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Modeling Urban Spatial Growth in Mountainous Regions of Western China

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The scale and speed of urbanization in the mountainous regions of western China have received little attention from researchers. These cities are facing rapid population growth and severe environmental degradation. This study analyzed historical urban growth trends in this mountainous region to better understand the interaction between the spatial growth pattern and the mountainous topography. Three major factors—slope, accessibility, and land use type—were studied in light of their relationships with urban spatial growth. With the analysis of historical data as the basis, a conceptual urban spatial growth model was devised. In this model, slope, accessibility, and land use type together create resistance to urban growth, while accessibility controls the sequence of urban development. The model was tested and evaluated using historical data. It serves as a potential tool for planners to envision and assess future urban growth scenarios and their potential environmental impacts to make informed decisions.

Keywords: *Mountain city; urban spatial growth; urban morphology; GIS; China.*

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Introduction and research questions

It has been predicted that the total population in China will reach 1.6 billion by 2050, while the number of people living in cities is expected to reach 1.12 billion. This means the urbanization level will grow from 36% in 2003 to almost 70% in 2050. By then, China will have 50 extra large cities, each with an urban population exceeding 2 million; 150 large cities; 500 medium-size cities; and 1500 small cities (Niu 2003). While this strong urban population growth has been well studied in recent years, most research has focused on cities in eastern China. The cities in mountainous western China have received less attention (Jiang et al 2012; Schneider et al 2015), despite the importance of these regions—about 69% of China's territory is mountainous, and 70% of its counties and cities are located in mountainous regions (Chen 2003). In recent years, cities in mountainous regions have grown as quickly as those in coastal regions. In Chongqing municipality, where cities are almost all in a mountainous area, the proportion of the urban population has grown from 17.38% in 1990 to 33.09% in 2000, resulting in about 9.42 million people in 19 cities or municipal districts. This growth is comparable to urban population growth in the coastal Jiangsu Province, which grew 21% to 41.50% in the same period (National Bureau of Statistics of China 1990–2010).

Accompanying this rapid urbanization in the mountainous regions of China is degradation of the environment, which many mountain cities in the global South are experiencing (The Abisko Agenda 2002). Today, the pressure that these cities and their surroundings face from urbanization is exacerbated by the mountain topography (Fan and Li 2009). Air quality in mountain cities in China is deteriorating because of the intensive use of fossil fuels and, in some such cities, the concentration of heavy industry. Overfarming and deforestation in the mountains have destroyed natural vegetation, which has directly caused soil erosion, landslides, and frequent flooding in and around some cities. To address these problems, one important research subject is the spatial pattern of urban expansion in mountainous regions; this not only affects the surrounding landscape but also the overall ecologic system.

Spatial patterns, with their associated processes, have long been a focus of urban geography. The spatial pattern is often analyzed and explained in the context of the urban social fabric, economic structures, and functions (Schneider-Sliwa 2015), resulting in many spatial models. Some of these models are conceptual, aiming to explain the distribution of land use, population, economic activities, and transportation in cities (Burgess 1927; Hoyt 1939; Harris and Ullman 1945). Others are simulation models that reveal the process of urbanization as the

TABLE 1 Basic information about the sample cities.

City	Location	Province, autonomous region, or municipality	2000 urban population	Years of available GIS data
Wanzhou	30°48′37″N; 108°22′56″E	Chingqing	494,000	1959, 1986, 1999
Dazhou	31°12′54″N; 107°29′51″E	Sichuan	350,000	1960, 1986, 1990, 1999
Fuling	29°42′28″N; 107°23′29″E	Chongqing	340,000	1963, 1987, 1999
Yibin	28°46′16″N; 104°37′25″E	Sichuan	280,000	1960, 1983, 1999
Changdu	31°08′20″N; 97°10′43″E	Tibet	50,000	1980, 1993, 2000

interaction of the factors mentioned earlier (Anas et al 1998; Waddell 2002; Cheng and Masser 2003; Leao and Bishop 2004; Jantz et al 2010; Güneralp et al 2012).

However, early research suggests that in the difficult physical environment of most mountainous areas, the spatial patterns of cities are the result more of topography than of the internal socioeconomic structure (Dorward 1989). Some recent studies have shown that traditional urban–geographic models do not explain urban spatial expansion in China because of China's unique socioeconomic background, urban history, and rapid growth (Whitehand and Gu 2006; Lin 2007; Schneider et al 2015). Although urbanization in mountainous regions has been documented and studied in areas such as the European Alps, the southern Andes, Mexico, Colorado, and northeastern India (Riebsame et al 1996; Perlik and Messerli 2001; Romero and Ordenes 2004), little research has been done on the spatial patterns of mountain cities with their distinctive geography and rapid urban growth.

Therefore, this study aimed to reveal the major factors shaping the spatial pattern in small and medium-size mountain cities, through a series of structured spatial analyses and the use of an urban spatial growth model incorporating these major factors to understand the dynamics of Chinese mountain cities for planning purposes.

Data and study area

Study area

In Chinese studies, a "mountain city" has been typically defined quantitatively as a city with an average slope greater than 5% within a 1-km^2 urban area and an absolute 25-m difference in elevation within a 4-km^2 urban area (Zhen 2004). Based on this definition, this study focused on 5 small to medium-size mountain cities in different provinces with populations ranging from 40,000 to 500,000 (Table 1). The analysis introduced later was conducted on each city, but the city of Yibin is used as an example in this paper to illustrate the process of analysis.

Data sources

The study focused on 1960 to 2000, the years for which the datasets were most complete and during which rapid urbanization started to form a complex urban spatial pattern that differed from the traditional concentric form of urban expansion in western China (Schneider et al 2015). It drew on 3 major sources of data:

1. A set of 1:50,000 topographic survey maps from the 1960s, 1980s, and 1990s from the National Geomatics Center of China, for which the urban areas, surface water systems, land cover, and contour lines were digitized and converted into geographic information system (GIS) files;
2. Landsat satellite images of different cities around the year 2000, from which land use data were derived using a supervised classification approach in the ArcGIS program; and
3. City transportation and tourism maps from different times, which provided the boundaries of urban areas, road networks, and other information.

Definition of domain for spatial growth

It is almost impossible for a mountain city to expand continuously over the landscape because of physical barriers such as rivers and steep slopes. To analyze the spatial growth of a city, this study used the concept of "domain," defined as an area of land within which spatially continuous urban development is possible. A mountain city's domains are typically divided by physical barriers and linked by transportation corridors (Figure 1).

Factors affecting urban spatial growth

Urban spatial growth consists of a series of expansions of built areas over the landscape. A combination of topographic and physical conditions affects the spatial pattern of this expansion. This study focused on 3 major contributing factors—slope, accessibility, and land use type before development. (For this study, accessibility was

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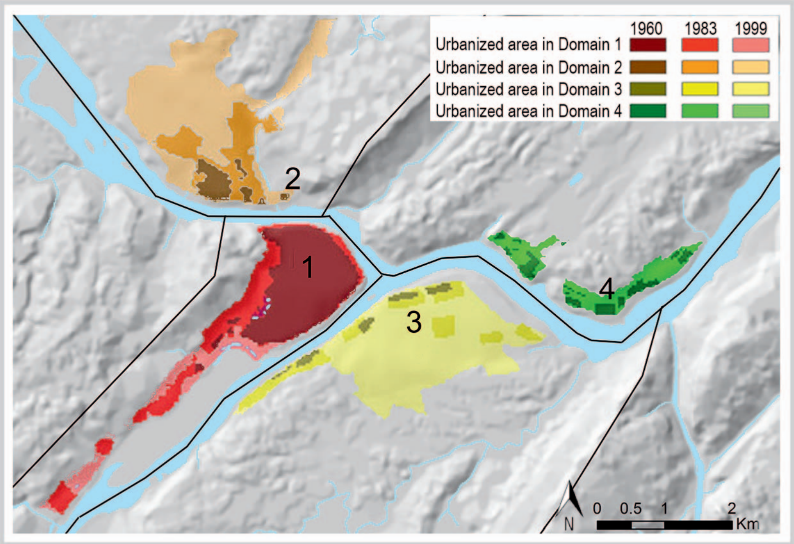
FIGURE 1 Illustration of the domain concept using Yibin as the example.



about distance from the city center. Because of the varied and sometimes difficult terrain, this was measured in terms of estimated travel time rather than strict physical distance.)

Slope

The cost of building construction increases as the topographic gradient increases, and a steep slope increases the risk of landslides and other natural disasters (Xu et al 2011). Thus, slope is often regarded as a limiting factor to urban development. The quantitative relationship between slope and urban area was studied by calculating the total amount of urban area on different grades of slopes in the city of Yibin (Figure 2A).

Development on land with a 5–15% slope was strong during 1960–1983, which suggests the old city was running out of buildable flat land. From 1983 to 1999, the city expanded evenly on different degrees of slope, suggesting that the city developed on a narrow strip of gentle slope because of limited buildable land.

The relationship between slope and urban development appears as an exponential curve. An exponential trend line was generated to best match each set of data. The R^2 value of the trend line in Figure 2A gradually gets closer to 1 from 1960 to 1999, which suggests the stronger exponential resistance that slope poses to urban development as the city approaches the limit of its land supply. This appears to be because the construction cost increases exponentially as the slope increases.

Travel time

Accessibility has long been an important factor affecting urban spatial growth (Hansen 1959), and it is often a major component in many simulation models (White et al 1997; Waddell 2002). Because of the topography of mountain cities, Cartesian distance often fails to represent accessibility correctly. Therefore, the shortest travel time by car from a potential new urban area to the city center via the existing road network was used to represent accessibility in this study. During the study time frame, the city center was easily identifiable as the location of the central business district and the civic center. The calculation was performed on the transportation network of the city with the network analysis function in ArcGIS.

The relationship between travel time and new urban area is shown in Figure 2B for all cities in the study. The amount of new urban area was greatest in the 5- to 10-minute zone and decreased evenly as the travel time increased. (Because of the smaller total area and limited available land, the 0- to 5-minute zone had less new urban area.)

However, travel time can be changed by new transportation infrastructure, and the amount of urban area in each time zone is limited by the amount of buildable area in that zone. The adoption of the domain concept thus helps further reveal the relationship between travel time and urban area across time and space (Figure 3). In 1960, most of the urban area was concentrated in Domain 1. There were few urban areas in domains 14 minutes or longer from the city center. Since 1960, urban development has spread to the periphery of Domain 1. Gradually, urban development reached the 14-minute zone, in which Domain 1 no longer had a travel time advantage over the other domains. In 1968, a bridge was built between Domains 1 and 2, and a new ferry line was established between Domains 1 and 3. These transportation improvements changed the spatial pattern

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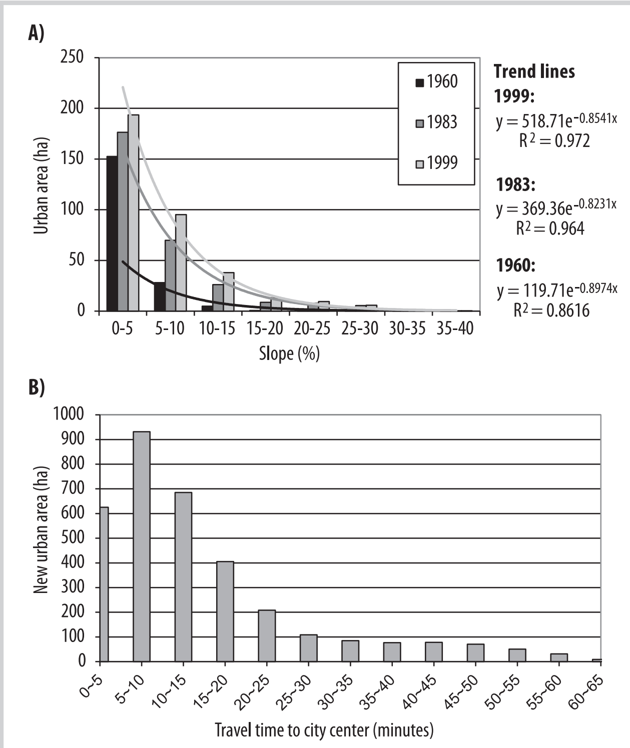
FIGURE 2 (A) Relationship between slope and urban area in Domain 1 of Yibin; (B) relationship between travel time and new urban area in all sample cities.



of travel times, and as a result, new development shifted to Domain 2. Domain 2 was almost filled up by urban development again between 1983 and 1999; another new bridge was built in 1990, allowing urban development to expand into Domain 3.

Land use

The analysis of the relationship between existing land use types and new urban area used the same approach as the analysis of slope. The newly developed urban areas between 2 time slices were overlaid with a land use map of the earlier stage to reveal associations between new urban area and land use types. The amount of new urban area on different land use is documented in Figure 4 for 4 of the 5 study cities for slightly different time frames ending in 1999.

Study results indicated that farmland and shrubland were most likely to be developed. However, this phenomenon was not universal across all sample cities. Further study of the original land use survey map indicated that the reason for this trend might simply be that farmland and shrubland were usually closer to the city. For example, in Dazhou, almost all land surrounding the urban area was either farmland or shrubland in 1960; in 1986, all surrounding land was farmland. Other land types, such as wetland and water, showed significant resistance to development for all cities and time frames analyzed.

Modeling urban spatial growth

Based on the analysis described earlier, a conceptual raster-based model was created of the process of urban spatial expansion in mountainous regions. Such a model provides a way of describing the interactions among different factors and projecting changes (Harris 2001). Besides showing the relationships between individual factors and urban spatial growth, the model can suggest answers to the following questions: (1) How do these factors collectively influence spatial growth? (2) How is the sequence of development governed in the process? (3) How could the model be used to predict spatial growth?

The model is based on the minimum cumulative resistance theory, in which the expansion of a geographic phenomenon over the landscape is regarded as a series of movements, which face different amounts of resistance in different parts of the landscape, toward areas with lower resistance. This resistance comprises a number of factors, including slope, land use type, and physical distance to the source of expansion; "cumulative resistance" is the sum of resistance from these factors (Knaapen et al 1992). During urban growth, while all lands around the existing urban area have the potential to be developed, the resistance to development varies. New urban development is most likely to occur on a site with minimum cumulative resistance. As suggested in the preceding analysis, the likelihood of lands to be developed is also affected by accessibility, which is represented by travel time to the city center in the study.

The algorithm of the model simulating this process is illustrated in Figure 5 using a hypothetical city under 2 scenarios: 1 without a bridge crossing the river that divides the city (Scenario 1, illustrated on the left of Figure 5) and 1 with a bridge (Scenario 2, illustrated on the right of Figure 5). The raster grid representing the city was divided into 42 cells, of which 9 were defined as existing urban areas and 12 would be chosen for a new urban area.

First, travel time was measured hypothetically as the minimum number of cells to the city center (Figure 5A). Next, a COSTDISTANCE function in the ArcGIS program was used to calculate the minimum cumulative resistance to development for each cell in the raster, given the hypothetical slope of the cell, land use type, and physical distance from each cell to the nearest urban area. Thus, the minimum cumulative resistance represented total cost to convert available land into urban area. The results varied, as shown in the chart of Figure 5B.

For each cell, minimum cumulative resistance and travel time to the city center were then compared and plotted for the primary domain (solid dots) and for 3 cells in another domain across the river from it (small circles). According to the analysis of the effect of travel time, new urban development can be expected to decrease as the

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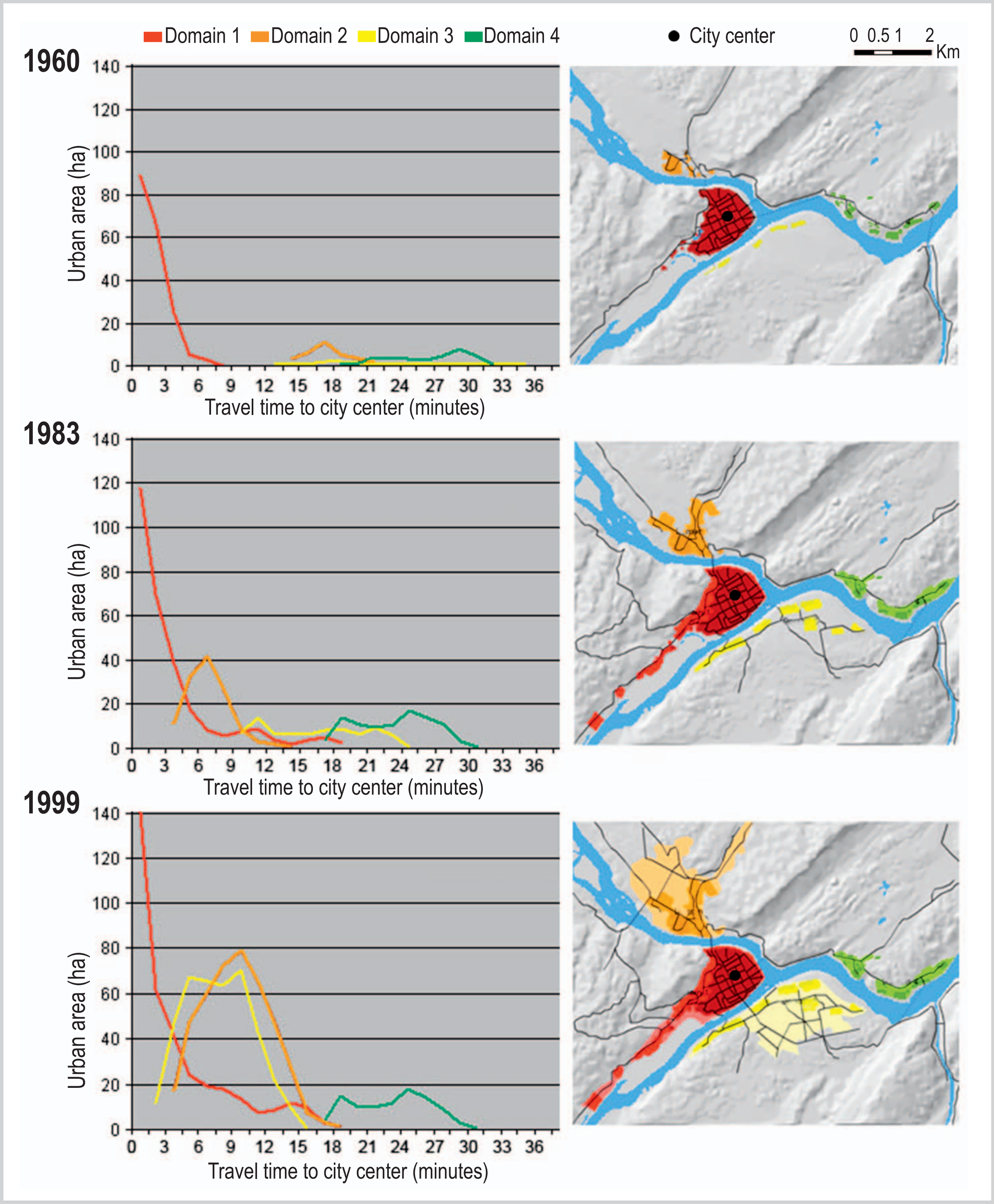
FIGURE 3 Relationship between travel time to the city center and urban area of Yibin in different domains and years.



travel time to the city center increases, so it can be assumed that the sequence and possibility of development is governed by accessibility. Thus, the cells most likely to be selected first for new urban area were those with the least cumulative resistance and greatest accessibility to the city center (as shown in Figure 5B), with expansion gradually moving into areas with greater resistance and less accessibility.

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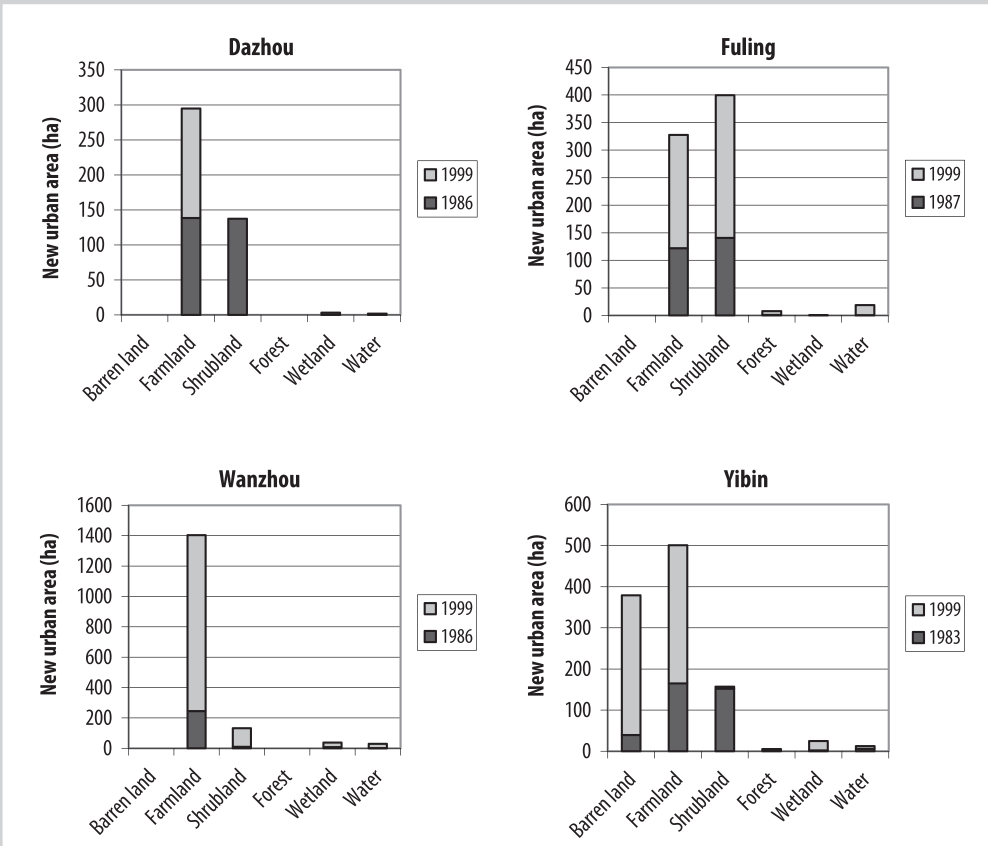
FIGURE 4 Amount of each land use or cover type that has been converted into new urban area. (The city of Changdu does not have complete land use and cover data and is therefore not shown.)



The selection process was represented as a line with a constant slope on the chart to select points (ie, cells on the maps) below it. The line moved up constantly on the chart until it reached f1 when enough points below were selected (Figure 5B, Scenario 1). In the end, 12 points were selected when the line reached travel time 6 (Figure 5B, C, Scenario 1; several points overlap on the chart, so only 10 points are visible). But when the selection line reached points with a travel time to the city center that was as great as those of the next available urban domain, continuous growth in the initial domain was no longer efficient. In the latter situation, it would be more efficient to build a new transportation corridor like a bridge to access more buildable and reachable lands in the second domain. This changed travel time values of those cells in the second domain, in 1 case to as low as travel time 3. Then, the selection process resumed on the chart until enough points were selected when the line reached f2. In the end, 12 cells had been selected when the line was short of travel time 6, with 1 cell in another domain (Figure 5B, C, Scenario 2).

While the analysis thus far provided a good general starting place, it was necessary to consider 2 additional issues:

1. The resistance of slope to urban development increases exponentially, as indicated earlier. To show the trend, the slope value was converted by an exponential function before being applied to the model as one element in the cumulative resistance. The calculation was as follows:

$$S_{\text{new}} = e^{(S_{\text{old}} \times a)}$$

where S_{new} is the newly calculated slope resistance, S_{old} is the slope value, and a is the slope resistance variable, which is explained by the exponential relationship between slope and new urban area.
2. The slope of the straight line used in the selection of cells on the chart is the intercept selection variable. If this variable is high, more cells with higher cumulative resistance will be selected, which means the city is likely to expand into steeper areas. If it is low, more cells with higher travel time will be selected, which means the city is likely to expand into less accessible areas.

Model testing

To test the conceptual urban spatial growth model and the conclusions of the preceding analysis, a GIS script in ArcGIS (Figure 6) was created to generate urban spatial growth scenarios, based on the amount of land developed

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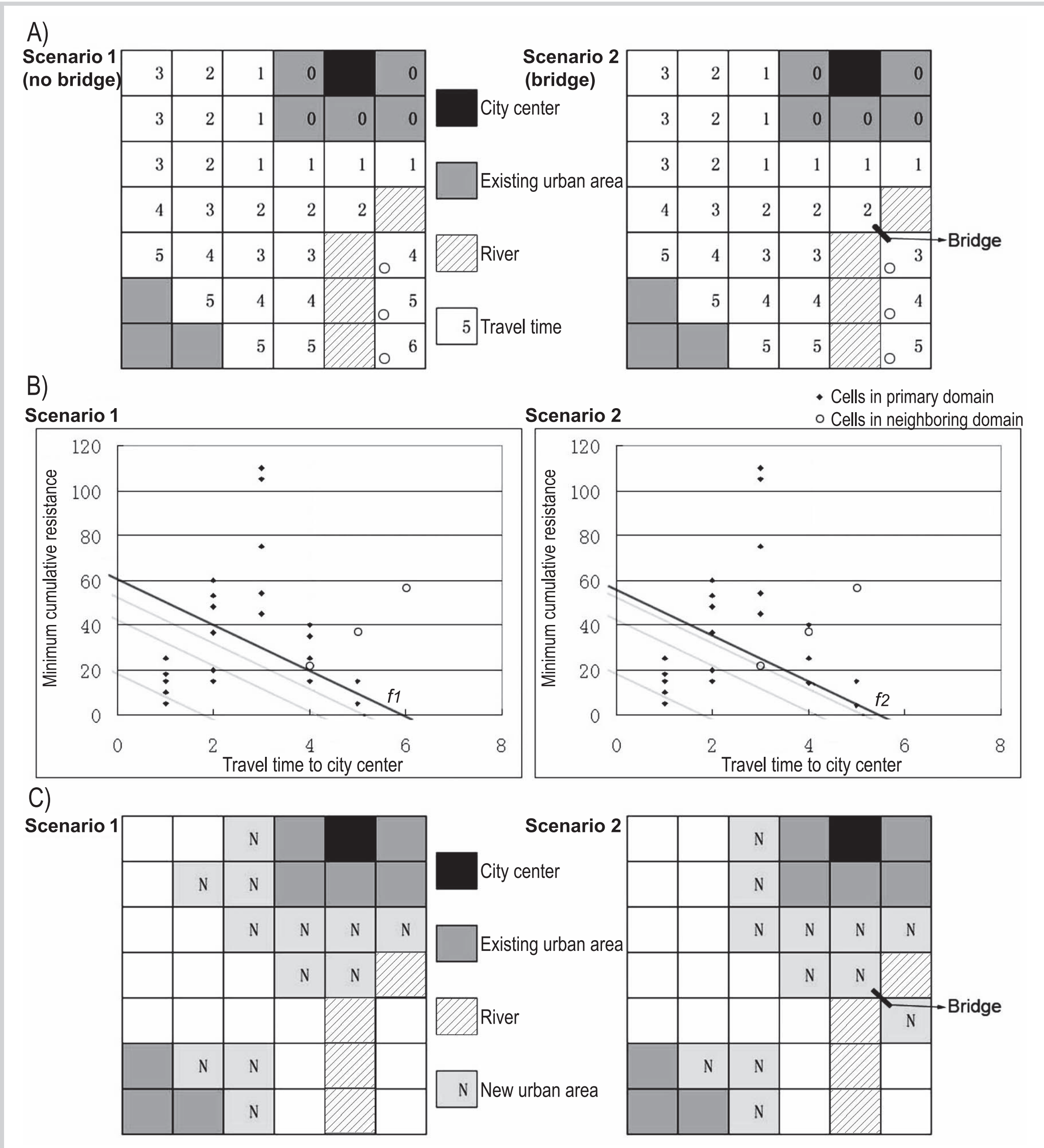
FIGURE 5 Theoretical illustration of urban spatial growth. (A) Travel time to city center; (B) Scatter plot of minimum cumulative resistance and travel time; (C) Result of selection. (For the purpose of illustration, travel time values and minimum cumulative cost values are hypothetical.)



between 2 specific years (in other words, the number of cells used for growth from the start year to the end year). The accuracy of the model was then tested by comparing its results with the urban area that was actually developed during the same period. Different combinations of the slope resistance and intercept selection variables were tested with an exhaustive search algorithm to find the combination that generated the most accurate outcome. The accuracy of the model was calculated as follows:

$$C = \frac{N_p}{N_s} \times 100\%$$

where C is the accuracy of the model, ranging from 0 to 100%; N_p is the number of cells predicted by the model and developed; and N_s is the total number of cells predicted by the model to be developed. Under this equation, when there are cells sharing the same minimum cumulative resistance value, all cells will be selected; therefore N_s is sometimes slightly larger than the number of cells used.

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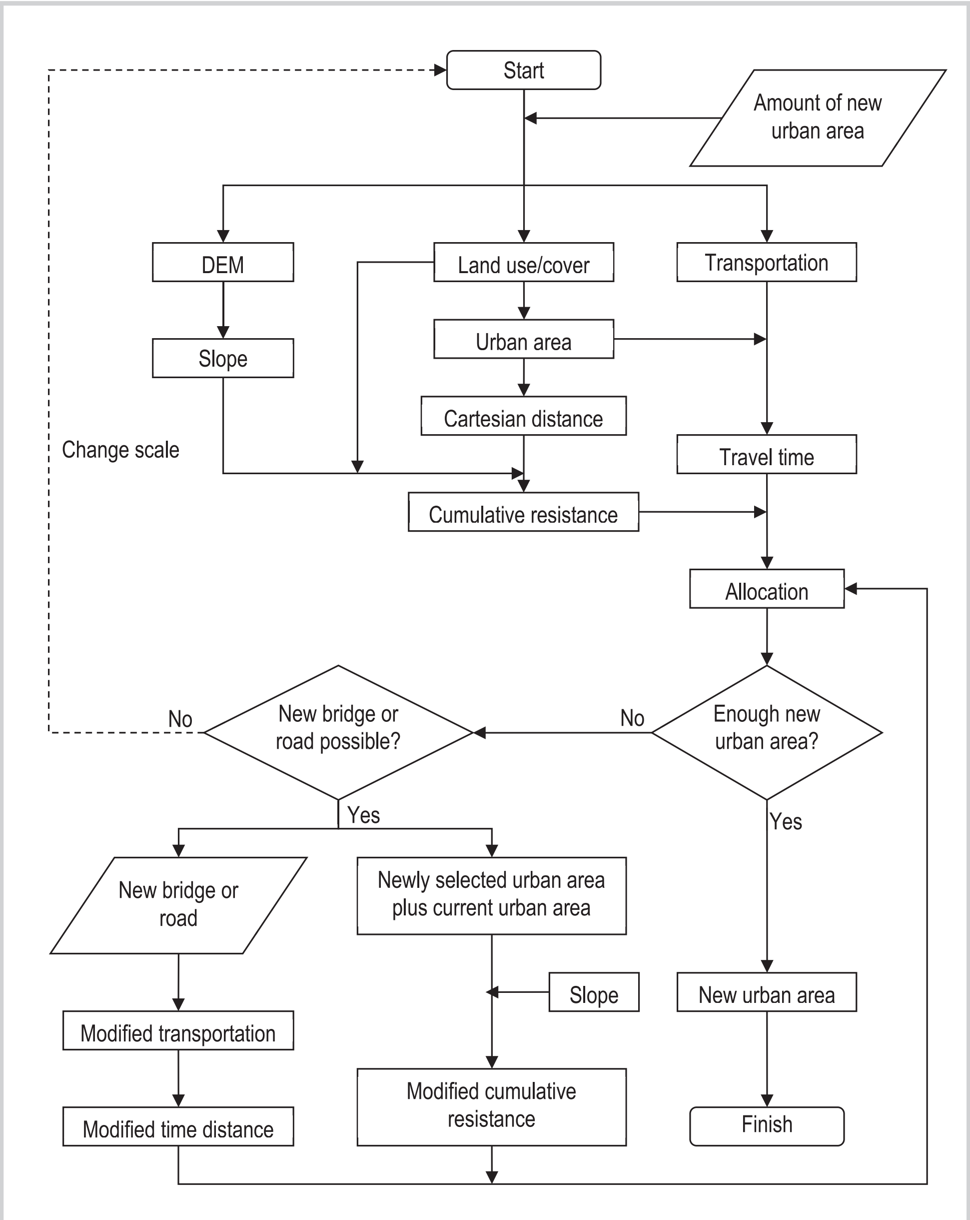
FIGURE 6 Flowchart of the urban growth model in GIS script. (DEM, digital elevation model. For allocation, cells with the least minimum cumulative resistance and least travel time to the city center were selected sequentially until enough cells for the new urban area were selected or the travel time did not have a relative advantage over another domain.)



The resulting combination of variables from the most accurate modeling result for each of the 5 sample cities is presented in Table 2, and Figure 7 shows the spatial results from the model.

Observations and discussion

In the results, the slope resistance variable was quite close across different cities, suggesting that it is a common practice to limit urban development at certain slopes. What varied the most among these variables was the intercept selection variable, which represents the difference in weighting between slope and accessibility when urban development is decided in different cities.

The results suggest that this urban spatial growth model is generally useful in understanding the spatial growth of mountain cities for the following reasons:

1. The model correctly predicts the general spatial pattern of future urban development with different factors, including slope, accessibility, and land use. For example, the model correctly predicted the direction of major urban growth for Yibin and Changdu, which confirms that these factors affect the spatial pattern collectively, as the analyses have suggested.

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TABLE 2 Results of the urban growth model.

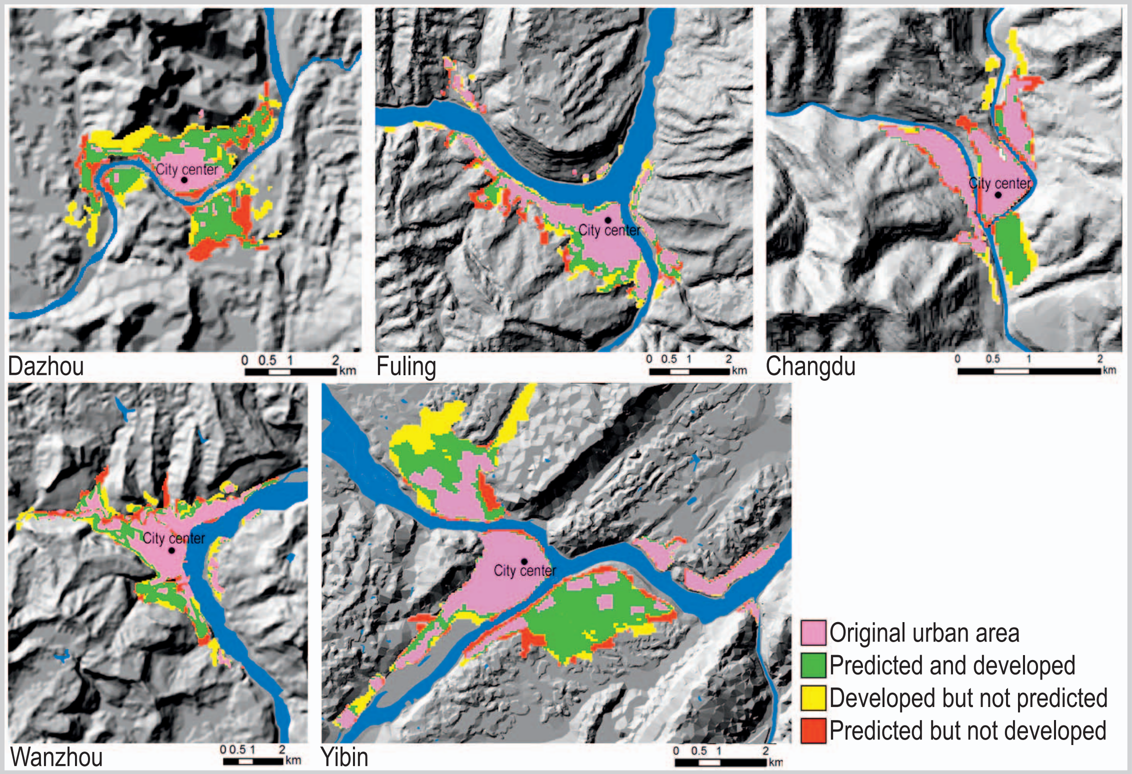
City	Variable		Cells developed	Cells predicted to be developed[a)]	Cells predicted and developed[b)]	Accuracy (%)
	Slope resistance	Intercept selection				
Wanzhou	0.9	0.7	1649	1630	1092	67
Dazhou	1.1	0.3	1688	1582	1139	72
Fuling	1.0	0.3	932	903	650	72
Yibin	0.9	0.3	2784	2530	1948	77
Changdu	1.1	0.7	290	273	161	59

[a)] One cell equals 0.25 hectare.
[b)] Shown in green in Figure 7.

2. The model reveals how the sequence of development is governed by accessibility, as can be seen in the result for Dazhou, where growth has spread to approximately the same travel time zones in neighboring domains (as shown in Figure 7).
3. Areas where development occurred even though it was not predicted by the model were scattered at the outskirts without a systematic pattern of distribution. This suggests that the model has captured the major factors contributing to urbanization, although there might be minor contributing factors in each city affecting this complex process.

Some large areas of unpredicted development occurred mostly because big infrastructure projects were not included in the model. For example, a new railway station was built to the northwest of Yibin between 1990 and 2000, which generated large-scale development there that was not predicted by the model. The model performed with the least accuracy for the smallest city, Changdu, while accuracy levels were similar for the medium-size cities including Wanzhou, Dazhou, Yibin,

FIGURE 7 Outcome maps produced by the urban spatial growth model.



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and Fuling. This might suggest that the model fits medium-size mountain cities better than others.

This spatial growth model has strength in projecting the spatial pattern of future urban growth in mountainous regions. Challenges related to mountain topography often make transportation infrastructure improvement projects more expensive. This model helps evaluate the development potentials in different domains, thus helping with infrastructure planning. It is also able to project future interactions between the urban development and the surrounding landscape, enabling further research into the impact of development on ecologic processes. Most importantly, it can generate different development scenarios based on the scale of development, choice of infrastructure improvement, importance of accessibility, and other values so that different consequences can be evaluated. It provides a way for spatial tradeoffs between future urban development and conservation to be negotiated by different stakeholders. This tool and associated impact assessment can assist planners in mountain cities to make informed planning decisions that effectively address the new challenges facing the fragile mountain environment.

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