Research on spatial resilience characteristics and response mechanism of Chengdu-Chongqing urban agglomeration based on power-law

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Abstract. Urban agglomeration is the spatial organization form of urban development and the main carrier of population, economy and information gathering to promote regional coordinated development. Therefore, it is important to research the sustainable development of urban agglomeration. Focus on the scientific issue of the relationship between power-law distribution structure of spatial elements and spatial resilience of urban agglomeration; using the number of urban permanent population and urban built-up area size as the key spatial elements of Chengdu-Chongqing urban agglomeration, firstly, we discussed the spatial-temporal evolution law of power-law characteristics of key spatial elements of Chengdu-Chongqing urban agglomeration. Secondly, we revealed the response mechanism of spatial resilience to power-law distribution of key spatial elements of Chengdu-Chongqing urban agglomeration. The conclusions as following: (1) The spatial resilience of Chengdu-Chongqing urban agglomeration characterized as "concentration" dominated by large cities. (2) The spatial resilience and Pareto distribution of Chengdu-Chongqing urban agglomeration have a remarkable and stable response relationship. (3) In order to maximize the spatial resilience of Chengdu-Chongqing urban agglomeration, it is urgent to control the number of urban permanent population and built-up area scale of large cities.

1. Introduction
"Building inclusive, safe, disaster-resilient and sustainable urban agglomeration and human settlements" is not only the requirement of cities and urban agglomeration in the 2030 Agenda for sustainable development, but also the embodiment of international urban development agreements such as the Sendai Framework for Disaster Risk Reduction and the New Urban Agenda [1]. From the perspective of the current research on resilience of urban agglomerations at home and abroad, it mainly focuses on the non-material aspects related to environment, society and system of urban agglomerations [2], and the physical aspects related to urban buildings, energy systems, regional infrastructure, etc. [3]. In contrast, there are few studies on the stability, adaptability, self-organization and spatial resilience of urban agglomerations facing natural disasters and manmade emergencies. According to the classical theory of urban geography, the closer the distribution structure of urban spatial elements is to the Pareto distribution of Zipf law (ideal power-law distribution structure), the stronger the resilience properties such as network connectivity [4-5], stability [6-7], modularity [8-10] and self-organization ability [11-12] will be in the spatial structure of this urban agglomeration. That is
to say, in an urban agglomeration system, the closer each key element (such as population, land use and roads, etc.) that forms an urban agglomeration is to Zipf distribution law in terms of scale layout and level, the higher resilience the urban agglomeration system has to cope with disasters and adapt to risks. Therefore, in order to realize the optimization of internal structure of space governance, it should to better to research on urban agglomeration spatial distribution characteristic of key elements and clarify response mechanism of urban agglomeration spatial resilience. Moreover, it has important theoretical and practical significance to achieve the urban sustainable and high quality development. Finally, it has gradually become the focus and hotspot in the research of the urban geography and urban agglomeration [13-14].

Research on the relationship between power-law distribution and spatial resilience of urban agglomeration, we found that the development of urban agglomerations has a significant scale and hierarchy structure [15-16]. The structure also has significant power-law relations with many spatial elements in urban agglomeration [17-18]. Based on the spatial elements of London, New York, Paris, Tokyo and other urban agglomerations, it is found that the distribution of subway stations, density of residential and working areas, commuter flow, and accessible facilities in cities of different grades all conform to the power-law distribution principle [19-20]. The analysis of energy economic indicators such as energy consumption and greenhouse gas emissions in urban agglomerations also shows obvious power law phenomenon with different scales [21]. Salat summarized the reasons why urban agglomerations with power-law distribution are more resilient, namely, spatial fractal geometry is one of the reasons why power-law urban agglomeration has more resilient development ability”. Fractal geometry with power law distribution makes sub-modules in urban agglomeration system relatively independent and loosely connected. The former can protect each sub-module from the adverse effects of high connectivity. The latter makes information and resource flow in the system controllable [22]. Urban agglomeration with power-law distribution of spatial elements has obvious modularization characteristics, and is a harmonious whole that can operate independently and work together so it is more sustainable and resilient.

The spatial distribution of urban systems in China generally conforms to the power-law distribution characteristics. Fanjie et al. compared the regional differences and spatial evolution of China's and India's urbanization and urban system, and found that the urban systems in both countries, mainly large and medium-sized cities, were in line with power-law distribution characteristics [23]. Gu Chaolin used urban population distribution to prove the power law characteristics of urban scale structure and spatial pattern [24-25]. In the latest study on the resilience ranking of China's three major urban agglomerations (Beijing-Tianjin-Hebei, Yangtze River Delta and Pearl River Delta), the Yangtze River Delta ranks the first in terms of its urban agglomeration resilience due to the agglomeration effect of its power-law distribution characteristics [26].

Due to spatial complexity and urban heterogeneity, the urban spatial structure of the Beijing-Tianjin-Hebei urban agglomeration does not conform to the power-law perfectly. As a result, the central area of the Beijing-Tianjin-Hebei urban agglomeration is overpopulated, with no buffer space and disorderly expansion of the marginal area, and the spatial resilience of the urban agglomeration is low [27]. Peng Xiongliang [28] discussed the resilience spatial strategy of the Guangdong-Hong Kong-Macao Greater Bay Area from the perspective of adapting to typhoon climate, and believed that the adaptability and resilience of the Greater Bay area should be better to improve from the aspects of hierarchical governance, ecological security, engineering defense, and self-organization ability.

Therefore, takes Chengdu-Chongqing urban agglomeration as the research area, and the number of urban population and urban built-up area as the key spatial research elements. By analyzing the spatial resilience level and change characteristics of Chengdu-Chongqing urban agglomeration, this study reveals its spatial resilience characteristics. This paper explores the spatial response mechanism of Chengdu-Chongqing urban agglomeration based on power law through the multiple response relationship between spatial resilience characteristics and "unit-element to multiple elements".
2. Study data and methods

2.1. Overview of the research area
Chengdu-Chongqing urban agglomeration is an important platform for western development, strategic support for the Yangtze River Economic Belt, and an important demonstration area for the country to promote new urbanization. Therefore, the research on spatial resilience characteristics, response mechanism and optimization strategy of Chengdu-Chongqing urban agglomerations is the hotspot and frontier of the research on urbanization and sustainable development, and a powerful supplement to the bottleneck of spatial resilience construction in regional planning and territorial space planning at the level of urban agglomerations.

2.2. Data sources and processing
According to the research framework, relevant data of key spatial elements of Chengdu-Chongqing urban agglomeration were collected through various forms such as statistical yearbook, questionnaire, and in-depth interview and so on, and then a standardized database is established. The data used in this paper mainly include the number of urban permanent population and the urban built-up area size from 2011a to 2018a. The data concerned Sichuan province was gotten from Sichuan annual Report of construction statistics, and others from Statistical yearbook and statistical bulletin of Chongqing municipality and its districts and counties.

![Location map of Chengdu-Chongqing urban agglomeration](image)

Figure 1. Location map of Chengdu-Chongqing urban agglomeration

3. Research model construction

3.1. Analysis of spatial-temporal evolution of power-law characteristics of key spatial elements
The time panel data of two categories of key spatial elements in each prefecture-level city sorted according to the numerical values to obtain the bit-scale distribution database of all key spatial elements of Chengdu-Chongqing urban agglomeration.

The logarithmic transformation model of power-law used to calculate the change of power-law characteristic index of key space elements. According to the calculation results, the power-law distribution of key spatial elements divided into three categories: (1) Balanced, (2) Concentrated, (3) Decentralised. Though space superposition of the distribution characteristics of each research element
in time series, judge the type and change trend of each key spatial elements, so as to reflect the evolution law of key spatial elements in Chengdu-Chongqing urban agglomeration.

\[ \log P_{(j,t)} = \log P_{(i,t)} - q_{(i,t)} \log R_{(j,t)} \]  

(1)

3.2. Response mechanism analysis method of spatial resilience to power law structure of key spatial elements in urban agglomerations

3.2.1. Analysis of the response relationship between single factors. With Pareto distribution curve of single element \( S_{qi} \) as the independent variable, \( q_i \) is one of the two Pareto distribution index for the urban population and urban built-up area, \( i = 1, 2 \), and power law distribution of single element \( U_y \) as the dependent variable, we established the model of the unary response relation of the key spatial elements (single element) to Pareto distribution \( U_y = f(S_{qi}) \) to measure the response equation and response curve between independent and dependent value. The expression is:

\[ U_y = \beta_0 + \beta_1 S_{qi} + \beta_2 S_{qi}^2 + \beta_3 S_{qi}^3 \]  

(2)

3.2.2. Analysis of the response relationship between multi-factors. Taking Pareto distribution of various key spatial elements \( S_q \) as independent variable and the spatial resilience system \( U_y \) of Chengdu-Chongqing urban agglomeration as the dependent variable. We established the multi-factor response relationship model \( U_y = f(S_q) \) to quantitatively express the multi-factor response relationship. The basic model is as follows:

\[ U_y = \beta_0 + \beta_1 S_q + \beta_2 S_q \]  

(3)

The value of \( q_1 \) and \( q_2 \) represent the two types of key space element respectively. \( \beta_0 \) is the constant term, \( \beta_i \) is the parameter. The relationship between \( U_y \) and \( S_q \) is established, and the relationship characteristics between the elements of the spatial elements of the urban agglomeration are reflected in the analysis of the coefficients \( \beta_1 \), \( \beta_2 \) and \( \beta_3 \), which are the characteristics of the relationship between the space resilience and the key space elements.

3.2.3. Analysis of the overall response of Chengdu-Chongqing agglomeration. Based on single factors and multi-factor response relationships, the Pareto distribution curve \( S_q \) and power law distribution curve \( U_y \) were obtained by the weighted average of various key spatial elements. \( S_q \) as the independent variable and \( U_y \) as the dependent variable, the overall response model of spatial resilience is power-law distribution structure of key spatial elements in Chengdu-Chongqing urban agglomeration was established. Essentially, this single element response relationship can be modeled using formula (2). By judging the characteristics index of spatial resilience from 2010a to 2018a, urban agglomeration is divided into three types: (1) Balanced, (2) Centralized and (3) Decentralized.

4. Results

4.1. Power-law index of urban permanent population and built-up area

4.1.1. Analysis of power-law exponential. The rank-size distribution of population dimension of spatial resilience is a power function with \( R^2 \) between 0.8954-0.9228 and the power-law index \( |q| \) between -1.268 and -1.407 (See in Figure 2). \(|q| > 1\) indicates that the urban permanent population distribution is relatively centralized, the urban permanent population scale in larger cities is too high, and the population of small and medium-sized cities has not reached the optimal scale. The development trend of \(|q|\) is far away from one, which shows that the population permanent distribution tends to be more concentrated than decentralized. In the future, the development of urban population will still maintain the trend of continuous increase of urban population in high order. That is to say, among the key elements of the spatial resilience, the power-law distribution of the urban
permanent population does not strictly obey the Pareto distribution, and shows the agglomeration trend of large city leading.

4.1.2. Analysis of power-law exponential change trend.

(1) The value of $|q|$ gradually decreases and approaches 1 from 2011 to 2014. It indicates that dispersed forces are greater than concentrated forces in the order, scale distribution of urban built-up area, and tend to be Pareto distribution. In addition, the middle and lower rank cities develop faster than the higher rank cities in the key spatial factor of built-up area.

(2) The value of $|q|$ gradually grows larger and moves away from 1 during 2015 to 2018. The power of the centralization is greater than the dispersion of the rank-size distribution characteristics of urban permanent population scale and urban built-up area size. In this stage, the degree of urban primacy continues to strengthen. The number of permanent residents and the size of built-up areas in the higher-order cities exceed the ideal threshold, which leads to the prominent polarization effect. While the number of permanent residents and the size of built-up areas of middle-sized and small cities in the lower rank is insufficient. In other words, among the key spatial elements, the power-law distribution characteristics of urban resident population scale and urban built-up area size showed the development trend of "concentration".

Table 1. The power-law distribution characteristics of key spatial elements and spatial resilience from 2011-2018

| Key spatial elements                              | $R^2$          | Status value of $q$ | Dynamic tendency of $q$ | Power law distribution type |
|--------------------------------------------------|----------------|---------------------|-------------------------|-----------------------------|
| Urban permanent population                        | 0.8954-0.9228  | $q_{0.0}>1$         | $\Delta q_{t}>0$       | Concentrated                |
| Urban build-up area                               | 0.8928-0.9237  | $q_{0.0}>1$         | $\Delta q_{t}>0$       | Concentrated                |
| Weighted of urban permanent population and build-up area | 0.8968-0.9228  | $q_{0.0}>1$         | $\Delta q_{t}>0$       | Concentrated                |

4.2. Spatial resilience characteristics of urban agglomeration

The spatial resilience change characteristics based on urban permanent population scale and urban built-up area size are power function distribution with $R^2$ between 0.8964-0.9228 and power law index ($U$) between -1.263 and -1.176 (See in Figure 4). According to the specific values and development trend, Chengdu-Chongqing urban agglomeration spatial resilience development can be divided into two stages: In the first stage from 2011 to 2014, the value of $U$ ranged from -1.218 to -1.176. $|U|$ was greater than one but decreased gradually. $|U|$ is always greater than one, which indicates that the centering effect of big cities for the spatial resilience in higher rank of Chengdu-Chongqing urban agglomeration is too high, while the comprehensive efficiency of the spatial resilience of small and medium-sized cities in lower rank is weak. Therefore, the spatial resilience of urban agglomeration does not reach the ideal state.

In addition, the spatial resilience formed by the weighted scale distribution of urban permanent population scale and urban built-up area size is "concentrated". However, $|U|$ decreases gradually in this stage, indicating that the strength of spatial resilience efficiency tends to dispersed rather than concentrated, and the "relatively concentrated" state gradually weakens, belonging to the "concentrated" type dominated by small cities in this stage. In the second stage from 2015 to 2018, the values of $U$ ranged from -1.181 to -1.263, and $|U|$ was greater than one and gradually increased. The difference from the first stage are the value of $|U|$ grow bigger, showing the spatial resilience more "concentration" in large cities in a higher rank. In general, the spatial resilience of Chengdu-Chongqing urban agglomeration is characterized by "concentration" dominated by large cities from 2011 to 2018.
4.3. Pareto response Mechanism of urban agglomeration

4.3.1. Single factor response. The response between the rank-size distribution characteristics and Pareto distribution of urban permanent population scale from 2011 to 2018 was a unitary linear regression model (see in Table 2). The value of Sig. of the regression curve is less than 0.01, and $R^2$ is between 0.919-0.936. The rank-size distribution feature of spatial resilience of urban permanent residents scale ($U_1$) has a significant response to Pareto population rank-size distribution ($S_1$). From the value of Bate that the significance of this response relationship is still rising. Similarly, the response between the power-law characteristics of the rank-size distribution of urban built-up area size and the Pareto urban built-up area distribution is also a unitary linear regression model from 2011 to 2018 (see in Table 2). The value of Sig. of the regression curve is less than 0.01, and $R^2$ is between 0.93-0.948. Through the comparative analysis of the static values of $R^2$ and Beta, the significance of response between urban built-up area size ($U_2$) and Pareto distribution is higher than that of urban permanent population scale ($S_2$). However, through the dynamic comparison of $R^2$ and Beta sequence values, the significance of response between urban built-up area ($U_2$) and Pareto distribution has a tendency of slow decline, which is the opposite of urban permanent population.

Table 2. The response model of urban permanent population and urban built-up area.

| Year | $U_1$ | $R^2$ | Beta | $U_2$ | $R^2$ | Beta |
|------|-------|-------|------|-------|-------|------|
| 2011 | -130.379+0.982$S_1$ | 0.922 | 0.96 | -62.075+1.022$S_2$ | 0.947 | 0.973 |
| 2012 | -134.138+0.978$S_1$ | 0.921 | 0.96 | -68.792+1.020$S_2$ | 0.948 | 0.974 |
| 2013 | -137.166+0.976$S_1$ | 0.920 | 0.959 | -68.239+1.009$S_2$ | 0.946 | 0.972 |
| 2014 | -139.780+0.976$S_1$ | 0.919 | 0.959 | -74.831+1.021$S_2$ | 0.942 | 0.971 |
| 2015 | -146.395+0.978$S_1$ | 0.920 | 0.959 | -83.129+1.014$S_2$ | 0.944 | 0.971 |
| 2016 | -155.616+1.002$S_1$ | 0.932 | 0.966 | -99.313+1.054$S_2$ | 0.93 | 0.965 |
| 2017 | -153.530+1.008$S_1$ | 0.936 | 0.968 | -106.816+1.048$S_2$ | 0.935 | 0.967 |
| 2018 | -162.760+1.012$S_1$ | 0.936 | 0.967 | -120.156+1.041$S_2$ | 0.942 | 0.971 |

4.3.2. Multiple factors response. It is a bivariate linear regression model of the response relation between spatial resilience ($U_y$) and the Pareto distribution of population ($S_1$) and build-up area ($S_2$) (Table 3). The value of Sig. of the regression curve is all less than 0.01, and $R^2$ is between 0.944 and 0.968. Spatial resilience ($U_y$) of Chengdu-Chongqing urban agglomeration has a remarkable response relation to Pareto distribution ($S_1$), and the value of $U_y$ still strengthening. Through the value of Beta, the same as the single factor response is that the response of urban built-up area size to spatial resilience response still tends to strengthen slightly higher than that of urban permanent population scale. The difference from single factor is that the explanatory power of urban built-up area size to spatial resilience response still tends to strengthen in multi-factor, while the explanatory power of urban resident population scale tends to slow down.

4.3.3. The overall response. The response is the single regression model between spatial resilience ($U_y$) and Pareto distribution ($S_1$) (See in Table 3). The value of Sig. of the regression curve is less than 0.01; $R^2$ is between 0.944 and 0.954, which shows that the response has the trend of decline. While the result is consistent with the development trend of power-law index, the value is far away from one, which leads in the weak risk of spatial resilience. Therefore, it is scientific to guide the planning and construction of spatial resilience through Pareto distribution principle.

Table 3. Response Model of Urban agglomeration Spatial Resilience and Pareto Distribution.

| Year | Spatial resilience of Multiple factors response | $R^2$ | Beta ($S_1$) | Beta ($S_2$) | Spatial resilience of overall response | $R^2$ | Beta ($S_1$) |
|------|-----------------------------------------------|-------|-------------|-------------|--------------------------------------|-------|-------------|
| 2011 | -98.842+0.424$S_1$+0.617$S_2$ | 0.858 | 0.496 | 0.488 | -0.685+1.684$S_1$ | 0.951 | 0.975 |

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### 5. Conclusion

1. The power-law index of the key spatial elements of Chengdu-Chongqing urban agglomeration is greater than one. Therefore, spatial resilience is centralized dominated by large cities. The change of power-law index of key spatial elements is greater than zero, so the development of spatial resilience presents a downward trend.

2. The spatial resilience and Pareto distribution of Chengdu-Chongqing urban agglomeration have a significant response relationship overall. Therefore, it is scientific to guide the planning and construction of spatial resilience through Pareto distribution principle.

3. The "centralization" development trend of urban permanent population and urban built-up area is likely to reduce the spatial resilience of Chengdu-Chongqing urban agglomeration. Therefore, to maximize the spatial resilience, it is urgent to control the urban permanent population scale and urban built-up area size of large cities, improve the population and activate the built-up area scale small and medium-sized cities in the lower rank of the urban system.

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| Year | \( U_y = \) | \( Sq_1 \) | \( Sq_2 \) | \( Sq_3 \) | \( Sq_4 \) |
|------|-------------|---------|---------|---------|---------|
| 2012 | \(-104.42 + 0.442 Sq_1 + 0.588 Sq_2\) | 0.860 | 0.507 | 0.479 |
| 2013 | \(-106.168 + 0.445 Sq_1 + 0.578 Sq_2\) | 0.920 | 0.506 | 0.478 |
| 2014 | \(-110.292 + 0.454 Sq_1 + 0.568 Sq_2\) | 0.919 | 0.506 | 0.478 |
| 2015 | \(-118.49 + 0.455 Sq_1 + 0.565 Sq_2\) | 0.920 | 0.498 | 0.485 |
| 2016 | \(-131.769 + 0.47 Sq_1 + 0.579 Sq_2\) | 0.932 | 0.483 | 0.502 |
| 2017 | \(-130.639 + 0.456 Sq_1 + 0.579 Sq_2\) | 0.936 | 0.452 | 0.522 |
| 2018 | \(-142.197 + 0.471 Sq_1 + 0.561 Sq_2\) | 0.936 | 0.454 | 0.520 |
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