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Assessment of urban growth dynamics in Mumbai Metropolitan Region, India using object-based image analysis for medium-resolution data

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1. Introduction

Cities are emerging as the economic drivers, both in developed and developing nations. The share of global population of over 7 billion residing in cities crossed the 50% mark in 2014 and it is expected that this would touch 60% by the year 2025. Most of this imminent growth is likely to take place in the developing countries in Asia (particularly China and India) and Africa (United Nations, 2014).

Physically, cities or urban areas are characterised by a dense outlay of Built-Up Area (BUA) comprising man-made structures and physical infrastructure networks that are characterised by permanent expansion and growth. The urban morphology is a derivative of the existing topography and affects the demand for travel and energy (Seto, Fragkias, Güneralp, & Reilly, 2011). Coastal cities, in particular, have greater role to play in the regional economics because of their locational advantage as a port and centre of trade. On the other hand, they have limited growth directions and are further constrained due to typical ecological challenges, when interspersed with hills and wetlands. The conservation of the biological diversity in such eco-sensitive zones is challenged by the urban growth of these cities.

Urban growth is characterised by expansion of physical limits while urbanisation results from change in lifestyle (Bhatta, Saraswati, & Bandyopadhyay, 2010). Urban growth 'consumes' the surrounding land along with its air, water and food resources in a non-renewable manner (Moeller et al., 2004). Land is a central resource for all forms of life and anthropogenic activities thereupon are causing the most irreversible changes with respect to land cover, hydrological systems, biogeochemistry, climate and biodiversity (Seto et al., 2011).

Considering that land and energy are finite resources, increasingly consumed by cities, the need to develop compact cities cannot be overlooked. This can largely be achieved through efficient public transport systems and Transit-Oriented Development (TOD). Transit-oriented development "reduces reliance on cars," improves transit service and promotes development "without adding to sprawl" (Curtis, Renne, & Bertolini, 2009).

The role of urban planning is to identify new resources to facilitate growth, addressing changing land use and expectations of the future with reasonably correct foresight and to augment the existing service capacities (Yang, 2011). However, with increasing focus on sustainable development, urban planning plays a significant role towards resource conservation and ecological impact evaluation so as to facilitate and promote land cover changes that circumvent the climatic extremes that have come to be associated with cities worldwide.

The total BUA is regulated through the Floor Space Index (FSI), the ratio of total Built-Up Area (BUA) on all floors to the plot area, which determines the intensity of land use in a city or the permissible vertical development with regard to a given building footprint. It is majorly used by government and urban planners to monitor the extent of BUA and thereby population that may be sustained with respect to acceptable infrastructure service levels.

Urban planners with knowledge of the existing growth pattern can unarguably secure a better future through an efficient city plan that facilitates better administration in the future (Bhatta et al., 2010). Enhanced computational abilities and access to remote sensing data through availability of the 2.6 million image USGS Landsat archive in late 2008 have expanded the domain of smart urbanisation beyond

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urban planners to all citizens (Woodcock et al., 2008).

The archived optical remote sensing data pertaining to geospatial changes since the 1970s forms a key resource for urban planning with regard to sustainability (Moeller et al., 2004). An overview of the spatiotemporal land cover changes through medium resolution images of the last four decades provide critical decision support for resource management to promote sustainable urban growth. Numerous studies based on remote sensing data have been carried out to study various aspects of urban growth (Angel, Parent, Civco, Blei, & Potere, 2010; Arsanjani, Kainz, & Mousivand, 2011; Bagan & Yamagata, 2012; Ramachandra, Aithal, & Sanna, 2012).

A series of spatiotemporal changes observed as growth trends can then be simulated to facilitate appropriate policy and fiscal initiatives in order to plan urban growth directions (Moghadam & Helbich, 2013). Simulation and modelling for generation of alternate scenarios using the information based on past trends in a GIS framework enables individuals to make faster, and possibly better, decisions concerning their lives.

Ironically, there is no uniform definition of 'cities', while a number of parameters like population thresholds, municipal boundaries, historical centres, livelihood sources of the inhabitants, or their geographical extent are deployed to identify them. As this study uses optical satellite images to study the morphology of urban areas, it is identified through the spread of built up area. The spatial configuration of cities is defined by the location of built-up areas with respect to different land cover.

However, consistent temporal digital image interpretation of urban areas remains a challenge as typical landscapes comprise an intricate mosaic of spectrally complex land cover types, with heterogeneity of land uses and building materials (Mesev, 1998; Thapa & Murayama, 2009; Tuia & Camps-Valls, 2011). While overall accuracy may be high, the user's accuracy for critical land use classes like barren and built-up, displaying mixed pixels, is observed to be relatively lower than other classes having distinct spectral signature (Schneider, Friedl, & Potere, 2009). Owing to differences in temporal and spatial characteristics of remotely sensed data, inconsistent land use classification and false land use class transitions, particularly with regard to built-up areas, therefore need to be addressed in multi-temporal image interpretation (Samal & Gedam, 2015). However, salt and pepper effects generated through pixel based classification of Landsat images having 30 m spatial resolution and inconsistencies in interpretation of multi-temporal images remain a serious drawback.

Object Based Image Analysis (OBIA) techniques have evolved for interpretation of high-resolution images, wherein pixels displaying similar spectral properties form image objects (Navulur, 2006). In urban studies, where focus is on larger expanse rather than details, with the support of ancillary information, object based approach provides a realistic framework for analysis (Aplin & Smith, 2011). OBIA was deployed for interpretation of the archived images of the last four decades from 1972 to 2011, as large amount of mixed spectral information exists at pixel level and land cover comprising an urban area is extremely heterogeneous (Taubenböck et al., 2009). Further, by creating objects at different levels, parent-child relationships can be leveraged to improve feature extraction process on applications such as change detection (Navulur, 2006).

It is envisaged that the OBIA approach in image analysis would enable better decision support in natural resource management for metropolitan regions. This paper attempts to use OBIA to classify the medium-resolution images of the above time period to obtain consistent multi-temporal land use classification results, specifically for the heterogeneous classes. The emerging urban morphology and the urban growth dynamics during this time period form the subject of this study.

The practically infeasible land use class transitions are identified through the change matrix and spatially resolved using a GIS platform in order to support the urban planning process by tracking the fast changing landscape. The spatiotemporal changes detected during the study period are used for a) quantification of urban growth, b) identification of the growth directions of urban in the region to be used for modelling future urban form in the Mumbai Metropolitan Region (MMR) subsequently and c) observation of morphological changes in existing topography and form.

2. Study area

Mumbai, India's financial capital comprises Greater Mumbai and Mumbai Suburban districts for administrative reasons and is located on a wedge shaped, historical conglomeration of islands that is fully urbanised. The Mumbai Metropolitan Region (MMR) further includes parts of Thane and Raigad districts that are in the process of being urbanised. Geographically, the MMR lies between 18°33' - 19°31′ N and 72°45' - 73°28′ E and is spread over an area of 4355 km^2, with a peculiar coastal topography.

The mainland is low-lying and traversed by the confluence of rivers flowing into, and creeks from the Arabian Sea on the west and Thane Creek on the east. A series of north-south trending Sahyadri hill ridges exist in the centre of the island city and the mainland. A mosaicked Landsat image of 2011 and a Digital Elevation Model (DEM) from Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) showing topographical features of the area in the same year, along with extent of the Region is shown along with its regional context, in Fig. 1.

The Thane Creek separates the island city from the mainland comprising low-lying marshy lands, and is lined by north-south trending Western Ghats on either side. Named after the adjoining city/district on its north, it is narrow and shallow at the mouth of the Ulhas river, grows broader and deeper as it extends towards the Mumbai harbour situated about 26 kms southwards; and is defined by saltpans and stretches of mangroves (Birdlife International, 2004). As seen in Fig. 1, the hills are located at a maximum distance of about 3 km on the western coast while the arc of hills beyond Asia's largest Thane Belapur Industrial Area (TBIA) on its eastern coast is about 4 km at its farthest. The Creek has historically served as the natural channel to discharge the storm water for the high rainfall in the catchment defined by its adjoining hills and domestic/industrial effluents from the city.

Owing to the peculiar topography, the city has a distinct linear morphology wherein the habitable area along the Creek lies between the water front and these hills. The alignment of transportation corridors is guided by its topography that conserves the environment and minimizes public expenditure on infrastructure networks. With a population of about 20 million, and a growth of almost 12% in the last decade, it is among the largest megapolis in the world today. Demographically, it is among the most densely populated urban areas in the world. Mumbai has been historically known for its compactness.

3. Data sources

The Area of Interest (AoI)) includes a buffer of 2 km from the MMR boundary in order to observe the intertidal zone at the interface of the water and wetland classes, whereby the study area admeasures 5087 km^2. The major portion of the MMR falls in path 148 and row 47 of the Landsat 4 satellite's orbit (path 158 and row 47 for Landsat 1–3). However, small portions on the north and west fall in the images in adjacent row 46 and path 147 respectively. The years of image data have been chosen in keeping with the availability of demographic data through the national Census. Considering the high precipitation in the study area, post monsoon images between October to February have been chosen in order to obtain cloud free data with uniform vegetation status. Periodic data for the last four decades – Multi Spectral scanner (MSS) images for 1972, Thematic Mapper (TM) data for 1990/1992 and 2011 along with Enhanced Thematic Mapper (ETM +) data for 2002, are downloaded from the United States Geological Survey (USGS) Landsat Archive L1 data products for geometric and radiometric