Assessing urbanization patterns over India using temporal DMSP–OLS night-time satellite data

Many of the important and most significant changes around the world are associated with urbanization. Incidentally, more than half of the population (3.3 billion people) resides in the urban areas and by 2030 more than 70% of the population will be concentrated in the urban areas[1–3]. As of now, 19 mega cities and 22 cities exist, holding more than 10 million and 5–10 million population respectively. Apart from this, 370 cities with 1–5 million people, and 433 cities with 0.5–1 million people are growing at a high rate[1,4,5]. The current rate of urbanization (0.8%) will grow in a rapid and unbalanced pace (1.6%), most dominantly in the developing countries[6]. Asia being one of the most populous realms is expected to have more than 54% of the world's urban population by 2050. This will result in political and economic transformations, including migration of communities and urbanization.

In India, urbanization has witnessed an unprecedented rate of growth over the last four decades. During the last 50 years, the population of India (today 1.2 billion) has grown more than double and the urban population nearly five times. Around 400 million people (~28%) live in the cities, in sharp contrast to 60 million people (~15%) in 1947. It is estimated that 140 million people will move to the cities by 2020, and another 700 million by 2050. The number of Indian mega cities will increase from the current three (Mumbai, Delhi and Kolkata) to six (including Bangalore, Chennai and Hyderabad) by 2021, when India will have the largest concentration of mega cities in the world[7,8]. The number of cities is expected to be 68 by 2021, which will result in urban housing shortage of about 30 million units. Such interactions will create a coupling impact between the global environmental changes and the local environment of urban areas.

Monitoring, measurement and assessment of this urban growth is essential for city-planners, economists, environmentalists, ecologists, resource managers and the government at large. Such information will enhance the ongoing initiatives to use spatial data for local planning and better governance. Multi-temporal remote sensing is one of the important data-gathering tools for analysing land-use and land-cover changes[9]. The potential use of Defense Meteorological Satellite Program–Operational Linescan System (DMSP–OLS) night-time satellite data in population studies, inventories of human settlements and energy consumption patterns has been noted since the early 1980s (refs 10 and 11). The potential use of this in mapping the population and urban areas[12], socio-economic parameters and greenhouse gas emissions[13], urban heat island[14] and energy consumption[15] has also been documented.

In this study we used temporal night-time DMSP–OLS satellite data over the Indian region, to detect urban footprints and their changes, with a special emphasis on 12 large Indian cities (currently ranging from 2.5 to 20 million inhabitants). Development of a country is best represented in the spatial increase in towns and cities (urban sprawl or agglomeration), as they provide living for people of all groups and are the centres of attraction. Spatial analysis on enhancement in the night-time lights is a potential indicator of urban sprawl. The study attempts to characterize the spatial pattern of the cities to detect similarities and differences in spatial growth in the large Indian urban agglomerations.

Figure 1 shows a map of India with state boundaries and location of important cities. It also shows the population growth between 1991 and 2001. The mega cities in India are Mumbai, Delhi and Kolkata[2], of which Delhi (4.1%) and Mumbai (3.1%) have the highest population growth rate of all mega cities in the world. The other important cities are Chennai, Hyderabad and Bangalore. Besides these, other urban agglomerations (Ahmedabad, Jaipur, Poona, Kanpur, Lucknow and Surat) currently have more than 2.5 million habitants[2]. These cities

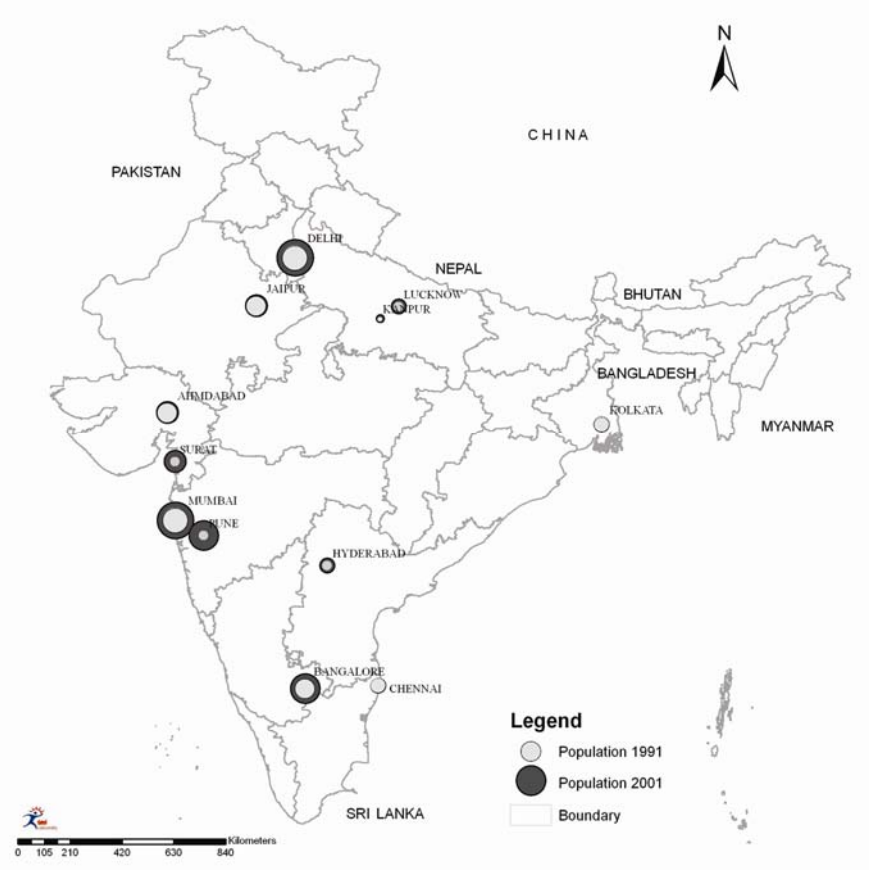

Figure 1. Location map of the study area.

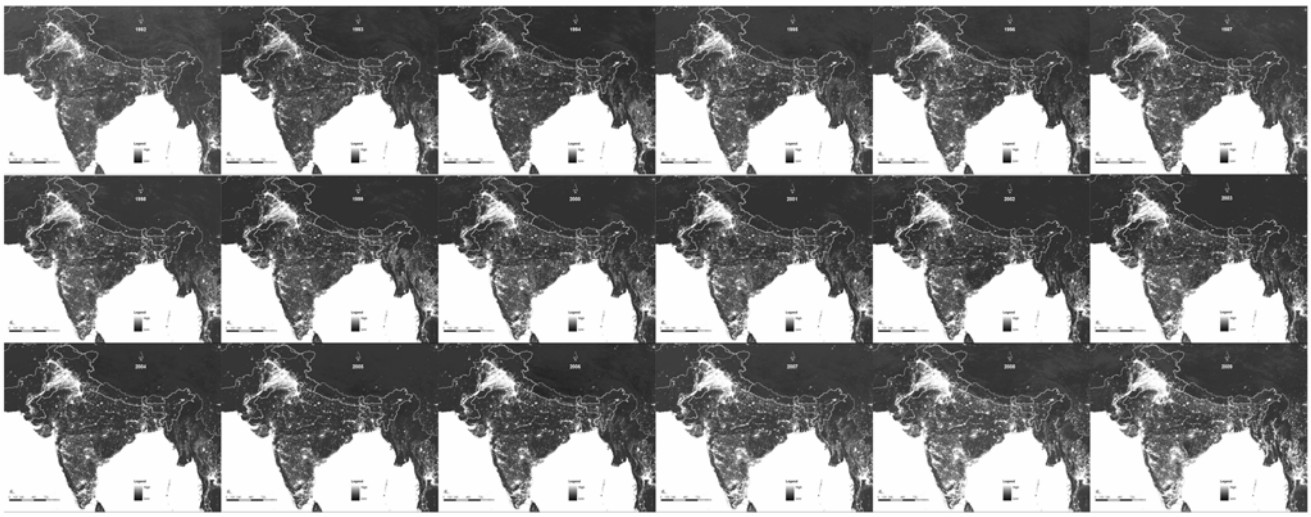

Figure 2. Temporal DMSP–OLS night-time satellite data showing urbanization patterns over India (1992–2009).

along with other developing cities are flooded with immigrant populations from different parts of the country every year, resulting in rapid urban agglomeration[8,15].

DMSP operates in sun-synchronous orbits with night-time overpasses covering the Indian region from 7 to 10 pm local time. The Indian region is observed in two or three OLS orbital passes on a swath width of 3000 km. The OLS is an oscillating scan radiometer with two spectral bands, visible (0.5–0.9 μm) and thermal (10.5–12.5 μm), and has a unique capability of picking up faint sources of visible–near infrared emissions (lights) at night on the Earth's surface, including cities, towns and villages, with a DN value ranging from 1 to 63. DMSP–OLS is basically designed for global observation of cloud cover. At night, the visible band is intensified with a photo-multiplier tube to permit detection of clouds illuminated by moonlight. The light intensification enables observation of faint sources of visible–near infrared emissions present at night on the Earth's surface, including cities, towns, villages, gas flares, heavily lit fishing boats and fires. It provides a contrasting image of urbanization through the detection of city lights as they are seen from space. The stark contrast between lighted and unlighted lands and the large area covered per scene makes it an obvious choice for classifying and mapping land transformation to urban and suburban uses over large areas[15,16].

Methodologies for deriving stable light images from DMSP–OLS along with the sensor characteristics are explained in detail elsewhere[16,17]. 'Stable light image' refers to temporal composite build-up of cloud-free images of the Earth at night over a six-month (October–March) period[16]. Night-time light images for cloud-free dates given by the DMSP–OLS from 1992 to 2009 were segregated into the respective years and were integrated to generate one 'stable light image' per year. In this, city lights were identified because they are temporally stable, represented as small areas of saturated DN values decreasing towards the periphery. So for mapping the large city footprints, its spatial dimension and developments over the years, the data provided enough information for assessing changes. Comparative analysis on the increase in the number of DMSP–OLS light pixels and the number of saturated light pixels with respect to the previous one was carried out. DN values along linear transects passing from the periphery through the centre of major Indian cities were plotted in order to study the periphery development (extension and spread of the city). In India, the urban population apart from industrial, agricultural and domestic sectors, consumes most of the commercial energy. The rest of the population in the rural areas still depends on non-commercial sources of energy such as wood, cow dung and agriculture by-products to meet major energy needs[15].

Datasets of 1992–94 did not show many changes in the urbanization pattern (Figure 2). However, the dataset of 1995 indicated a rapid change in the north-western plains of India with acute increase in light intensity. Variations were also observed in southern India, indicating changes around Mumbai and Bangalore. The light intensity increased in 1996 and the rate of expansion accelerated in 1997, with incremental variation in northwestern India. The expansion around Delhi was also remarkable, with indication of increase in Surat, Hyderabad, Bangalore, Kolkata and Mumbai. Year 2007 and onwards such expansions have been relatively fast; showing increase in energy usage pattern and urbanized work represented by the bright pixels of night-time data.

The mega cities, like Delhi, Kolkata and Mumbai clearly stand out from the other urban agglomerations in India. With 15.1, 14.3 and 18.2 million inhabitants respectively, in 2005 and high average annual population growth rates of 3.1%, 4.1% and 2.0% respectively, between 1975 and 2000 (ref. 2), the mega cities represent a unique cluster of urban agglomeration. Mumbai is expected to have population of more than 25 million, whereas Kolkata and Delhi will have more than 16 million by 2015 (ref. 2). These cities show a unique pattern of high built-up density at the core with decrease towards the buffer. Kolkata and Mumbai showed an elongated and disaggregated growth unlike Delhi, which had grown radially over the periods (Figure 3 (i)–(iii)). In the recent past, Kolkata and Mumbai have also shown radial growth as a result of amalgamation of developed urban centres in the peripheries. The degree and extent of brightness indicated that energy consumption in Delhi has

Figure 3. Temporal DMSP–OLS night-time satellite data showing urbanization patterns in different cities of India (1992–2009): (i)–(iii), Mega cities; (iv)–(vii), Incipient mega-cities and (viii)–(xi), Urban agglomeration.

increased between 2000 and 2005, whereas Mumbai and Kolkata showed such distinct variations in 2003 and 2007 respectively.

Hyderabad, Chennai, Ahmedabad and Bangalore stand out as incipient mega cities with population ranging between 5 and 7 million. Among these, Hyderabad is expected to have more than 10 million inhabitants by 2015, whereas the other three will have nearing 8 million. The sprawl in this set of cities is complex and unstructured, with redensification of urban areas (Figure 3 (iv)–(vii)). The pattern of growth of these cities is close to Delhi and Mumbai, which have grown rapidly over the last few decades. All these cities showed a distinct sprawl in 2000 and 2007.

The urban agglomeration with 2.5–5 million inhabitants, such as Jaipur, Kanpur, Luknow, Poona and Surat are the third set of cities having extensive urban sprawl. Poona shows a distinct characteristic in terms of increase in population, which may go beyond 5 million by 2015. Lucknow, Surat and Jainpur have also shown steep growth in urban population, unlike Kanpur. The urban sprawl timeline is distinct for these cities, as Jaipur, Kanpur and Lucknow showed a steep change in 2007, whereas Poona emerged in 1996 and Surat in 2000 (Figure 3 (viii)–(xii)). These cities have mono-centric and dense settlements with complex expansion over time and at the periphery. But in recent periods, these have shifted from mono-centric to poly-centric, with complex spatial growth pattern, low density spatial urbanization and satellite cities.

The study has demonstrated urbanization patterns over India, with a comparison across 12 mega cities. The chosen DMSP–OLS night-time satellite data are not exhaustive, but provide a specific feature of the urban system for all mega cities, incipient mega cities and urban agglomerations. The temporal dataset adequately provides the details and pattern of urbanization over the period. It is also suitable to differentiate between the urbanized and non-urbanized areas. Such measurement of both areal coverage and spatial distribution is necessary to describe the urban morphology adequately.

The fastest growing urban areas in India are medium-sized cities[18]. These face similar problems as those of mega cities; they have significantly fewer resources to devote to the complex infrastructural, social and environmental issues associated with rapid urbanization. Urban growth is characterized as complex and diversified at various spatial scales[19]. It is linked to topography, land use, lifestyle, social structure and economic type, but is closely related to demography and economic changes in any city[20]. Temporal monitoring of the urban areas of India indicates stark changes in the footprints and developments over time. The incipient mega cities show similar trend of expansion and increase as that of mega cities. The urban agglomeration also indicates similar pattern of urban sprawl, with more scattered development and relatively low density urbanization in comparison to the mega cities and incipient mega cities[12]. Overall, the urban sprawl is clearly reflected in the population growth pattern and economic changes in these locations. However, it falls under two unique categories: (i) cities having compact structure and amalgamation with surrounding areas, and (ii) cities showing increasing complexity with irregular and interspersed development. These findings are important to develop models to predict the future of morphology of urban agglomerations.

In India, several studies have addressed urbanization and urban growth in relation to transportation linking energy[21], land use[22], vehicular emissions[23], etc. However, not many studies have addressed the problem of urban sprawl[24,25]. Mapping and monitoring of these changes is scale-dependent. But such monitoring tools at the national level are important to provide a level of stratification of the area for detailed analysis of urban footprints and identification of linkage with other ancillary and legacy datasets. The high-resolution data like Cartosat, World View, Ikonos or Quick Bird series should be used for detailed mapping and working out the road map of urban development. Incidentally, the urban nation is overloaded and under-planned. Some of the important dimensions of planning require identification and development of small towns as magnets for rural rates, rather than allowing metropolies to grow into mega cities. To achieve this, public transport needs to be strengthened to augment the linkage among the satellite cities. For the sustainable act of recycling buildings and old structures, both economic investments and better livelihoods are needed. At the same time, civic sense and green manifesto are also important.

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ACKNOWLEDGEMENTS. P.K.J. and R.S. thank the Department of Science and Technology, New Delhi for funds.

Received 2 December 2010; revised accepted 22 March 2011

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