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Modeling urban growth boundary based on the evaluation of the extension potential: A case study of Wuhan city in China

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ABSTRACT

The urban growth boundary (UGB) concept is useful in the field of urban planning, but models that can simulate the change in UGBs remain limited to date. In this paper, we propose a model known as UBEM that can simulate the future UGB. UBEM combines historical trajectories of UGB development and its extension potential in each azimuth to predict the future UGB for one city. UBEM consists of two parts: 1) the radiation method (RM) is used to describe the incremental length between the urban boundaries. In RM, urban centroids are used as the origin points to generate a set of radial lines from each azimuth, and we calculate the total and annual urban boundary length increments for each azimuth. 2) the extension pressure of the urban boundary is evaluated for different azimuths based on the potential value, which is generated by selecting a set of variables that are related to urban growth potential. Multiple time series maps were used to calibrate the model to reduce the randomness in future modeling. We compare the calibrated modeling result with those generated by the uncalibrated UBEM and a separate null model, applying two goodness of fit metrics to evaluate model accuracy: percent area match (PAM) quantity and PAM location were used to demonstrate that the calibrated UBEM performed better than the uncalibrated UBEM and null model when modeling the change in the urban boundary. Wuhan City in central China is used as a case study to test the viability of UBEM and predict the future UGB in 2020. The predication result offers helpful guidelines for Wuhan's future urban planning and UGB design.

1. Introduction

Urbanization promotes social and economic development and improves people's living standards. However, uncontrolled urban sprawl generates a series of problems, such as the deterioration of ecological security and a loss of agricultural land (Habibi & Asadi, 2011; Long, Liu, Hou, Li, & Li, 2014; Su, Jiang, Zhang, & Zhang, 2011). These problems seriously threaten the human environment as well as economic and social sustainable development. The science-based and effective control of urban growth has become an important component of city planning that must be considered in urban planning and policy design. Urban containment policies, the basic goal of which is to increase the density of urban land use and protect open space, have been widely used (Han, Lai, Dang, Tan, & Ci-Fang, 2009). This type of policy includes three practices: greenbelts, urban growth boundaries (UGBs), and urban service boundaries (USBs). Among these practices, UGBs are the most widely discussed in academics. UGBs draw lines between the urban area and the rural area using regional development licenses and other land use policies to direct the legal urban expansion within the UGB to control the scale, time sequence, and shape of the urban area (Calthorpe & Fulton, 2001; Martin, Pendall, & Fulton, 2002). UGBs, as useful tools for government planning departments to develop future urban development planning policies, have been widely used all over the world (Ball, Cigdem, Taylor, & Wood, 2014; Bengston and Yuon, 2006; Eddo, 2007; Gunn, 2007; Han et al., 2009; Sinclair-Simth, 2014; Tayyebi, Delavar, Saeedi, & Amini, 2008; Wang, Han, & Lai, 2014; Wan et al., 2014). The UGB concept originated in the United States in the 1960s and 70s, when the country was in the middle-late stages of urbanization and many

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cities were facing the problem of disordered urban sprawl. In order to resolve these issues, many new theories were proposed to explore and implement UGBs, such as Smart Growth, Growth Management, Infill Development and New Urbanism (Benfield et al., 2001; David & Shayne, 2005). After the subsequent use of UGBs in Great Britain (Gunn, 2007), Australia (Eddo, 2007), Saudi Arabia (Mubarak, 2004), and Korea (Bengston & Youn, 2006) this concept was accepted as the most effective way to curb urban sprawl and resolve corresponding problems. Zhang first introduced the UGB concept and other urban growth management tools in China, and they have been applied in some cities throughout the country (Han et al., 2009; Long, Han, & Mao, 2009, 2013; Wang et al., 2014). The Ministry of Housing and the Ministry of Land and Resource selected 14 cities in which to conduct UGB pilot. The first set of pilot cities in July 2014 included Beijing, Shanghai, and Guangzhou, among others. Their goals were to delineate the UGBs when implementing urban planning, limit the expansion scale, and limit the scope of construction in the city. The next phase will expand this planning approach to more than 600 cities in China to develop the UGBs. There is no doubt that UGB as an urban planning tool plays an important role in promoting sustainable city development. However, models that can simulate changes in UGB are quite limited to date (Tayyebi, Pijanowski, & Pekin, 2011; Tayyebi, Pijanowski, & Tayyebi, 2011). Therefore in this paper, we propose a model that can simulate UGB to help urban planners identify and forecast the future urban boundary extension.

1.1. Literature review on UGB modeling

UGB modeling can be viewed as one form of urban dynamics simulation. Traditional urban dynamics simulation mainly focused on modeling the change in individual urban pixels, describing urban boundaries using what is known as “planar” expansion, while boundary modeling is referred to as “linear” expansion modeling. Cellular automata (CA) and CA-based model are the most frequently used among the “planar” expansion methods. They use simple and dynamically updated local rules to convert the status of the cells to simulate the complex process of urban expansion, and have a wide range of applications in the field of urban dynamic change modeling around the word (Clarke & Gaydos, 1998; Clarke et al., 1997; Rienow & Goetzke, 2014; Yang & Xia, 2006; Yeh & Li, 2002; Yeh and Li, 2002). Some scholars use CA in combination with other models to simulate future urban shape and then delineate the outline of the built-up area as the UGB (Long et al., 2009, 2013; Puertas, Henríquez, & Meza, 2014). However, these efforts have been at very small scales (the pixel level) and they fail to directly simulate and forecast urban boundaries.

In “linear” urban expansion modeling, Tayyebi and his team have made significant contributions to urban boundary simulation. Tayyebi, Pijanowski, and Pekin (2011), Tayyebi, Pijanowski, and Tayyebi (2011), Tayyebi, Perry, and Tayyebi, (2014) suggest UGB models that can directly simulate the urban boundary. These include two rule-based UGB models (TR-UGBM) (Tayyebi, Pijanowski, & Pekin, 2011), artificial neural networks UGB model (ANN-UGBM) (Tayyebi, Pijanowski, & Tayyebi, 2011) and spatial logistic regression UGB model (SLR-UGBM) (Tayyebi et al., 2014) The TR-UGBM used the two rule-based models Distance Dependent Method (DDM) and Distance Independent Method (DIM), to simulate the UGBs, calculating the straight line azimuth and the distance from the urban center to simulate change in UGBs. The ANN-UGBM combined artificial neural networks (ANN) with GIS and RS to predict UGB, using variables that affect the urban boundary extension as input training parameters for the ANN on the predictor variables of urban boundary geometry, with satisfactory results. The SLR-UGBM used spatial logistic regression to quantify how the driver variables influence the urban boundary extension at each iteration over time, and forecast the future urban boundary expansion. Aside from the generation of UGB models, Tayyebi and others also established quantity and location metrics that enable us to evaluate the accuracy of urban boundary models: percent area match (PAM) quantity and location (Tayyebi, Pijanowski, & Pekin, 2011; Tayyebi, Pijanowski, & Tayyebi, 2011, 2014). However, TR-UGBM simulations of the UGBs only consider the azimuth and distance and ignore some important driving forces affecting urban expansion, such as distance to water, distance to urban centroids, distance to major roads, elevation, and slope (Müller, Steinmeier, & Küchler, 2010; Poelmans & Rompaey, 2010; Sunde, He, Zhou, Hubbart, & Spicci, 2014; Vermeiren, Rompaey, Loopmans, Serwajja, & Mukwaya, 2012). Although ANN-UGBM and SLR-UGBM take some driving forces of urban expansion into account, these models only use two temporal periods, It is difficult to guarantee a reliable conclusion if the result is obtained from sparse data and a small number of variables. Furthermore, these UGBMs can be easily applied in cities (in Tehran, Iran and Las Vegas, US, for example) where natural conditions (such as terrain and climate) or urban design cause the urban boundary to adopt a relatively regular morphology without encountering obvious obstacles (for example, big lakes, high mountains); however, such favorable simulation conditions don't exist in our study area of Wuhan. Wuhan has a complex urban morphology with lakes and rivers throughout the territory, so we cannot apply these UGBMs to simulate the boundary directly. We need to develop a UGBM that will fit Wuhan's situation.

1.2. Research questions, significance and paper structure

In this paper, we propose a model known as UBEM to simulate UGBs. UBEM combines the historical development trajectory of the UGB and its extension potential in each azimuth to predict the future UGBs. Wuhan City in Central China is selected as a case study to verify the utility of UBEM. We apply the model to simulate Wuhan's UGBs for the future and propose some urban planning guidelines according to the projected results. The research questions include: (1) How can we combine the radiation method (RM) with evaluation of the extension potential in each azimuth to simulate the extension of the urban boundary? (2) How can we use temporal data to calibrate the model and reduce randomness? (3) How can the predication results be used to guide urban planners? UBEM provides a new way to identify trajectories of urban dynamic change, and this study is significant because the UBEM product provides a reference for future urban planning, helping city managers design Wuhan's UGBs to promote coordinated urban development and environmental protection. This article is organized as follows: Section 2 gives a brief introduction to the study area and describes the model construction and calibration of the UBEM in detail. Section 3 describes the results, including the model calibration result using the temporal data and the predicted urban boundary for 2020, and Section 4 presents some discussion between the current study with existing studies in the literature as well as guidance for the design of Wuhan's UGBs. The final section provides the conclusions of this research.

2. Materials and methods

2.1. Study area and data

Wuhan, the capital of Hubei Province, China, lies at latitude 29° 58′–31° 22′ N and longitude 113° 41′–115° 05′ (Fig. 1). It is recognized as the political, economic, cultural, financial, educational, and