# Spatiotemporal analysis of Indian mega cities

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**ABSTRACT:**

Urbanization is arguably the most dramatic form of highly irreversible land transformation. While urbanization is a worldwide phenomenon, it is exceptionally dynamic in India, where unprecedented urban growth rates have occurred over the last 30 years. In this uncontrolled explosive situation city planning lacks of data and information to measure, monitor, understand urban sprawl processes. The analysis of such changes has become an important use of multitemporal remote sensing data. Using a time-series of Landsat data to classify the urban footprints since the 1970s enables detection of temporal and spatial urban sprawl, redensification and urban development in the explosively growing large urban agglomerations of the mega cities Mumbai, Delhi and Kolkata in India. Combining gradient analysis with landscape metrics the spatiotemporal pattern of urbanization are quantified. Spatial parameters are the absolute areal growth, urbanization rates, built-up densities, landscape shape index, edge density, patch density, or largest patch index. The study aims to detect analogies and differences for spatial growth in Indian mega cities, cities in the same cultural area at about the same development stage regarding absolute population. The results paint a characteristic picture of spatial pattern gradients and landscape metrics of the three Indian mega cities.

## 1. INTRODUCTION

Over the last 50 years, the world has faced dramatic growth of its urban population. The number of so-called mega cities increased in the period from 1975 until today from 4 to 22, mostly in less developed regions (Münchner Rück, 2005). Especially Indian mega cities are among the most dynamic regions on the planet. During the last 50 years the population of India (today 1.2 billion) has grown two and a half times, but the urban population has grown nearly five times. The number of Indian mega cities will double from the current three (Mumbai, Delhi and Kolkata) to six by the year 2021 (new additions will be Bangalore, Chennai and Hyderabad), when India will have the largest concentration of mega cities in the world (Chakrabati, 2001).

Intra-city migration from smaller to bigger cities is continuing along with the migration from rural to urban areas besides an enormous natural population pressure. This explosive urbanization resulting in unplanned and uncontrolled growth of large cities has had dramatic negative effects on urban dweller and their environment. Cities are facing serious shortage of power, water, sewerage, developed land, housing, transportation, and communication mixed with dramatic pollution, poor public health or educational standards, unemployment and poverty. Thus, understanding and monitoring past and current urbanization processes is the basis for future predictions and preparedness, and thus for sustainable urban planning. This study focuses on the spatiotemporal urban growth of the current Indian mega cities, Mumbai, Delhi and Kolkata, assumingly the urban agglomerations at the furthest urban development stage as basis to analyse trends to be due in incipient mega cities in India.

For many decades, in some cases centuries, cities have been spreading (Anas et al., 1998). Research in the description, mapping, characterization, measuring, understanding and explanation of form, morphology, and evolution of urban environments has a long tradition in geographic research and planning. The classic theories of urban morphology define urban pattern as concentric rings with different land use types (Burges, 1925), as sectors, where the transportation network modifies the form of the concentric zone pattern (Hoyt, 1939), and the multiple nuclei theory having a patchy urban form with multiple centers of specialized land use (Harris and Ullman, 1945). Since the 1960s various theories were used to characterize urban form: for example fractals (Batty and Longley 1989), cellular automata (Tobler, 1979), dissipative structure theory (Allen & Sanglier, 1979), or landscape metrics (O'Neill et al, 1988).

In general, the application, performance and outputs analysing and comparing the development of urban form of various cities depend strongly on the data available for parameterization (Longley and Mesev, 2000). Remote sensing techniques have already shown their value in mapping urban areas at various scales, and as data sources for the analysis of urban land cover change (Donnay et al, 2001; Batty and Howes 2001; Herold et al, 2002). Recent research has used remotely sensed images to quantitatively describe the spatial structure of urban environments and characterize patterns of urban morphology. Critical in the description, analysis, and modelling of urban form and its changes are spatial metrics (Herold et al., 2003). These indices can be used to objectively quantify the structure and pattern of an urban environment. Most of the studies on urban landscape metrics focus on a single city (Luck and Wu, 2002; Herold et al., 2002, Herold et al., 2003; Zhang et al, 2004). However, there are few studies like these in developing countries which compare cities at about the same development stage in the same cultural area (Seto et al., 2005).

In this study a spatiotemporal analysis using a time series of Landsat data aims at the detection of the urban footprints and the changes in the three current Indian mega cities, Mumbai, Delhi and Kolkata, since the 1970s. The land-cover classification is based on an object-oriented hierarchical classification approach (Taubenböck, 2008). Using parameters like urban growth rates, built-up densities, the spatial form, direction of growth, or landscape metrics like e. g. the shape index or patch density enable the identification of similarities or dissimilarities in urban characteristics of the Indian mega cities. We aimed to address several specific questions on their spatiotemporal development:

- What are spatial and temporal patterns of urban change?
- Is there analogy of patterns in shape, size, growth, gradients and metrics in Indian mega cities, thus in cities at about the same development stage in the same cultural area?
- Does the spatial configuration of Indian mega cities converge toward a standard form?

The idea behind this approach is to learn from the characteristics from current mega cities, to understand the emerging growth pattern to support planning processes and formulate policies to guide or redirect spatial growth in incipient Indian mega cities, like Hyderabad, Chennai or Bangalore.

## 2. STUDY AREAS AND DATA

Our study areas are the three current mega cities in India, Mumbai (Bombay), Delhi and Kolkata (Calcutta), who are spatially distributed on the large subcontinent. Mumbai is located at the west coast on seven now-merged islands in the state Maharshtra. Delhi, located in northern India on the flood plains of river Yamuna, has the status as the National Capital Territory. Kolkata, the capital of the Indian state West Bengal, is located in eastern India in the Ganghes Delta in a flat surrounding at the Hooghly River (Figure 1).


**Figure 1:** Geographic location of Indian mega cites

Referring to the United Nations (UN, 2005), in the year 2005 approximately 18,2 million people were living in Mumbai, 15 million people were living in Delhi and 14,3 million people were living in India's third mega city Kolkata. The dramatic pace of urbanization shows Mumbai (3.1%) and Delhi (4.1%) among the highest population growth rates of mega cities worldwide, while in contrast Kolkatas' pace slows down to 1,7 % (UN, 2005). Figure 2 shows the dramatic population development of Mumbai, Delhi and Kolkata since 1970 and a prognosis until 2015. The mega cities more or less quadrupled their population, and are expected to grow even faster intensifying the urban crisis of the largest Indian urban agglomerations.

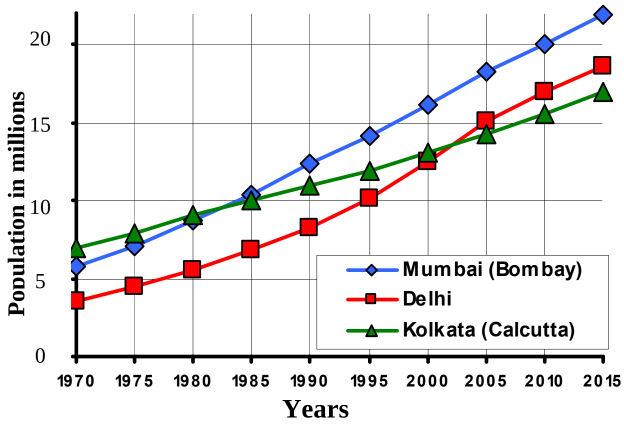



**Figure 2:** Population growth in Indian mega cities since the 1970s

For a spatiotemporal analysis of the large urban areas of the Indian mega cities remote sensing data proved to be an independent and cost-effective data basis. The choice of data predominantly depends on technical aspects. These are represented by the following determinants:

- Extent of the test sites
- Number of aimed land cover classes and their spatial differentiation potential
- Length of study period
- Requirements for accuracy of thematic classification (Radberger, 2001).

The Landsat program represents a series of earth observation satellites that have been continuously available since 1972. Therefore this system allows for an analysis of extended time series. It started with the Multi-Spectral-Scanner (MSS) featuring a geometric resolution of 79 meters and a spectral resolution of four spectral bands (green, red, two near infrared bands). Since 1982 the Thematic Mapper (TM) has operated with 30 meter geometric resolution and seven spectral bands. Since 1999 the Enhanced Thematic Mapper (ETM) has operated with an additional panchromatic band and 15 meter geometric resolution. Having continuous, constant spectral bandwidths guarantees the comparability of the different sensors. With its field of view of 185 km the satellite is able to survey the large metropolitan areas of the study sites. Measurement of areal coverage and spatial distribution are both needed to describe the morphology of an urban area adequately (Schweitzer et al. 1998). The chosen level of description with Landsat features is not flooded with microscopic detail, but incorporates specific features of the urban system. In return, the requirements for the differentiation of classes are limited to the classification of built-up and non-built-up areas. Also the accuracy of classifications is limited due to coarse geometric resolution and therefore many "mixed-pixels" containing information on various thematic classes. This limited differentiation and accuracy potential nevertheless enables monitoring and detection of the correct dimension of spatial and temporal changes, of urban sprawl and of the spatial direction of urban development. For the analysis Landsat data for Mumbai were available for the years 1973, 1991 and 2001, for Kolkata for the years 1977, 1990 and 2000, and for Delhi for the years 1977 and 1999. Figure 4 shows as one example false colour Landsat imagery from the coastal region of the large urbanized areas of mega city Mumbai in 2001.

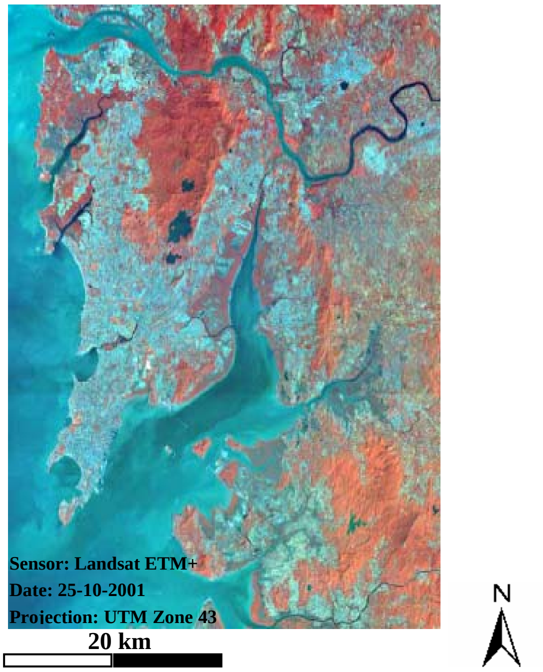



**Figure 3:** False-Colour (Bands 1,2,4) Landsat imagery from the metropolitan area of Mumbai

## 3. CHANGE DETECTION USING REMOTE SENSING DATA AND METHODS

A land cover classification extracting the classes built-up areas, bare soil, vegetation, and water was performed separately on all images. The main goal is to identify the urban built-up areas to measure the changes of the urban extension over the time interval. For that purpose the classification methodology is based on an object-oriented hierarchical approach (Taubenböck et al., 2007; Taubenböck 2008; Berger, 2007). The object-oriented methodology was used to combine spectral features with shape, neighbourhood and texture features.

Due to a large amount of mixed spectral information in such a coarse ground resolution the accuracy is limited. But for the requirement of mapping the city footprint, its spatial dimension and the spatial developments over the years, the Landsat images provide enough information for an assessment of urban change. An accuracy assessment has been performed by a randomization of 150 checkpoints and a visual verification process. Table 1 shows the accuracy assessment for the various scenes.

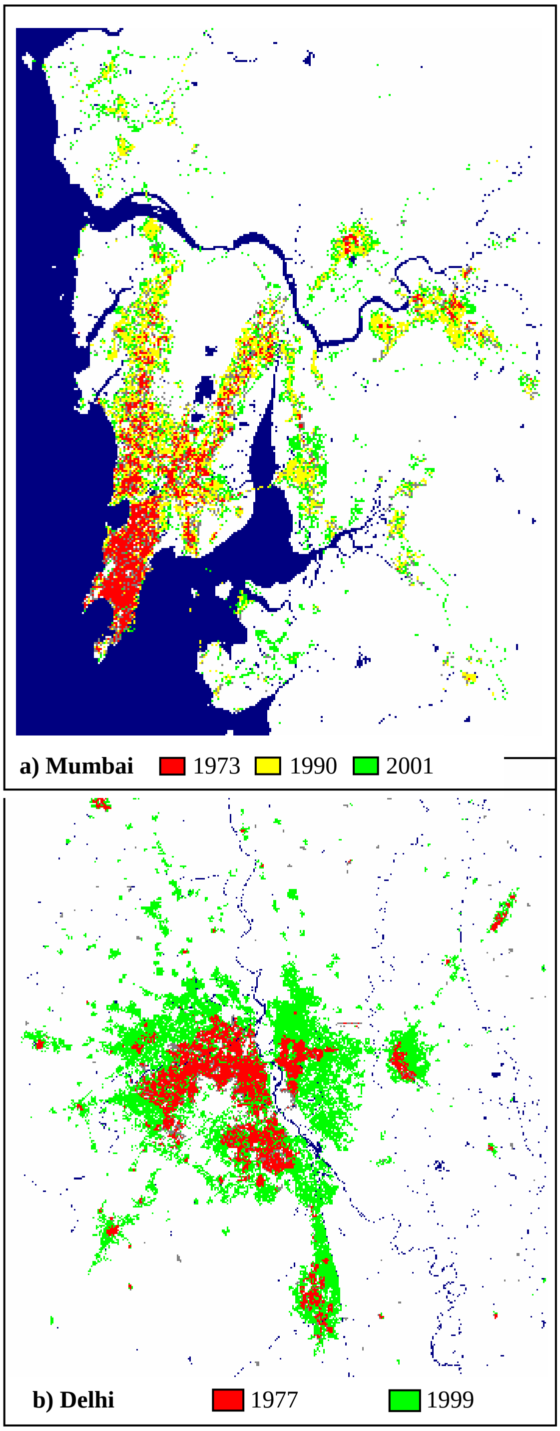
| | Landsat MSS | Landsat TM | Landsat ETM |
|---|---|---|---|
| **Mumbai** | 87,0 % | 90,4 % | 90,8 % |
| **Delhi** | 89,4 % | - | 91,8 % |
| **Kolkata** | 90,6 % | 90,8 % | 91,6 % |

**Table 1.** Accuracy assessment of the classification of Landsat data

Post classification comparison was found to be the most accurate procedure and presented the advantage of indicating the nature of the changes (Mas, 1999). A comparative analysis of land cover classifications for the available times performed independently was therefore implemented to monitor and analyse the land cover changes in the metropolitan areas of Mumbai, Delhi and Kolkata. Pixelwise change detection was implemented checking the land cover classes individually of the available years. Figure 4 shows the result of the change detection for all three Indian mega cities, displaying the urban footprints and their spatiotemporal evolution since the 1970s.

The result of the change detection shows three very different urban footprints of the Indian mega cities. While the urban footprint of Mumbai is determined by the coastal and hilly orography, the urban footprints of Delhi and Kolkata are not subject to orographic restrictions.

The peninsula of Mumbai forces the urbanized areas on available land, with an axial growth in the outskirts caused by transportation networks and hilly barriers. The polycentric structure and development of satellite cities in the 1970s steadily increased due to land shortage in the urban center and dramatic population pressure. The result is a complex urban footprint,



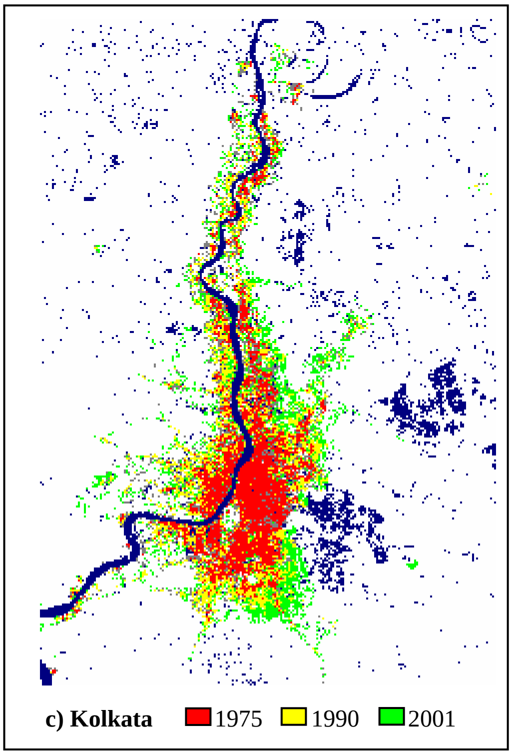



**Figure 4.** Change detection of urbanized areas in Mumbai, Delhi and Kolkata since the 1970s

spatially polycentric with axial growth lines, a large urban core and a dispersed urban-rural fringe. The urban footprint of Delhi, only slightly influenced by orography, results in a classic concentric urban ring-shaped growth with axial growth sectors caused by transportation networks. The polycentric structure of the 1970s shows coalescence between the satellite cities and the urban core today. Growth is predominantly laminar and clustered, with dispersion solely in the peripheral catchment area of Delhi. Kolkata shows an oval urban footprint along the Hooghly River not influenced by orographic barriers. The monocentric spatial structure shows oval-shaped and laminar growth with little dispersion.

## 4. SPATIOTEMPORAL ANALYSIS OF THE URBAN PATTERNS OF INDIAN MEGACITIES

Urban structure is very much scale-dependent. This study uses Landsat data for large-area analysis to survey urban growth and its spatiotemporal form based on built-up and non built-up areas. For a highly detailed structural analysis of the heterogeneous inner structures of urban morphology satellite data with higher geometric resolution (f. e. Ikonos or Quickbird), but for it with small swath widths limiting area-wide analysis of mega cities, are needed.

Urbanization may be linked with details related to topography, transportation, land use, social structure and economic type, but is generally related to demography and economy in a city (Li et al., 2002). In the following, urbanization is analysed by spatial urban form and its changes over time. We chose parameters like areal growth, urbanization rates, or built-up densities for a spatiotemporal gradient analysis of urbanized areas. In addition we chose landscape metrics (or spatial metrics) like the SHAPE index, patch density and largest patch index as quantitative indices to describe structures and pattern of the mega city landscapes. In general, spatial metrics can be defined as quantitative and aggregate measurements derived from digital analysis of thematic-categorical maps showing spatial heterogeneity at a specific scale and resolution (McGarigal et al., 2002; Herold, et al, 2003). The main idea is to learn mechanism of the complex process of spatial urban growth by finding analogy and differences between cities past development.

### 4.1 Areal growth and urbanization rates

The physical process of urban land-cover change is most commonly described as either a change in absolute area of urban space (a measure of extent) or the pace at which non-urban land is converted to urban uses (a measure of rate) (Seto et al. 2005).

The absolute growth of urbanized areas shows Mumbai and Kolkata at about the same gain over time. Significantly differing is Delhi which was at about the same level than Mumbai and Kolkata in the 1970s. The capital city of India shows explosive spatial growth with today almost a double-sized urbanized area in comparison with the two other mega cities. Figure 5 displays the growth gradient, resulting in just fewer than 400 km² urbanized areas in Mumbai and Kolkata and approximately 750 km² urbanized areas in Delhi. The latter more or less tripled their urbanized areas since the beginning of the 1970s, in the same period of time Delhis urbanized areas grew 4-5 times its size.

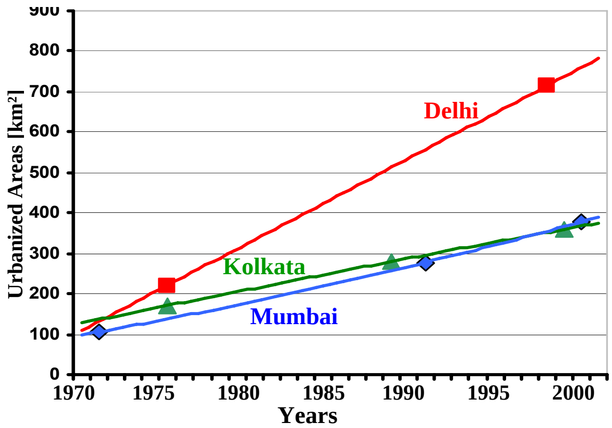



**Figure 5:** Areal growth of urbanized areas of the Indian mega cities, Mumbai, Delhi and Kolkata

Figure 6 shows as one example the urbanization rates and their spatial distribution in Mumbai. In the time period of 1973 until 1991 redensification processes are detected at the city center, while immense urban sprawl with rates up to 100 % is detected on the axial transport lines as well as in the subcenters around the urban core. From 1991 until 2001 redensification processes almost stop in the urban center, while urban sprawl at the subcenters and satellite cities as well as along the axial transportation lines takes place. Thus, an increasing urbanization gradient is detected with distance to the urban core showing a relocation of the main urban growth to the edges of the city. A very similar trend is detected in both other mega cities, but due to no orographic barriers a monocentric ring-shaped growth evolved.

Using artificial concentric rings, urbanization rates with respect to their location are calculated for various spatial zones. The zoning aims at a standardized analysis of spatial gradients for

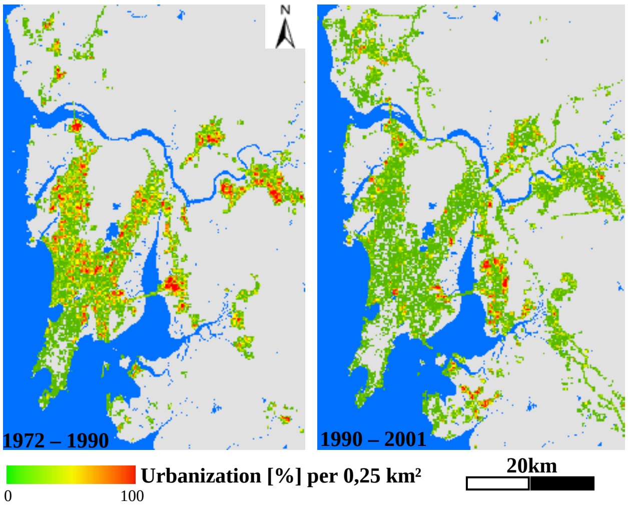



**Figure 6:** Spatial distribution of urbanization rates [%] in Mumbai

the various urban patterns of the study sites. The center is calculated using a 5 km circle (zone 1), while zone 2 entails a ring in 5 – 10 km distance, zone 3 in 10-20 km distance, zone 4 in 20-30 km distance, zone 5 in 30-40 km distance and eventually zone 6 in 40-50 km distance to the particular city center. Figure 7 shows the spatial gradients of urbanization rates for all three mega cities.

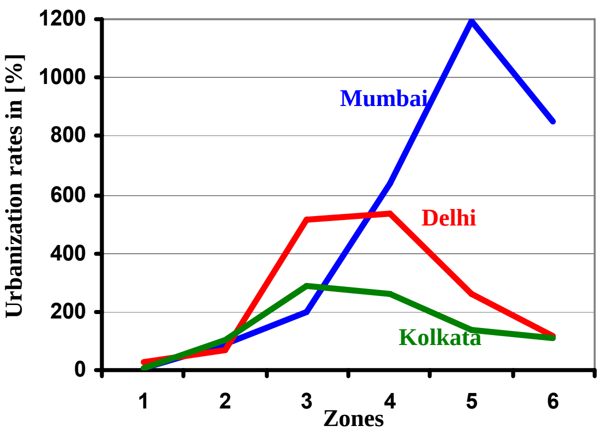



**Figure 7.** Spatiotemporal urbanization rates [%] since the 1970s

The gradients of the urbanization curves are basically similar for all three mega cities, with relatively low urbanization rates in the center (zone 1 & 2), and an immense increase to the urban fringe, and eventually a decrease to the peripheral areas. While in Delhi and Kolkata urbanization takes place mainly in zone 3 and 4, a result from their classic ring-shaped growth, the most dramatic urbanization in Mumbai is relocated to zone 5, due to shortage of space at the peninsula. With no orographic barriers Delhi and Kolkata enable concentric sprawl reflected in the climax of the urbanization curves at the current urban fringe in zone 4. In dependency of built-up densities at those zones, urbanization rates will stay high or will be relocated to open spaces and rural areas of the more peripheral zones. In Mumbai urbanization in zones 1-4 is much lower due to shortage of space, but results in explosive rates in the more peripheral zones 5 and 6, where the geographic location does not limit urbanization processes.

### 4.2 Built-up densities

Built-up density is a measure to characterize spatial urban pattern and structure. Densities vary substantially from city to city and from the urban center to periphery areas. Using the same artificial concentric rings, built-up density is calculated for the zones 1-4. Without consideration of the water body, the ratio between the areas in the circles to the areas classified as built-up from the Landsat data results in the built-up density of the particular zone. Figure 8 shows the temporal and spatial distribution and development of built-up densities of the three Indian mega cities.

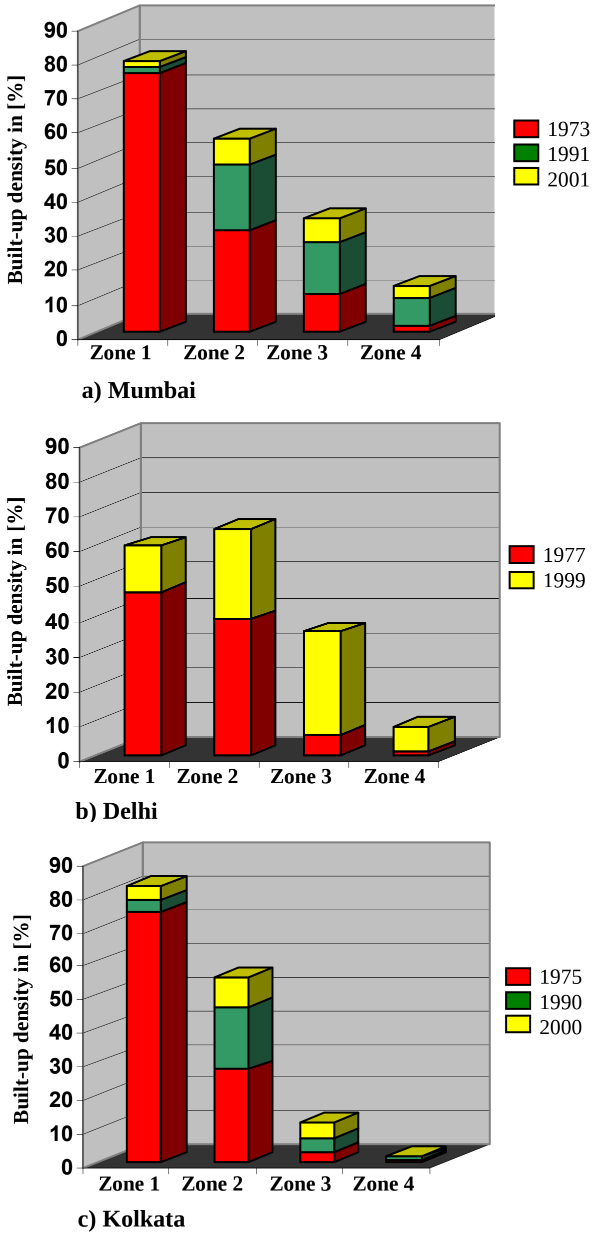



**Figure 8:** Cumulative spatiotemporal analysis of built-up densities

Mumbai and Kolkata show the highest built-up densities in zone 1 (center) with little redensification since the 1970s. Coming from already high built-up densities with low land availability or open spaces a saturation effect at 80 % becomes apparent. With decreasing growth rates zone 2 shows very similar effects in both mega cities at around 55 %. Zone 3 and zone 4 show clearly a decreasing built-up density gradient converging to the urban-rural fringe. Indeed, the complex urban footprints still show locally high built-up densities in this distance, like for example to the north of oval-shaped Kolkata.

The situation in Delhi is slightly different with the highest built-up density in zone 2 of about 63 %. The difference in zone 1 is caused by the double structure of Old Delhi and New Delhi spatially next to each other. New Delhi, a planed and structured center, decreases the built-up density of the typical Indian structure of Old Delhi which reaches around 90 % built-up density in zone 1. The built-up density of zone 2-4 is higher than in the two other study sites due to classic concentric urban growth, but the urban-rural gradient decreases equivalent to Mumbai and Kolkata.

With this exception of central Delhi, all three Indian mega cities clearly show a decreasing and similar built-up density gradient with distance to the main urban center, although their urban footprints differ significantly.

### 4.3 Landscape shape index (LSI)

In the following, the landscape metrics are calculated on the complete urbanized areas, not specifying spatial urban zones. The Landscape Shape Index (LSI) provides a standardized measure of the perimeter length of all patches of one land cover type (here: urbanized areas) in the landscape (McGarigal et al., 2002; Schneider et al. 2005). If the urbanized area is composed by simple geometric rectangles, the LSI will be small, approaching 1.0. If the landscape contains dispersed patches with complex and convoluted shapes the LSI will be large. Table 2 shows the spatiotemporal results of the LSI calculation of the whole study sites.

| LSI | ≈1975 | ≈1990 | ≈2000 |
|---|---|---|---|
| **Mumbai** | 7,07 | 16,51 | 22,00 |
| **Delhi** | 7,61 | - | 22,62 |
| **Kolkata** | 7,70 | 14,30 | 21,12 |

**Table 2.** Spatiotemporal results of the LSI

The urban footprints of all three Indian mega cities differ significantly, but the temporal evolution of the LSI is very parallel. The rapid urban sprawl apparently involves a dramatic increase in urban complexity. Even the polycentric urban growth of Mumbai does not reflect divergent effects in comparison with monocentric spatial forms of growth in Delhi and Kolkata.

### 4.4 Patch density (PD)

The patch density (PD) which is the number of urban patches is a measure of discrete urban areas in the landscape and is expected to increase during periods of rapid urban nuclei development, but may decrease if urban areas expand and merge into continuous urban fabric (McGarigal et al., 2002; Seto et al., 2005).

| Patch density | ≈1975 | ≈1990 | ≈2000 |
|---|---|---|---|
| **Mumbai** | 9,74 | 19,09 | 15,01 |
| **Delhi** | 3,89 | - | 4,12 |
| **Kolkata** | 10,78 | 27,25 | 44,99 |

**Table 3.** Spatiotemporal results of the PD

The three mega cities show significant differences in their patch density. While Mumbai and Kolkata had a similar PD in the 1970s, their PD development differs from there. Kolkatas' growth type shows a highly dispersed urban fabric, while Mumbais' PD increased slower with even a decreasing trend after a climax around 1990. These differing trends emphasize coalescence and redensification even in the outskirts of the urban core as well as in the satellite cities for Mumbai, while in Kolkata the ring-shaped growth takes place with punctual, dispersed patches. In contrast to Mumbai and Kolkata, the PD of Delhi stays constantly at a low level highlighting a laminar coalescence and a laminar urban footprint.

### 4.5 Largest Patch Index (LPI)

The Largest patch index (LPI) gives the proportion of total area occupied by the largest patch (Luck et al, 2002). It is a measure that represents the separation of the urban landscape into smaller individual patches versus a dominant urban core. Table 4 shows the temporal characteristics of the LPI in Mumbai, Delhi and Kolkata.

| LPI | ≈1975 | ≈1990 | ≈2000 |
|---|---|---|---|
| **Mumbai** | 0,49 | 1,77 | 3,22 |
| **Delhi** | 1,28 | - | 5,95 |
| **Kolkata** | 1,11 | 1,99 | 3,92 |

**Table 4.** Spatiotemporal results of the LPI

The increase in all three Indian mega cities represents the spatial growth of the urban core and the increasing coalescence of individual urban patches to the central urban area. Delhis' laminar growth type shows a significantly high increase, while Mumbai and Kolkata once more show a parallel evolution of the landscape metric. All three mega cities show an increasing LPI gradient, highlighting redensification and coalescence of as analogue urbanization process at all urban cores.

## 5. RESULTS AND CONCLUSIONS

The study has demonstrated that urbanization and its spatiotemporal form, pattern and structure can be quantified and compared across cities using a combination of gradient analysis and spatial metrics. Landsat data proved to be an independent, area-wide, and with respect to the limited geometric resolution, an adequate data source for the analysis of fast changing and large areas of Indian mega cities. The results address the three questions we defined earlier in the introduction. 1) What are spatial and temporal patterns of urban change? 2) Is there analogy of patterns in shape, size, growth, gradients and metrics in Indian megacities, thus in cities at about the same development stage in the same cultural area? 3) Does the spatial configuration of Indian mega cities converge toward a standard form?

The study shows that spatiotemporal patterns of current Indian mega cities growth are reflected in decreasing redensification processes and a saturation effect for built-up densities around 80 % in the centers. It becomes apparent that the decreasing built-up density gradient from center to urban fringes comes along with increasing urbanization rates or relocation of urbanization to satellite cities. Independent from the cities footprint, explosive urban growth increases the spatial complexity.

Urban growth in India may take various spatial forms, however, many parameters in Mumbai, Delhi and Kolkata showed similar results. Especially Mumbai and Kolkata emerged as a very similar growth type, with similar areal growth, corresponding in the spatiotemporal urbanization and built-up density gradients, identical spatial complexity as well as the ratio of the urban core to dispersed patches. Both cities only differ in the patch density, showing highly dispersed growth in Kolkata compared to Mumbai. Delhi differs through an enormous areal growth, a coalesced urban center, with laminar growth resulting in a dominant urban core. Still, built-up density gradients and urbanization gradients correspond to Mumbai and Kolkata, as well as the increasing complexity.

Due to different urban orographic conditions in combination with socio-economic and political impacts Indian mega cities due not converge toward a standard form. Contrasts include poly- versus monocentric spatial growth, absolute areal growth, and the patch density. But nevertheless aspects of spatial urban growth proceeded very similar.

The time series of gradient analysis and landscape metrics is important for describing, understanding and monitoring the spatial configuration of urban growth. A comparative analysis is crucial for urban growth trajectories across cities. Measuring the development stages of the three Indian mega cities, conclusions on incipient mega cities in the same cultural area like Hyderabad, Bangalore or Chennai may support planning, future modelling, and thus decision-making for sustainable and energy-efficient urban futures.

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