Science of the Total Environment 627 (2018) 264–281

Contents lists available at ScienceDirect

Science of the Total Environment

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

Measuring spatio-temporal dynamics of impervious surface in Guangzhou, China, from 1988 to 2015, using time-series Landsat imagery

Jianhui Xu [a,b,c], Yi Zhao [d,e,a], Kaiwen Zhong [a,b,c,*], Feifei Zhang [f], Xulong Liu [a,b,c], Caige Sun [a,b,c]

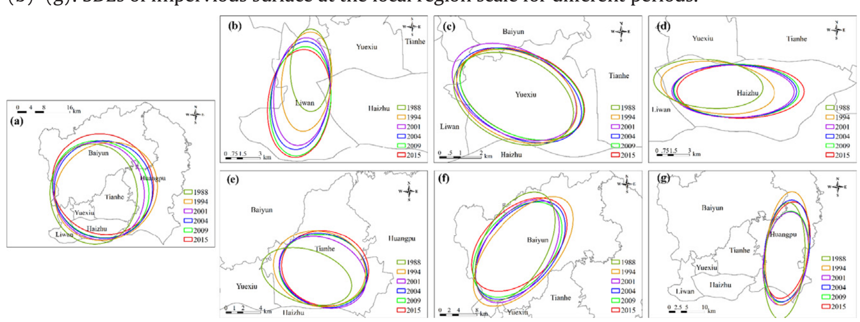
[a] Guangzhou Institute of Geography, Guangzhou 510070, China
[b] Key Laboratory of Guangdong for Utilization of Remote Sensing and Geographical Information System, Guangzhou 510070, China
[c] Guangdong Open Laboratory of Geospatial Information Technology and Application, Guangzhou 510070, China
[d] Guangzhou Institute of Geochemistry, Guangzhou 510640, China
[e] University of Chinese Academy of Sciences, Beijing 100049, China
[f] Department of Computer Science, Guangdong University of Education, Guangzhou 510310, China

HIGHLIGHTS

- A modified LSMA method was used to extract IS fraction.
- The spatio-temporal characteristics of IS were investigated with ISWMC and SDE.
- The ISWMC spatio-temporal dynamics revealed different evolutionary tracks of IS.
- IS expansion exhibited different change characteristics in various directions.

GRAPHICAL ABSTRACT

(a): SDE of impervious surface at the whole region scale for different periods.
(b)–(g): SDEs of impervious surface at the local region scale for different periods.



ARTICLE INFO

Article history:
Received 27 November 2017
Received in revised form 16 January 2018
Accepted 16 January 2018
Available online xxxx

Editor: Simon Pollard

Keywords:
Impervious surface
Urban expansion
Improved linear spectral mixture analysis
Impervious surface weighted mean centre
Standard deviational ellipse

ABSTRACT

This study evaluated the spatio-temporal change characteristics of urban development at different scales with time-series impervious surface fractions. Landsat-5 Thematic Mapper (TM) and Landsat-8 Operational Land Imager (OLI) images were used to extract impervious surface fractions using a modified linear spectral mixture analysis method in Guangzhou from 1988 to 2015. The results indicated that the impervious surface area has substantially increased, from 70.3 km^2 in 1988 to 580.5 km^2 in 2015. In 2015, the impervious surfaces were distributed almost throughout the whole region of the study area, except in the forest region. Next, impervious surface weighted mean centre (ISWMC) and the standard deviational ellipse (SDE) methods were used to systematically analyse the principle orientation, direction, spatio-temporal expansion trends, and the distribution differences of impervious surfaces at the whole and local region scales from 1988 to 2015. The spatio-temporal dynamics of ISWMC exhibited different expansion directions and intensities of impervious surfaces at the whole and local region scales. On a whole region scale, the principle expansion direction of impervious surfaces was northward. However, the expansion trend of impervious surfaces in the different districts was significantly different from other trends at the local region scale. The parameters of SDE were used to investigate the orientation and the clustering or dispersion degree of impervious surface at different scales. The results from SDE analysis indicated that the impervious surfaces exhibited uncertainty in the expansion direction at the whole region scale; in contrast, they had a distinct preferred orientation and expansion direction at the local region scale. The analysis revealed that urban expansion exhibited different change characteristics in various directions at the local region scale. In

* Corresponding author.
E-mail address: zkw@gdas.ac.cn (K. Zhong).

https://doi.org/10.1016/j.scitotenv.2018.01.155

summary, the results at the local region scale can better reflect the change trajectory of spatio-temporal dynamics of urban development and its fine spatial structure than at the whole region scale.

1. Introduction

China has experienced unprecedented rapid urbanization over the past few decades (Lei et al., 2012; Xu and Min, 2013). This rapid urbanization has significantly influenced and altered the urban land use structure; impervious surface areas have obviously increased, and other land cover types, including forest, soil, farmland, wetland, and river, are suffering from rapid decline (Xu et al., 2016). Impervious surface expansion has become one of the most important land use/land cover changes that occur during the urbanization process. However, the rapid increase in impervious surface area may lead to increased risk of serious environmental problems, including air pollution, urban heat island effects, extreme rainfall, rainstorm waterlogging, and water quality deterioration (Brabec et al., 2002; Jantz et al., 2005; Li et al., 2017; Liu et al., 2013; Luo et al., 2017; Xie et al., 2013; Yao et al., 2017). Because impervious surface can absorb heat from sunshine during the daytime and then releases it slowly at night (Wang et al., 2015), which leads to higher LSTs in urban areas than rural counterparts during both daytime and nighttime (Yao et al., 2017), it has become a key factor in studying urban development and the related environmental issues (Jat et al., 2008; Mallick et al., 2013; Miller et al., 2014; Shahtahmassebi et al., 2016; Zhang et al., 2017). Thus, accurate time-series impervious surface extraction and mapping at higher resolutions are relevant to the research of urban expansion and development.

Traditional research on the spatio-temporal dynamics of urbanization has been based on land use/land cover changes (Dewan and Yamaguchi, 2009; Ma and Xu, 2010). However, the mixed land cover pixels in pixel-scale research were considered to be pixels of only one land cover type (Peng et al., 2016). This may introduce errors in the quantitative analysis and evaluation of urban growth. Based on the vegetation-impervious surface-soil (V-I-S) theory (Ridd, 1995), a linear spectral mixture analysis (LSMA) method was proposed to quantitatively extract the impervious surface fraction (Wu and Murray, 2003). The impervious surface fraction was recognized as continuous spatial data at a subpixel scale (Peng et al., 2016). Currently, the impervious surface fraction has been a key indicator for measuring and analysing urban development and its eco-environmental effects because it can quantitatively reveal the spatio-temporal dynamics and change trends of urban growth (Hao et al., 2015; Peng et al., 2016). However, quantitative analysis of urban expansion has been highly dependent on the accuracy of the impervious surface fraction. The conventional LSMA and normalized spectral mixture analysis (NSMA) methods were successfully implemented to extract the impervious surface fraction in mixed pixels from remote sensing images (Wu, 2004; Wu and Murray, 2003; Yang and Li, 2015). However, conventional LSMA and NSMA methods may still encounter difficulty in accurately extracting the impervious surface fraction, because different land cover types have similar spectral reflectances. Thus, significant efforts have been made to improve the accuracy of impervious surfaces with different modified LSMA methods. In order to reduce the effect of low-albedo fractions from pervious surfaces on the estimation of impervious surface fractions, a modified LSMA method was proposed to extract high-precision impervious surface, vegetation, and soil fractions (Xu et al., 2016). In the modified LSMA method, the impervious surface, vegetation, and soil fractions of the LSMA were post-processed by combining a Normalized Difference Built-up Index (NDBI) and Normalized Difference Vegetation Index (NDVI) (Xu et al., 2016). The modified LSMA has been applied to extract the impervious surface fraction in Guangzhou with the Landsat 8 Operational Land Imager (OLI) images from October 18th 2015. The results confirmed the usefulness of the modified LSMA at extracting the impervious surface fraction. In this study, we will use this modified LSMA method to extract the impervious surface fractions.

The impervious surface area has already been widely used in mapping the impervious surface, revealing the spatio-temporal dynamics of urban development, and analysing urban environmental effects (Weng, 2012; Wu and Murray, 2005; Xiao et al., 2007; Xie et al., 2013; Zhou and Xu, 2007). Li et al. (2016) analysed the spatial patterns and dynamic changes in the Hangzhou metropolis with time-series urban impervious surface area datasets, which were extracted from Landsat imagery between 1991 and 2014. Henits et al. (2017) used the impervious surface fractions to map impervious surfaces and monitor the effects of increasing impervious surface ratios on population and environment. Hao et al. (2015) examined the urban expansion changes in Beijing between 1990 and 2014 using multi-temporal impervious surface area data and evaluated the relationship between impervious surface fractions and relative annual average surface temperatures. The results indicated that Beijing exhibited internal urban land transformation and outward urban expansion from 1990 to 2001 and that high-density urban areas, between the fifth and sixth ring roads, experienced the greatest increase from 2001 to 2014. Furthermore, the correlation analysis result indicated that the impervious surface fraction had a positive impact on the land surface temperature. Other studies have also shown that the impervious surface fraction had a stronger linear relationship with land surface temperature than other urban components and exponents, such as the vegetation fraction and normalized difference build-up index (Weng and Lu, 2008; Xu et al., 2013; Zhang et al., 2009). However, the above analytical methods have certain difficulty in revealing the principle orientation, direction, spatio-temporal expansion trends, and dispersion degree of impervious surfaces. The gravity center analysis (Griffith, 1984) and standard deviational ellipse (SDE) (Lefever, 1926) methods were widely used to assess the spatial distribution evolution and distributional trends in many fields (Al-Kindi et al., 2017; Vanhulsel et al., 2011; Yue et al., 2005), because they can reveal the spatial concentration of geographical phenomena and the change characteristics of the geospatial distribution (Li et al., 2017). Peng et al. (2016) used the Moran's I index and the standard deviational ellipse methods to detect urban expansion in Beijing, China, and estimated impervious surfaces from two periods of Landsat TM images in 2001 and 2009. Their results showed that the dominant direction of urban expansion was northeast.

As a pilot area of comprehensive innovation reform in Guangdong-Hong Kong-Macao Greater Bay, Guangzhou has experienced rapid urban growth, including population growth and socio economic development. The socioeconomic factor was the key driving force that directly affected urban land change in Guangzhou. This may cause a large increase in the amount of impervious surface areas. Previous studies have been conducted to analyse the spatio-temporal dynamics of urban growth over a long-time period by using the impervious surfaces estimated with remote-sensing data (Chen and Yu, 2016; Peng et al., 2016; Zhang and Weng, 2016). However, sufficient spatio-temporal details may still be required to understand the spatio-temporal distribution and evolution of urban growth at different spatial scales, including the principle orientation, direction, dispersion degree, and spatio-temporal expansion trends. Therefore, based on the impervious surface data, we undertook a comprehensive study to analyse the spatial and temporal characteristics of urban development using