landsat TM, ETM+, IRS P6 LISS III	Poyil and Misra
2015	Mumbai	IJAEOG	Landsat MSS, TM, ETM+	Moghadam and Helbich
2016	Chennai	JISRS	Landsat TM, IRS P6 LISS III, Aster GDEM	Bharath and Ramachandra
2016	Delhi	Earth Interact.	Landsat, IRS	Jain et al.
2016	India	Remote Sens.	Landsat ETM+, OLI	Goldbalt et al.

Table 4 (continued)

Year	Study area	Journal/conference/workshop/website	Satellite/sensor	Authors
2016	Kashmir	IOSR J. Human. Soc. Sci.	Landsat TM	Naqshbandi et al.
2016	NCR	Urban Clim.	Landsat TM, ETM+, ASTER DEM	Sharma and Joshi
2016	Patna	Arab. J. Geosci.	Landsat TM, ETM+, OLI	Mishra and Rai
2016	Pimpri-Chinchwad	Curr. Urban Stud.	IRS LISS III, LISS IV	Ranpise et al.
2016	Pune	Habitat Int.	Landsat TM, ETM+, OLI	Kantakumar et al.
2016	Ranchi	J. Environ. Geogr.	Landsat MSS, ETM+, OLI TIRS	Ahmad and Goparaju
2017	Ajmer	EJRSSS	Several sources- not mentioned	Jat et al.
2017	Chennai	Entropy	Landsat TM, ETM+	Padmanaban et al.
2017	Dehradun	Int. J. Sust. Built Environ.	IRS LISS IV	Bhat et al.
2017	Dehradun	38th Asian Conf. on Remote Sens. (C.)	Landsat	Saini and Tiwari
2017	Delhi, Mumbai, Chennai, Kolkata, Coimbatore	EJRSSS	Landsat TM, ETM+	Bharath et al.
2017	Dhanbad	EJRSSS	Landsat MSS, TM, ETM+, Cartosat 1 DEM	Lal et al.
2017	Gandhinagar	Int. J. Geosci.	Landsat TM	Badlani et al.
2017	Gurgaon	Adv. Comput. Sci. Tech.	Landsat TM, ETM+, OLI	Jain et al.
2018	Bangalore	Model. Earth Syst. Environ.	Landsat TM, ASTER	Bharath et al.
2018	Bhubaneshwar	World Geospatial Forum (C.)	IRS 1D LISS III, Cartosat 1	Mishra et al.
2018	Chandigarh	SPIE Remote Sensing (C.)	Landsat MSS, TM, ETM+, OLI	Saini and Tiwari
2018	Gujarat	Geocarto Int.	IRS 1C, 1D, IRS P6 LISS IV, Resourcesat 2 LISS IV	Jain and Sharma
2018	Khammam	Environ. Monit. Assess.	IRS series PAN, LISS IV	Sahani and Raghavaswamy
2018	Kolkata	EJRSSS	Landsat MSS, TM, ETM+	Shaw and Das
2018	Kurukshetra	Geocarto Int.	Landsat TM, ETM+, OLI	Anees et al.
2018	Lucknow	EJRSSS	Landsat TM, ETM+, OLI, Cartosat 1 DEM	Siddiqui et al.
2019	Ajmer	JISRS	Landsat TM, OLI	Lakra and Sharma
2019	Bhopal	Book Chapter	Landsat TM/ETM+	Tiwari and Mishra
2019	Bhopal	Model. Earth Sys. Environ.	Landsat TM, ETM+, OLI	Ghosh
2019	Chandigarh	J. Geomat.	Landsat TM, ETM+, OLI	Saini and Tiwari
2019	Chennai-Mangalore, Mumbai-Pune	Spat. Inf. Res.	Landsat TM, ETM+, OLI	Ramachandra et al.
2019	Delhi	Cities	Landsat TM, ETM+, OLI	Tripathy and Kumar
2019	Indo-Gangetic Plains	Book chapter	LISS II, LISS III, DMSP-OLS, MODIS NDVI	Maithani et al.
2019	Leh	Landsc. Urban Plann.	Corona, Quickbird. Worldview-2, Pleiadas	Dame et al.
2019	Lucknow	JISRS	Landsat TM/ETM+, Rapideye	Shukla and Jain
2019	Midnapore	Model. Earth Syst. Environ.	Landsat TM, OLI	Dinda et al.
2019	North 24 Parganas	EJRSSS	Landsat TM, ETM+, OLI	Dhali, Chakraborty and Sahana
2019	Pune	European Journal of Remote Sensing	Landsat TM, OLI	Kantakumar, Kumar and Schneider
2019	Pune	Book chapter	Landsat TM, OLI	Pandey et al.
2019	Vijaywada	Environ. Dev. Sust.	Landsat TM, OLI	Vani and Prasad

C. Conference, *DMSP-OLS* Defence Meteorological Satellite Program-Operational Linescan System, *EJRSSS* The Egyptian Journal of Remote Sensing and Space Sciences, *IJRS* International Journal of Remote Sensing, *IJAEOG* International Journal of Applied Earth Observation and Geoinformation, *JISRS* Journal of the Indian Society of Remote Sensing, *JSTARS* Journal of Selected Topics in Applied Earth Observations and Remote Sensing, *O.* Online Source, *W.* Workshop

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