

# Urban land expansion and its driving factors of mountain cities in China during 1990–2015

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**Abstract:** Land expansion of mountain cities in China is not systematically studied yet. This study identified 55 major mountain cities at and above prefecture level, and analyzed the land expansion characteristics and driving forces, based on visually interpreted data from TM images in 1990, 2000, 2010 and 2015. From 1990 to 2015, total built-up land area of the mountain cities increased by 3.87 times, 5.56% per year. The urban land growth was apparently accelerated after 2000, from 4.35% per year during 1990–2000 increased to 6.47% during 2000–2010 and 6.2% during 2010–2015. Compared to the urban population growth, the urban land expansion rate was 44% higher. As a result, the urban land area per capita increased, but it was still within the government control target, and also was much lower than the average of all cities in China. Urban development policy, changes to administrative divisions, GDP and population growth, and road construction were identified as the major driving forces of land expansion. Terrain conditions were not found a relevance to the urban land expansion rate during 1990–2015, but had a significant impact on the layout and shape, and also probably on the urban land efficiency.

**Keywords:** mountain cities; urban land expansion; driving forces; elastic coefficient; city compactness

## 1 Introduction

Since 1990, China's urban land has experienced a rapid expansion and as of the end of 2015, the total area from the statistical data was 40,941 km<sup>2</sup>, up 311.4%. This quick urban land expansion was not in a synchronous pace with the urban population growth, as the urbanization rate was 56.1% in 2015, increasing only by 29.7% compared to that in 1990. This illustrated that the urban land expansion was not only driven by urban population growth, but also by other factors such as economic development, transportation infrastructure construction, industrial restructuring, and new district development (Chen *et al.*, 2016; Li *et al.*, 2011; Tan *et al.*, 2005; Zhou *et al.*, 2007).

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For individual cities, the urban land area mostly showed a quick expansion during the past two decades, but the growth rate varied greatly over time and space (Chi *et al.*, 2015; Liu *et al.*, 2016; Tong *et al.*, 2016; Yu *et al.*, 2016). This implies that the pattern and driving mechanism of urban land expansion differed regionally, due to the influence of diversified socio-economic conditions (Huang *et al.*, 2007; Lin *et al.*, 2015; Tan, 2017; Yu *et al.*, 2017). In addition, the terrain and natural resource conditions also exerted a great influence on the urban land expansion (Cao *et al.*, 2016; Li *et al.*, 2016; Zhang *et al.*, 2016), particularly for mountain cities.

In China, two thirds of the territory is mountainous areas and 35% of the designated cities are mountain cities (Huang, 2006). So far, only a few studies have paid special attention to mountain cities, and discussed issues related to urban land use structure (Guo *et al.*, 2005) and urban planning (Liu, 2009). To understand the development process of mountain cities, we should make a systematic analysis of the urban land expansion and the driving mechanism. Therefore, this study selected the mountain cities at and above prefecture level as the representative to identify the urban growth characteristic and the causes. Firstly, the urban land area for each city was extracted in four representative years of 1990, 2000, 2010 and 2015 by visual interpretation using TM images, and then the urban land expansion rate and its spatio-temporal variation during 1990–2015 were analyzed using index approaches and ArcGIS tools. Finally, the driving factors were identified by ridge regression analyses.

## 2 Data and methods

### 2.1 Definition of mountain city and the urban area

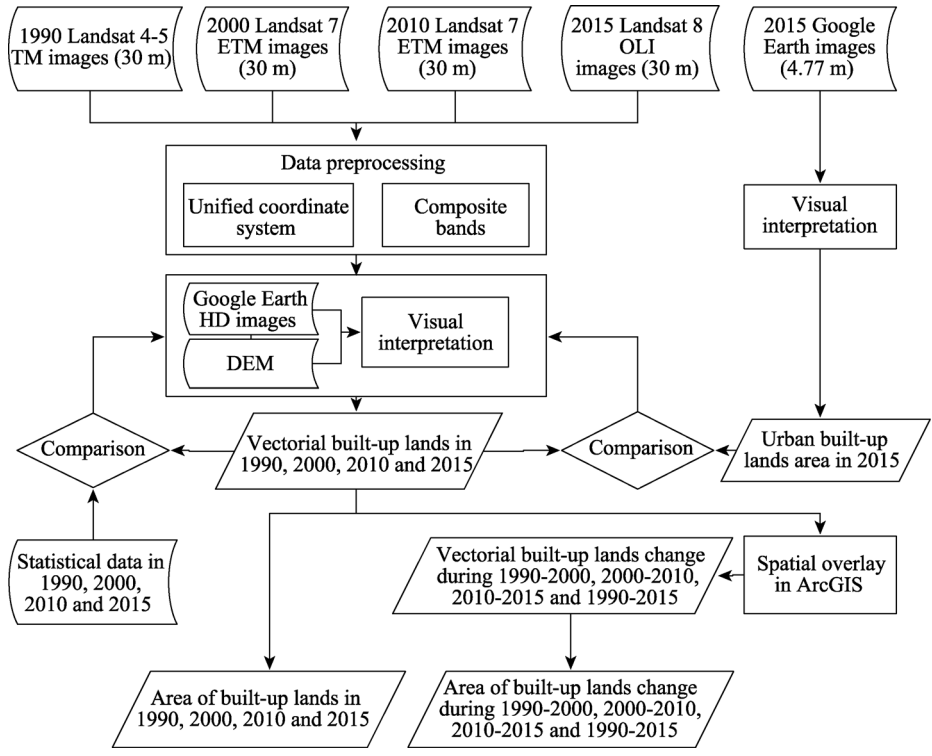
Based on the definition in previous studies (Chen, 2001; Huang, 2006), a city located in mountainous areas is simply identified as a mountain city. The built-up areas of a mountain city are generally distributed in valleys and basins or on gently sloping lands, and mostly surrounded by steep terrain. The urban area includes all the built-up lands within the city districts, the same as the city range defined in the *China City Statistical Yearbook*. In this study, only the mountain cities at and above prefecture level were studied. From the 295 same-level cities across China, a total of 55 cities were determined as mountain cities, using slope steepness and relative elevation as the major indicators based on the 30-m resolution DEM and imagery data. These mountain cities are mostly distributed in central, southwestern and northwestern China (Figure 1).

### 2.2 Extraction of urban land area

This study selected the years of 1990, 2000, 2010 and 2015 as representatives. The urban area of the mountain cities for each year was extracted using Landsat images and digital elevation data of ASTER GDEM V2. The data, as collected from the Computer Network Information Center, Chinese Academy of Sciences (<http://www.gscloud.cn>) included Landsat 4–5 TM images in 1989, 1990 and 1991<sup>1</sup>, Landsat 7 ETM images in 2000 and 2010, and

<sup>1</sup> As the images in 1990 were only available for 16 cities (Chenzhou, Hechi, Lishui, Longnan, Lvliang, Mianyang, Shangluo, Shaoguan, Tianshui, Tongren, Weihai, Yan'an, Zigong, Leshan, Yibin, and Zunyi), the urban boundary was delineated using the images in 1989 for 22 cities (Bijie, Dazhou, Fushun, Benxi, Guangyuan, Guiyang, Hegang, Huangshi, Liaoyuan, Lincang, Liupanshui, Longyan, Nanchong, Chongqing, Nanping, Panzhihua, Sanming, Wuzhou, Xining, Yangquan, Yichun, Yichun), and 1991 for other 17 cities.

Landsat 8 OLI images in 2015 at the same spatial resolution of 30 m. The imagery data were imported to ArcGIS to convert to the WGS-84 coordinate system, and then to make the false colored images based on the short-wave infrared band, near infrared band and green band using the Composite Bands tool in ArcGIS. With the colored images, the urban area in each of the four years was interpreted, respectively. In addition, the digital elevation data and Google Earth HD images were used to help determining the boundary when it cannot be clearly identified with the Landsat images. The interpreted urban area for each city in 1990, 2000, 2010 and 2015 was overlapped in sequence using analysis tools in ArcGIS to obtain the urban area changes in 1990–2000, 2000–2010, 2010–2015 and 1990–2015, respectively (Figure 1).



**Figure 1** The flowchart of urban land area extraction in the four years and calculation of its changes for the four periods

To examine the accuracy, we downloaded the high resolution color images (4.77 m) of 2015 from Google Earth for the 55 cities. With these images, we obtained the urban area for each city by visual interpretation. By comparison, the area obtained with the Landsat images in 2015 was overestimated by 0.16%–18.26% for 39 cities and underestimated by 0.26%–15.44% for the other 16 cities. The absolute value of the error was below 5% for 17 cities, 5%–10% for 16 cities, 10%–15% for 15 cities, and above 15% for 7 cities. The mean absolute value of the errors was 8.29% for all cities. Compared with the statistical data reported in the *China City Statistical Yearbooks*, the interpreted urban area was 23% lower in 2015, since the statistical data included the lands that obtained the Land Planning Permit and Land Construction Permit, but not constructed yet. In general, the data accuracy could be acceptable for the objective of this study mainly aimed to detect the urban land change dur-

ing 1990–2015.

## 2.3 Methods

Urban land expansion rate can be quantified using index methods, such as proportion index, extent index, and growth speed index. For the driving mechanism, multi-regression analyses were normally applied (Li *et al.*, 2017; Yu *et al.*, 2017). In this study, three indices were used to characterize the land expansion characteristic of mountain cities, and multi-regression analyses were applied for detection of the driving forces.

### 2.3.1 Quantification of urban land expansion

Annual growth rate of urban land area, the elastic coefficient to urban population growth, and city compactness index were used to describe the land expansion characteristics. For urban land growth rate, it is calculated with the formula below:

$$R = [(L_t / L_1)^{1/(t-1)} - 1] \times 100\% \quad (1)$$

where  $R$  is the annual growth rate (%) during the study period  $t$  (years), and  $L_1$  is the urban land area ( $\text{km}^2$ ) at the beginning year and  $L_t$  at the ending year of the study period.

Elastic coefficient is used to evaluate the coordination degree between urban land and population growths for each city from 1990 to 2015. This widely used coefficient (Yang *et al.*, 2013) is presented as the ratio of mean annual growth rate (%) of urban land area to that of urban population during a given period (An *et al.*, 2012). Based on the data availability, the urban population data in 1990 were collected from the *China City Statistical Yearbook*, in 2000 and 2010 separately from the fifth and sixth census data, and in 2015 from the statistical bulletin of the national economic and social development of each city district.

City compactness index is used to characterize the shape of a city (Mizutani, 2012; Pan *et al.*, 2015), by checking degree of the urban built-up area approaching to a circle shape. It is formulated as below:

$$C = \frac{2 \times \sqrt{\pi \times A}}{P} \quad (2)$$

where  $A$  represents the urban land area ( $\text{m}^2$ ),  $P$  stands the boundary length (m), and  $C$  is the compactness index for a city. The compactness index ranges between 0 and 1. The larger the compactness index is, the closer to a circle the city shape is, and thus the more compact the city is (Liu *et al.*, 2014). In this study, the urban area and its perimeter were calculated using the ArcGIS Calculator for each of the 55 cities in 1990, 2000, 2010 and 2015. For cities comprising several built-up areas, the compactness index was the weighted average of the index of each built-up area that was calculated with the same equation (2).

### 2.3.2 Identification of factors affecting urban expansion

Qualitative analyses were firstly applied to screen out possible factors affecting urban land expansion by literature reviews, and then ridge regressions that can eliminate the multicollinearity influence (Barcena *et al.*, 2014), was used to identify the driving factors and their contribution to urban land change. By preliminary analysis, seven socio-economic factors were considered, including GDP, urban income, urban population, fixed asset investment, foreign investment, urban green land area, and urban road area. The data during 1990–2015

were collected from *China City Statistical Yearbook* for 48 mountain cities<sup>2</sup> with complete available data. In addition, two terrain variables, i.e., slope steepness and elevation for the urban area, and three buffer zones of 500 m, 1000 m and 2000 m around the city were included for the analysis, with the data computed from the DEM data using ArcGIS. For GDP and income, the values at 2000, 2010 and 2015 were converted to the constant price at 1990. All variables were normalized using the Napierian logarithm to eliminate the heteroscedasticity (Zhang, 2007), and then regressed using ridge regression approach to identify the relevance degree and contribution to urban land area and the change. The general form of multivariable regression is presented below:

$$\ln A_i = \sum \beta_{ij} \ln V_{ij} + \varepsilon \tag{3}$$

where  $A_i$  is the urban land area (km<sup>2</sup>) in a year for city  $i$ ,  $V_{ij}$  is the independent variables involved such as GDP and population,  $\beta_{ij}$  is the coefficient of variable  $j$ , and  $\varepsilon$  is residual error. For the analysis of factors affecting the urban land change, the value for the variables is the total change during the given period.

3 Urban land expansion characteristics of mountain cities

3.1 Urban land expansion and its spatio-temporal variation

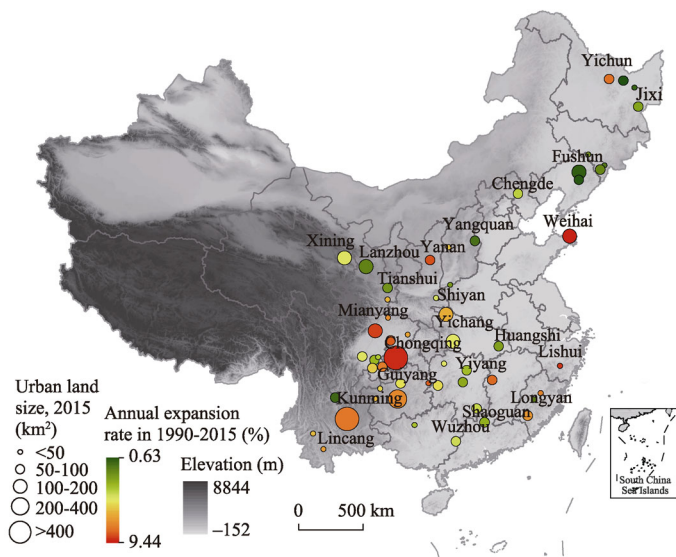
The urban built-up land area for all mountain cities, totalling 5047 km<sup>2</sup> in 2015, or 12.32% of the total built-up area for all cities in China, expanded by 387.01% in total or 5.56% per year, compared to that of 1304 km<sup>2</sup> in 1990. Regionally, western China showed the fastest urban land growth of 6.74% per year, followed by 6.33% in eastern China and 4.93% in central China (Table 1). For the mountain cities in northeastern China that are generally resource-based, the urban land showed a very low growth rate, only with an annual rate of 2.17%. At city level, the expansion rate varied greatly from 0.63% to 9.44% per year (Figure 2 and Table 2). In 15 cities including Chongqing, Yan'an, Mianyang, Tongren, and Weihai, the urban land area increased by 5.04–9.54 times during the past 25 years, while in 4 resource-based industrial cities of Hegang, Shuangyashan, Benxi and Fushun, the urban area was only increased by 17.1%–31.7%.

**Table 1** Total urban land area of mountain cities in 1990, 2000, 2010 and 2015 and annual growth rate in different regions of China during 1990–2015

Regions	Urban land area (km <sup>2</sup> )				Annual growth rate (%) 1990–2015
	1990	2000	2010	2015	
Eastern China	112.97	207.89	430.71	524.62	6.33
Central China	220.32	311.88	577.21	734.27	4.93
Western China	627.42	1064.76	2251.7	3201.00	6.74
Northeastern China	343.57	412.04	476.12	587.82	2.17

Note: Eastern China includes cities in provinces of Hebei, Shandong, Zhejiang, Fujian and Guangdong. Central China includes cities in Shanxi, Henan, Hubei, Hunan and Jiangxi. Northeastern China includes cities in Heilongjiang, Jilin and Liaoning, and western China includes cities in Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Guangxi and Qinghai and the city of Chongqing.

<sup>2</sup> Due to administrative changes, the socio-economic data during the study period were incomplete for other 7 cities including Lvliang, Tongren, Bijie, Pu'er, Lincang, Longnan and Hechi, thus these 7 cities were excluded for the analysis.



**Figure 2** Spatial variation of urban land area and annual expansion rate of mountain cities in China

The mean urban land expansion rate of all mountain cities was 4.35% per year during 1990–2000, increased apparently to 6.47% during 2000–2010, and then slightly decreased to 6.2% during 2010–2015. As for individual cities, the growth rate varied more greatly among the three periods (Table 2), with the greatest expansion not synchronized in the same stage. In 22 cities, the fastest urban expansion occurred in the second period of 2000 to 2010, 16 in the first decade, and 17 in the last five years. Several cities showed an abrupt increase in the urban land area, such as Yan’an and Shiyan during 2010–2015, Chongqing, Weihai, Tongren, Lishui, Nanchong and Puer during 2000–2010, and Longyan, Mianyang and Longnan during 1990–2000. This quick increase was largely caused by the administrative adjustment and new district development.

The elastic coefficient of urban land growth to urban population growth during 1990–2015 varied from 0.65 to 6.62 for the mountain cities (Table 2) except two resource-based industrial cities in northeastern China. The elastic coefficient of these two cities showed a negative value, due to the urban population decrease. In 15 cities including Lanzhou and Tianshui, the elastic coefficient was less than 1, as the growth rate of urban land was lower than that of the population, while in 23 and 15 cities the elastic coefficients ranged from 1.01 to 1.50 and above 1.50, respectively. As a result of the very low population growth, Liupanshui and Jixi showed a very high value of 6.46 and 4.94 (Table 2). Except the two cities with negative values, the mean elastic coefficient for all other cities was 1.44, implying that mean growth rate of urban land was 44% higher than that of population, exceeding the rational value of 1.10, as suggested in literature (An *et al.*, 2012; Marshall, 2007).

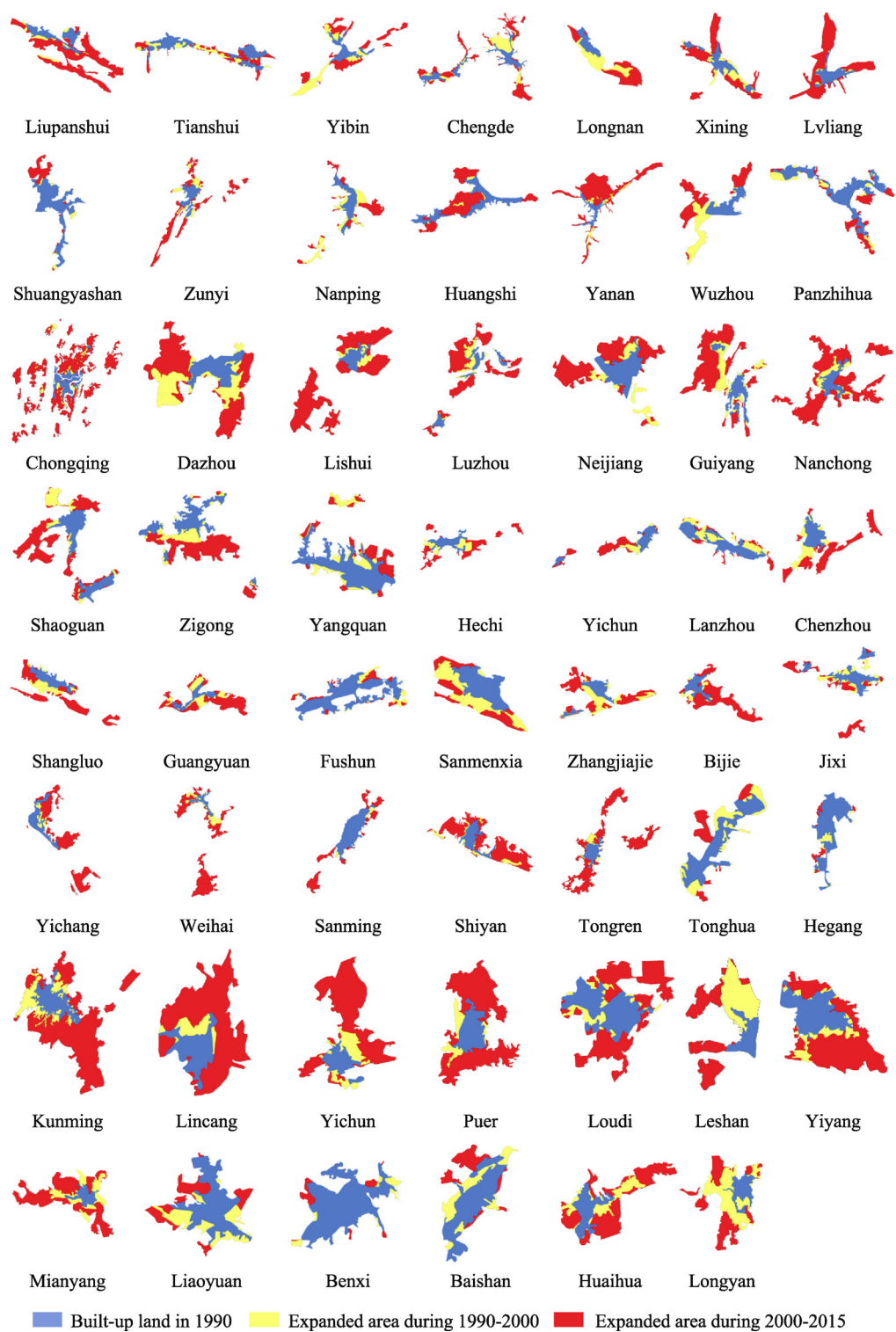
### 3.2 Urban sprawl characteristics

Figure 3 presents urban land sprawl of all mountain cities during 1990–2015, showing that the urban land expanded unevenly in terms of spatial distribution. In many cities such as Tonghua, Bijie, Yan’an, Panzhihua, Tongren, Shuangyashan, the new urban area extended along river valleys in a stripped pattern. In several cities including Chongqing, Guiyang,

**Table 2** Annual urban land growth rate (%) in different periods and the elastic coefficient for all mountain cities of China during 1990–2015

City	Annual urban land expansion rate (%)				Population growth (%) 1990–2015	Elastic coefficient 1990–2015
	1990–2000	2000–2010	2010–2015	1990–2015		
Chengde	6.50	5.06	2.07	5.02	3.59	1.40
Yangquan	2.68	0.08	4.94	2.08	2.67	0.78
Lyliang	1.19	12.45	4.42	6.22	7.76	0.80
Fushun	1.17	1.00	0.69	1.01	0.65	1.55
Benxi	0.66	1.49	0.27	0.91	0.74	1.23
Liaoyuan	3.73	1.85	2.13	2.65	1.11	2.39
Baishan	3.40	1.22	1.92	2.23	3.00	0.74
Tonghua	3.10	0.91	4.61	2.52	1.23	2.05
Jixi	3.94	2.26	7.20	3.90	0.79	4.94
Hegang	0.94	0.10	1.10	0.63	0.87	0.72
Shuangyashan	0.25	1.51	2.03	1.11	−2.71	−0.41
Yichun	2.73	5.61	23.26	7.73	−0.14	−55.21
Lishui	4.58	15.42	4.97	8.87	7.28	1.22
Sanming	0.65	3.18	3.73	2.27	2.28	1.00
Nanping	6.99	3.72	16.14	7.42	2.18	3.40
Longyan	12.81	4.38	1.07	6.98	5.50	1.27
Yichun	7.39	10.43	3.52	7.80	5.51	1.42
Weihai	8.68	12.50	5.03	9.44	7.75	1.22
Sanmenxia	6.31	2.43	1.19	3.71	3.62	1.02
Huangshi	0.85	7.91	1.36	3.72	2.49	1.49
Shiyan	4.03	6.54	11.60	6.51	4.59	1.42
Yichang	2.45	7.21	9.04	5.64	5.08	1.11
Chenzhou	5.54	6.06	3.22	5.28	6.01	0.88
Zhangjiajie	7.88	5.32	1.94	5.64	6.17	0.91
Huaihua	5.96	7.39	2.31	5.78	4.50	1.28
Yiyang	2.94	7.90	1.73	4.65	6.04	0.77
Loudi	2.25	5.23	4.85	3.96	5.50	0.72
Shaoguan	3.66	6.59	1.00	4.28	3.97	1.08
Wuzhou	7.99	4.06	3.12	5.42	3.42	1.58
Hechi	5.29	5.65	1.60	4.68	5.95	0.79
Zigong	4.27	3.70	6.41	4.47	2.89	1.55
Chongqing	4.03	11.86	15.05	9.27	7.30	1.27
Nanchong	5.29	14.40	3.23	8.41	7.52	1.12
Luzhou	6.45	8.07	8.28	7.46	5.63	1.33
Mianyang	10.90	8.06	5.48	8.66	5.18	1.67
Neijiang	4.37	6.31	2.91	4.85	3.86	1.26
Leshan	8.26	4.84	1.63	5.54	3.21	1.73
Yibin	8.79	4.48	3.81	6.05	5.45	1.11
Guangyuan	8.83	8.54	0.65	7.02	4.16	1.69
Dazhou	9.37	5.21	3.66	6.54	6.18	1.06
Panzhihua	2.10	2.02	1.93	2.03	1.97	1.03
Liupanshui	3.27	10.47	5.07	6.46	1.00	6.46
Tongren	3.29	13.02	9.90	8.41	5.80	1.45
Bijie	2.74	10.03	4.71	6.00	9.32	0.64
Guiyang	7.54	6.15	7.80	7.03	4.33	1.62
Zunyi	5.18	5.21	7.70	5.69	5.12	1.11
Kunming	6.78	11.74	1.20	7.58	4.75	1.60
Puer	3.79	12.17	1.68	6.63	5.66	1.17
Lincang	3.28	10.06	5.39	6.37	2.94	2.17
Shangluo	5.73	5.86	4.24	5.48	6.23	0.88
Yan'an	5.73	7.83	15.40	8.45	5.88	1.44
Lanzhou	4.45	1.01	1.27	2.43	3.74	0.65
Tianshui	3.20	1.74	3.73	2.72	4.04	0.67
Longnan	10.18	4.23	3.70	6.46	6.59	0.98
Xining	5.52	6.15	4.35	5.54	3.24	1.71



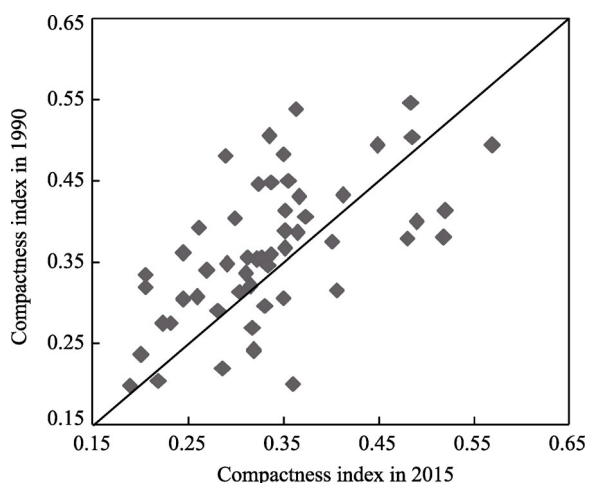


**Figure 3** Urban land expansion in all mountain cities of China during 1990–2015 (the maps are schematically presented, not at the same scale)



Nanchong, Lishui, Shaoguan, Hechi and Weihai, the new urban lands were separately developed in different areas with some distance from the old city areas. In cities including Lincang, Yiyang, Yichun, Pu'er, Longyuan, Baishan and Sanmenxia, the new urban area was continuously extended from the old city, because these cities are generally located in mountain basins, and thus there is continuous gentle land near the cities suitable for urban development.

The urban land area of most mountain cities is spatially discontinuous, irregular and incompact, and thus the compactness index was very low. The average index value was only 0.36, 0.34, 0.34 and 0.33 in 1990, 2000, 2010 and 2015, respectively, much lower than the



**Figure 4** Schematic comparison of city compactness index of mountain cities in China in 1990 and 2015

value of 0.375 to 0.739 for other cities reported in different studies (Liu *et al.*, 2014; Pan *et al.*, 2015). Of the 55 mountain cities, only 17 in 1990, 15 in 2000, 13 in 2010 and 12 in 2015 showed a compactness index value above 0.4, while 18 cities were found with the value below 0.3 in 2015. Compared to 1990, the compactness index in 2015 apparently decreased in most mountain cities (Figure 4), inferring that the suitable land surrounding the city could be becoming less available, and thus the terrain restriction on the urban layout was stronger.

## 4 Factors affecting the urban land expansion

This section analyzed the influences of policy, adjustment of urban administrative division, terrain and socio-economic factors on the urban land change during 1990–2015.

### 4.1 Urban development policy

As indicated by several studies (Huang *et al.*, 2012; Obeso Muniz *et al.*, 2017), the government policies have a great influence on the urban development, including industry policy, fiscal policy, land use policy, regional development policy, and urban planning policy. For the mountain cities involved in this study, changes in the urban land growth rate between different stages could be mainly caused by the national urban development policy. In 1990, the Chinese government issued the *City Planning Law*, to “strictly control the size of large cities and rationally develop medium-sized cities and small cities”. Meanwhile, various policies were simultaneously adopted to control the over-expansion of urban land, particularly that of large cities. After ten years, this control was relaxed in 2000 by the policy adjusted to “adhere to the coordinated development of large, medium and small cities, and small towns”, which was released in the China’s 10th Five-Year Plan (2001–2005) and the Report at 16th CPC National Congress in 2002. With this relaxed control, many cities enhanced the development, resulting in the much quicker urban land expansion after 2000.

## 4.2 Changes to administrative divisions

Changes to the administrative divisions involve the adjustment in administrative rank, economic status and territorial governance (Cartier, 2016). These changes were often associated with new area development, and thus greatly stimulated the expansion of city range (Wang *et al.*, 2016). During the study period, several mountain cities adjusted the city scope to extend the urban space. Such a well-known city is Chongqing. In 1997, it was approved as the fourth municipality directly under the central government, and since then the urban growth rate was doubled (Table 2). Another case is Kunming. After the new planning was implemented in 1998 (Luo *et al.*, 2015), Kunming city kept a high land expansion rate of more than 10% per year during 2000–2010. In several other cities, such as Tongren and Yan'an, the urban land showed an accelerated expansion after the new district development was implemented in 2006 and 2012, respectively.

## 4.3 Terrain conditions

As mentioned in Section 3.2, terrain conditions had a significant influence on the shape and layout of mountain cities, but its impact seemed insignificant on the city size and expansion speed of the urban land area. Terrain characteristics indicated by the slope steepness and elevation were not found to have a relevance to the total urban land area and urban land changes by paired correlation. This was also found in a previous study for all cities in China (Huang *et al.*, 2007). The reason might be that the terrain limitations can be largely removed by engineering measures such as building industrial terraces, truncating small hills, which has been practiced in mountain cities such as Yan'an and Tongren in recent years. Another reason is that the city can select a new area to break through the shackles of insufficient space around the built-up area for urban development (Zhang *et al.*, 2015).

Since larger investment is needed to realize the land expansion, the mountain cities generally showed a stronger tendency to more efficiently use the urban space than to expand the area, compared to other cities in China. From this angle, terrain condition could have a significant restriction on the development of mountain cities. For instance, the mean land area per capita in the mountain cities was 74.6 m<sup>2</sup> in 1990, 65.8 m<sup>2</sup> in 2000, 87.1 m<sup>2</sup> in 2010, and 97.3 m<sup>2</sup> in 2015, all below the target area (100 m<sup>2</sup> per capita) of urban land use control specified by the Chinese government (MLR, 2014). The cities with the urban land area below 100 m<sup>2</sup> per capita covered 84% of the mountain cities in 1990, and further increased to 95% in 2000. After then, the proportion decreased to 75% in 2010 and further to 58% in 2015, implying that the urban land expansion was highly accelerated in many mountain cities during the last 15 years. For all cities in China, the mean land area per capita was 87.1 m<sup>2</sup>, 107.1 m<sup>2</sup>, 117.0 m<sup>2</sup> and 113 m<sup>2</sup> in the corresponding year (MOHURD, 2016; Wang *et al.*, 2012; Yang *et al.*, 2013), which is expected to reach 165 m<sup>2</sup> in 2020 (Tan *et al.*, 2010).

## 4.4 Socio-economic factors

The ridge regressions indicated that total GDP, urban population, and green land area had a significant relevance to the urban land area in the four years. Road land area appeared to be a significant contribution factor in 2000 and 2015 (Table 3). Urban population was the most important factor influencing urban land area: the contribution coefficient was 0.296 in 1990, implying that the urban land area would increase by 2.96% with a growth of 10% in popula-

tion. After 1990, its influence showed a slightly declining trend, from 0.29 in 2000 to 0.276 in 2010 and 0.266 in 2015. Total GDP and green land area were also significant to the urban area, but their significance, i.e., the contribution coefficient decreased, from 0.258 and 0.279 in 1990 to 0.136 and 0.177 in 2015, respectively. Total urban road area was not found to have a significant relevance to the urban land area in 1990, but in 2015, it became the most important contributor, implying that transportation construction was becoming more important in promoting urban development. Assets investment was found to have a significant relevance only in 2010.

**Table 3** Regression results between urban land area and the driving factors in four years

Factors	1990	2000	2010	2015
LnGDP	0.258** (2.567)	0.189** (2.133)	0.139*** (2.876)	0.136** (3.109)
LnPOP	0.296*** (2.9)	0.29*** (3.242)	0.276*** (5.323)	0.266*** (4.763)
LnGR	0.279*** (3.314)	0.162* (1.987)	0.192*** (3.6)	0.177** (3.077)
LnINV	0.074 (0.742)	0.113 (1.337)	0.133** (2.555)	0.0308 (0.605)
LnRDA	0.039 (0.452)	0.172* (1.916)	0.231*** (4.24)	0.312*** (5.563)
$R^2$	0.78	0.751	0.897	0.845
Adjusted $R^2$	0.753	0.72	0.886	0.829
F statistics	29.14***	24.767***	82.117***	53.375***

Note: \*, \*\*, \*\*\* represent the significance level of 10%, 5% and 1%, respectively. The value in parentheses is the t test.

For the urban land expansion, urban population growth (Ln $\Delta$ POP) and urban road construction (Ln $\Delta$ RDA) were found to be the significant contributors in the four periods (Table 4). During the study period of 1990 to 2015, changes in GDP (Ln $\Delta$ GDP) showed a

**Table 4** Regression results between urban land increase and the driving factors during three periods

Factors	1990–2000	2000–2010	2010–2015	1990–2015
Ln $\Delta$ GDP	0.073 (0.713)	0.0635 (0.437)	0.121 (1.279)	0.197** (2.544)
Ln $\Delta$ POP	0.319*** (2.99)	0.334*** (2.767)	0.215** (2.188)	0.186** (2.257)
Ln $\Sigma$ INV	0.144 (1.386)	0.0929 (0.929)	0.259** (2.561)	0.101 (1.224)
Ln $\Delta$ RDA	0.225** (2.143)	0.284** (2.281)	0.232** (2.442)	0.365*** (4.272)
$R^2$	0.457	0.461	0.516	0.688
Adjusted $R^2$	0.406	0.411	0.472	0.658
F statistics	8.861***	9.404***	11.74***	23.191***

Note: \*, \*\*, \*\*\* represent the significance level of 10%, 5% and 1%, respectively. The value in parentheses is the t test.

significant contribution to the urban land expansion, and in the other periods, the contribution was not significant. In 2010–2015, total fixed assets investment ( $\text{Ln}\Sigma\text{INV}$ ) had a significant contribution to the urban land increase (Table 3), implying that the low-slope hilly and mountain land development promoted by the government since 2011 (MLR, 2011) obviously stimulated the land expansion of mountain cities. During the 25 years from 1990 to 2015, land expansion of the mountain cities was mainly stimulated by urban population growth, road construction and GDP growth, which can explain about 70% of the urban land increase. Income and foreign investment, and slope steepness and elevation were not found to have a significant relevance to the urban size or urban land expansion.

## 5 Discussion

### 5.1 Spatio-temporal variation of urban land expansion rates

From 1990 to 2015, the total built-up land area of the mountain cities increased by 3.87 times, or 5.56% per year. Affected by the urban development policy, the urban land expansion showed a periodic characteristic, with the annual growth rate varying from 4.35% during 1990–2000 to 6.47% during 2000–2010 and then to 6.2% during 2010–2015. This phased difference was also observed for the urban land change in other cities of China, but the difference extent was much lower in the mountain cities. For instance, Liu *et al.* (2014) found that the built-up land expansion rate of China during 2000–2010 was 2.14 folds of that during 1990–2000. According to the statistics, the annual growth rate in China's total urban area was 6.95% during 2000–2010, but it was only 2.12% during 1990–2000. This infers that the policy adopted in 1990 to control the over-expansion of large cities had a less impact on the mountain cities, because the cities are mostly small and medium-sized cities.

The urban land expansion showed an obvious regional difference, with an annual growth rate during the 25 years ranged from above 6.0% in the eastern and western regions of China, to 4.93% in the central region, and then apparently decreased to 2.17% in northeastern China (Table 1). For all cities in China, the urban land expansion showed a similar regional variation (An *et al.*, 2012; Wen *et al.*, 2016). As for individual mountain cities, the urban growth rate varied greatly, with the area increasing by 5.40–9.54 times in 15 cities and only 17.1%–31.7% in 4 cities in northeastern China. For the quickly growing cities, the land expansion was greatly promoted by the changes to administrative divisions and new district development, while for the slowly ones, the low land expansion was mainly due to the shrinkage of urban population associated with low economic development. Several similar cases were reported in previous studies. For instance, in Shanghai, the urban land area increased by 120% from 1990 to 2000 after the Pudong New Area was initiated in 1990 (Zhang *et al.*, 2015). In Tianjin, the urban land was expanded by 78% during 2000–2010, mainly as a result of the Binhai New Area development after 2000 (Zhang *et al.*, 2016).

### 5.2 Urban land expansion and population growth

Total growth of urban land for the mountain cities was much higher than that of urban population, with the mean elastic coefficient of 1.44 from 1990 to 2015. However, the urban expansion for the mountain cities as a whole was lower compared with other cities in China.

A study indicated that the mean elastic coefficient for all cities in China was 1.53 during 1990–1999 and 2.25 during 1999–2009 (An *et al.*, 2012), showing a much faster growth rate in the urban land area compared with population. As for specific cities, about half of the mountain cities showed an above 20% quicker growth in the urban land area than population. However, over 65% of the cities in China showed a much faster growth of urban land than that of population (Yang *et al.*, 2013; Zou *et al.*, 2015). In general, the urban land use intensity in the mountain cities was rather high, for instance, the mean land area per capita for the 55 mountain cities was 97.3 m<sup>2</sup> in 2015, while it was only 86.1% of the mean value (113 m<sup>2</sup>) for all cities in China in 2015 (MOHURD, 2016).

### 5.3 Urban land expansion mechanism

In most mountain cities, the terrain seems to have no significant influence on the urban land expansion rate, which is in accordance with the results reported by Huang *et al.* (2007); however, terrain condition significantly determined the main direction of urban expansion (Figure 3), and thus had an apparent impact on the city shape and sprawl pattern, as indicated by the compactness of the mountain cities that was generally very low (Figure 4). Similar results were also obtained by previous studies (Pan *et al.*, 2015; Wang *et al.*, 2005) that the compactness of the cities in plain areas of northern China was higher than that of the cities in southern China, as they are often restricted by the surrounding hills or rivers and lakes. For some cities such as Lanzhou, the urban development could be strongly restricted by the surrounding mountains, as the urban land increased by only 28 km<sup>2</sup> during 2000–2015.

For all cities in China, population and GDP growth were acknowledged as the main driving factors (Tan *et al.*, 2003; Zhang *et al.*, 2011). As for mountain cities, except policy and changes to administrative divisions, urban population growth, GDP growth and urban road construction were identified as the major driving factors of the urban land expansion from 1990 to 2015, and fixed asset investment made a great contribution to the urban land expansion in recent 5 years of 2010–2015. Other factors were not found to have a significant relevance to the urban land expansion in the mountain cities. It should be noted that the interpreted urban land only covered the built-up areas in the city districts, while the socio-economic data were collected for the whole city. Therefore, the space extent for the data may not be exactly matched. The urban population was all non-agricultural population as registered in the city, not including the floating population, which could cause bias errors on the results, particularly for per capita urban land area.

## 6 Conclusions

The study results indicate that most of mountain cities maintained a quick growth during 1990–2015, and after 2000 the urban expansion was markedly accelerated. Five factors identified in this study stimulated this quick growth, including policy, adjustment of administrative divisions, urban population and GDP growth, and urban road construction. Terrain conditions were not found to have a significant influence on the urban land expansion rate of mountain cities, but had a great impact on the city shape and compactness. Due to terrain restriction, the mountain cities presented a stronger tendency to more efficiently use the urban space than to expand the area, thus showed higher urban land use efficiency than cities

in plain areas.

During 1990–2015, total built-up land area of the mountain cities increased by 3.87 folds. However, this quick urban land growth could be reasonable for the mountain cities as a whole, as the urban land area per capita was still within the government control target. Considering their important role in absorbing the rural population and promoting the regional development, appreciate financial supports and preferential policies should be adopted to enhance the development of mountain cities. As these cities are mostly surrounded by mountains, the urban development should be aimed at building an ecological and livable city, instead of damaging the mountain landscape and natural ecosystems.

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