Ecological Indicators 93 (2018) 952–965

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

A neural network and landscape metrics to propose a flexible urban growth boundary: A case study

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ARTICLE INFO

Keywords:
Urban hard boundary
Urban soft boundary
Artificial neural network
Boundary demarcation
Landscape metrics

ABSTRACT

Urban sprawl is a major barrier for the precise demarcation of administrative boundary in the world. In India, medium and small towns have so far developed outside the envisaged planning, resulting in a leapfrog and haphazard growth. This paper has attempted to simulate the spatial extent of urban expansion and boundary demarcation for the purpose of efficient urban planning and land resource management. An Artificial Neural Network (ANN) model and a set of landscape metrics were used to delineate the Urban Growth Boundary (UGB) and characterize the future patterns of growth in Siliguri Municipal Corporation (SMC, India). In particular, two urban boundaries – namely, Urban Hard Boundary (UHB) and Urban Soft Boundary (USB) – were simulated. The results suggest a USB with the area of 123 km^2 to address the basic service delivery and a UHB with the area of 211.88 km^2 to manage the ecological fragmentation.

1. Introduction

The world's population is unprecedentedly becoming urbanized. According to the United Nations (2014), about 66% of the world's population will have settled in urban areas by 2050. The process of urbanization and urban growth across the world, however, does not follow a uniform pattern. In developing countries, population concentration has steeply increased in the medium-sized cities (with populations less than 1 million; United Nations, 2014). In India, it has been projected that most of the small and medium cities will find regional importance by 2030. As a consequence, these cities will improve their socio-economic conditions and infrastructures, and would serve the broader hinterlands (Shaw, 2013). However, several urban planning and environmental related concerns are associated with this trend (Banerjee-Guha, 2011; Bhatta, 2009a; Huang et al., 2017). To ameliorate these issues, compact urban growth is a solution for sustainable urban management (Ewing, 1997; Ewing and Cervero, 2017) though there is an ongoing debate between compact and sprawl development patterns. Within the theoretical discourses of compact growth, Urban Growth Boundary (UGB) demarcation is regarded as a useful planning tool (Tayyebi et al., 2011a,b). Nevertheless, urban planning in India has not prioritised the concept of Urban Hard Boundary (UGB) and its implementation is limited (Bhatta, 2009b; Goldblatt et al., 2016; Maithani et al., 2010). UGB can facilitate the restricted growth of large metropolitan areas while preserving the natural ecosystems (Jiang et al., 2016). It is also essential for farming, plantation, forestry, residential development, prioritization of development goals (Nelson and Moore, 1993), and differentiation between urban and rural areas (Carlson and Dierwechter, 2007; Pendall, 1999).

Application of UGB along with land regulations is critical to control urban sprawl (Jun, 2004). Although UGB has been widely accepted as an efficient tool in urban growth management since 1950, there is no universally accepted approach for its implementation (Jun, 2004). For example, Urban Constructions Boundary (UCB) is a Chinese equivalent approach to the UGB of the USA with similar implementation mechanism (Cheng and Masser, 2004; Weng, 2002). On the other hand, the strategy of UGB delineation has been extensively scrutinized by planners, decision makers and researchers. Knaap and Hopkins (2001) argue that expansion of the UGB size for an arbitrary number of years does not solve the sprawling problem, which requires careful observation of past urban growth processes (Bhatta, 2009a,b; Jiang et al., 2016). Apart from this, any rigidly simulated UGB is not a feasible solution in urban management; it should be flexible enough to assist planners in delineating the future administrative management program.

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https://doi.org/10.1016/j.ecolind.2018.05.036
Received 26 February 2018; Received in revised form 10 May 2018; Accepted 16 May 2018
1470-160X/

Since the last few decades, remote sensing and Geographic Information System (GIS) techniques have been extensively used to develop urban growth models (e.g., Puertas et al., 2014; Shafizadeh-Moghadam and Helbich, 2013; Tayyebi et al., 2016; Shafizadeh-Moghadam et al., 2017a). Meanwhile, few attempts have been made to demarcate UGB using urban growth models, such as Ideal Urban Radial Proximity (e.g., IURP; Bhatta, 2009a,b), Artificial Neural Network (ANN; e.g., Tayyebi et al., 2011a,b), SLR-UGB (e.g., Tayyebi et al., 2014), rule based cellular automata (e.g., Long et al., 2013), hybrid model (Ma et al., 2017), UBEM (He et al., 2016), and weight of evidence (e.g., Zheng and Lv, 2016;). Most of these computational models, however, have ignored the value of urban morphological direction in UGB delineation. For example, Tannier et al. (2011) used fractal geometry to determine urban morphological boundary of metropolitan areas. Recently, He et al. (2016) used landscape metrics to demarcate the UGB of Wuhan city, China, and concluded that landscape metrics are beneficial to show the landscape dynamics and can be useful in regulating the growth of low density settlement. Jiang et al. (2016) developed a more comprehensive UGB model by combining the SLEUTH model (Slope, Land use, Exclusion, Urban extent, Transportation and Hill shade) with the capacity of natural resources and land regulation policies. This study has broader relevance in ecological protection. However, simulation based models lack in characterizing the shape and pattern of future directions, whereas landscape metrics lack in future simulation.

The information of shape, pattern and configuration of urban patches at local level helps planners to reduce urban sprawl (Taubenböck et al., 2009; Bierwagen, 2005) because it is very difficult and overpriced to provide various services to the scattered areas. Further, in essence of environmental protection and natural resource management, urban sprawl and land fragmentation is a major threat to the planners. Thus, the creation of UGB by incorporating landscape shape and pattern is important to protect natural resources, reduce urban sprawl and landscape fragmentation. In this paper, we used ANNs and landscape metrics to simulate future urban growth, that exhibit the urban morphological patterns to delineate UGB for sustainable urban management. To the best of our knowledge, no published study has considered future expansion as well as size, shape and pattern of urban growth in UGB delineation. To address this lacuna, this study has adopted a comprehensive process to establish model capability on future boundary delineation.

In practice, boundary delineation mostly follows the arbitrary methods in India. Traditionally, a census based urbanization criterion has been adopted to delineate urban boundary. Without considering future demographics and economic structure at local level, any form of boundary is insignificant, given that census criterion is determinant in decision making (e.g. India). Therefore, in the current study, attempts were made to create urban soft boundary (USB) based on the economic and demographic structure, which is helpful for promoting future urban services, managing population growth, etc. In particular, this paper aims at: (1) simulating future urban expansion and identifying urban growth pattern based on an ANN model, (2) developing a flexible UGB model (3) and combining landscape pattern and Indian census criteria to delineate UGB.

2. Study area and data

The trajectory taken by this paper is as follows (Fig. 1): the first step included extraction of the land use maps of 1990, 2001 and 2010 from the Landsat images. The second step was examining physical and economic driving forces responsible for the urban growth. Then, an urban growth probability map through ANN- Multilayer Perceptron (ANN-MLP) model was created, which was used for investigation/estimation of future urban growth, with the quantity of change being estimated through the Markov Chain (MC). Next, urban growth for 2010 was simulated and compared with the observed map of 2010. It was evaluated using the agreement-disagreement method, Relative operating characteristics (ROC) and Total operating Characteristics (TOC). The model was finally recalibrated to generate future urban growth of 2020. At the end, future urban growth boundary was developed using landscape metrics in the light of an urban largest continuous patch index and census-based urbanization criteria.

2.1. Study area

The study area covered 335 km^2 including the Siliguri Municipal Corporation (SMC) (40 km^2), the census town (97 km^2) and rural areas (198 km^2). SMC is situated at the foothill of the Darjeeling Himalaya, on the bank of Mahananda river (Fig. 2) within the latitudinal and longitudinal extent of 26°39′7″N to 26°48′7″N and $88^0$18′26″E to $88^0$30′34″E respectively. The population of SMC was nearly half million (Census, 2011), whereas rural areas and town's populations were 200,000 and 300,000 respectively, hence having a total population of around 1 million in the study area. The annual population growth rate of SMC was 11.7% between 1991 and 2001 and decreased to 0.9% between 2001 and 2011, whereas the annual population growth rates in census town and rural area were 4.3% and 4.2% respectively. Starting from a hamlet, Siliguri got the status of municipality in 1951 and experienced a continuous and steady increase in population. After the establishment of the Assam Rail link and National Highway (NH-31), the strategic importance of Siliguri has ceaselessly heightened the trade relationship among Sikkim, Nepal, Bhutan, Tibet, Bangladesh and the North-Eastern states like Assam and Manipur.

In India, the master plan is the main guiding document for land use management, growth direction management and boundary demarcation. Nonetheless, only 23% of Indian cities have the master plan (The Hindu, 2012a,b). Further, Siliguri has no consistent approach to delineate imbalance of land supply and demand, a problem dominating urban, suburban and rural areas.

2.2. Data

Land use maps were extracted from the Landsat TM and ETM^+ images for the selected years of 1990, 2001 and 2010. In addition, municipal wards, census data for towns and villages, transportation network (including national highway, state highway and rail network) were taken from the administrative atlas of India and Google Earth imagery. Also, socio-economic driving variables were adopted from the census of India (2011) and West Bengal registration. It was subsequently verified through the field survey.

The existing literature shows a long list of explanatory variables, whose applicability varies from place to place. We prepared explanatory variables based on the literature, characteristics of the study area and data availability (Fig. 3), which were arranged into three broad groups: proximity factors, socio-economic factors, and neighbouring factors. Besides, we incorporated a few limiting factors to show growth resistance areas. *Proximity factors:* As Siliguri is the transportation junction in North Bengal, different transport networks have been developed. Planning documents show the direction of the urban growth in Siliguri is largely driven by transportation networks so that the intensity of growth is more salient near to the road networks. Hence, Euclidian distance was used to generate proximity factors (e.g., distance from C.B.D, airport, main roads, minor roads, railways and suburban centres). *Socio-economic factors:* Apart from the proximity factors, the growth process of a city is driven by the population and land value of the city. Most of the urban growth models ignore the demographic character and local land market. These two are the most important criteria for the future urban growth. *Neighbouring factors:* Concentration of built-up and cropland was used to account for the vicinity existing built-up areas. Development of new built-up is more possible to occur near the existing developed areas. *Resistance factors:* Finally, a binary exclusionary layer consisting of water bodies, reserved forests, major