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ORIGINAL PAPER

Resilience assessment of metro stations against rainstorm disaster based on cloud model: a case study in Chongqing, China

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Abstract
Extremely heavy rainfall has posed a significant hazard to urban growth as the most common and disaster-prone natural calamity. Due to its unique geographical location, the metro system is more vulnerable to waterlogging caused by rainstorm disaster. Research on resilience to natural disasters has attracted extensive attention in recent years. However, few studies have focused on the resilience of the metro system against rainstorms. Therefore, this paper aims to develop an assessment model for evaluating metro stations' resilience levels. Twenty factors are carried out from dimensions of resistance, recovery and adaptation. The methods of ordered binary comparison, entropy weight and cloud model are proposed to build the assessment model. Then, taking Chongqing metro system in china as a case study, the resilience level of 13 metro stations is calculated. Radar charts from dimensions of resistance, recovery, and adaptation are created to propose recommendations for improving metro stations' resilience against rainstorms, providing a reference for the sustainable development of the metro system. The case study of the Chongqing metro system in china demonstrates that the assessment model can effectively evaluate the resilience level of metro stations and can be used in other infrastructures under natural disasters for resilience assessment.

Keywords Rainstorm disaster · Resilience · Metro stations · Assessment · Cloud model

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1 Introduction

In the background of global climate change, various natural disasters such as floods, typhoons, drought, hailstorms, earthquakes, and low-temperature freezing have severely affected people's lives with different frequencies and degrees (Lyu et al. 2020). Extreme heavy rainfall is the most common and disaster-prone natural calamity among them (Srinivas et al. 2018). Its increasing frequency has threatened urban development and the safety of residents' lives and properties globally (Zhang et al. 2021; Li et al. 2019; Wang et al. 2020a). Meanwhile, the metro system has gradually become the most significant transportation component for sustainable development in urban areas due to its large capacity, energy-saving, environmental protection, better safety and high punctuality (Shen et al. 2015; Lin et al. 2021). Compared to road traffic, such as ground transportation and elevated transportation, the metro system is more vulnerable to waterlogging caused by extremely heavy rainfall due to its unique geographical location and characteristics, i.e., exposure of exits and enclosed structures in the relatively low elevation. (Lyu et al. 2019a, 2019b, 2020; Wang et al. 2020b). Recently, metro systems worldwide have been forced to suspend operations because of extremely heavy rainfall. For example, in 2012, heavy rainfall hit seven metro lines in New York, seriously impacting the metro operation (Blake et al. 2013). In 2016, because of the high-intensity extreme heavy rainfall outbreak, many metro stations were flooded in China and stopped operating, such as those in Shanghai, Guangzhou and Wuhan (Lyu et al. 2018, 2019a). In 2021, a severe rainstorm hit Henan Province in China, causing the metro systems to be severely flooded. Even the passengers were trapped in the underground space in Zhengzhou, where the maximum rainfall reached 201.9 mm in an hour. The increasing frequency of extremely heavy rainfall has seriously threatened the regular operation of the metro system. Therefore, scientifically and rationally developing prevention work of waterlogging in the metro system to improve the reliability of metro operation and the travel safety of residents under the damage of extremely heavy rainfall has become an urgent problem that needs to be resolved.

Research has been carried out from different perspectives to protect the metro system from damages caused by the rainstorm disaster. For example, Derrible et al. (2010) developed indicators to measure state, form, and structure by studying 33 metro networks worldwide and analysing rainstorms' impacts on the metro system. Aoki et al. (2016) proposed anti-inundation measures such as developing and installing waterproofing doors for metro stations in Tokyo. Wu et al. (2020) constructed an evaluation index system of emergency plans for waterlogging disasters. They selected Huilong Road West Station Project in Chengdu to verify the feasibility of the group decision-making method. Wang et al. (2020b) proposed an emergency decision-making method based on regret theory to assess the emergency decision-making of the metro system in different rainstorm scenarios. Liu et al. (2020a) investigated the vulnerability of the metro system under the background of rainstorms based on the accessibility metrics proposed. Lyu et al. (2018) constructed a flood risk assessment structure of a metro system, including average rainfall, slope, land use and so on, from dimensions of hazard, exposure and vulnerability, and analysed the flood risk of the metro system by using analytic hierarchy process (AHP) and interval AHP methods. Furthermore, fuzzy AHP, fuzzy clustering analysis and triangular fuzzy number-based AHP are also applied to assess the flood risk of the metro system (Lyu et al. 2019a, 2020).

Nevertheless, with the frequent occurrence of natural disasters, more and more scholars have explored the ability to resist natural disasters from the resilience perspective to develop disaster prevention and mitigation management. Resilience is defined initially as a measure of the persistence and the ability to absorb systems disturbances while maintaining the relationship between the population and the variables by Holling and applied in the ecological field (Xiao et al. 2020). In recent years, research on resilience assessment has attracted extensive attention. For example, Li et al. (2019) constructed a flood resilience evaluation system covering the dimensions of resistance, coping and recovery, and adaptation. Zhang et al. (2021) diagnosed the resilience to flooding disasters in 31 cities in China based on the entropy-weighting TOPSIS method. Chen et al. (2021a) investigated the relationship between city resilience against COVID-19 and factors including the virus, city agglomeration characteristics, and healthcare resources. By applying structural equation modelling, Guo et al. (2020) proposed that new information channels contribute to city resilience in the background of the typhoon. Vona et al. (2018) built a resilience model to quantify the city's resilience under an earthquake. For the resilience of the metro system, Deloukas et al. (2017) conceptualized the resilience of the metro system and developed resilience management guidelines by considering static and dynamic resilience. Zhang et al. (2018) established a large-scale resilience framework for the metro system and verified its practicality by using the Shanghai metro as a case study. Integrating the network topological and passenger volume characteristics, Lu (2018) raised the resilience to assess the model of the metro system in response to emergencies to quantify the metro resilience.

However, few studies concentrated on the resilience of the metro system against rainstorm disaster. Goldbeck et al. (2019) developed an integrated, dynamic modelling and simulation framework to assess the resilience of the metro system in London to a local flooding incident. Zhou et al. (2021b) analyzed the spatio-temporal characteristics of passenger flow under rainstorms by utilizing big data and introduced the meteorological warning signals and ridership resilience curve to analyse the resilience of the operation of the metro system.

Based on the above discussion, the existing research mainly concentrated on urban resilience assessment. A mechanism is required to help analyse the metro system's resilience to improve stability and safety. Therefore, this study aims to (1) develop an assessment model to evaluate the level of resilience of metro stations based on the cloud model; (2) demonstrate the application of the model through the case study of the metro stations in the city of Chongqing in China; (3) analyse the calculation results of the metro stations through radar chart to reflect the comparison between comprehensive resilience level and resilience level in three dimensions of resistance, recovery and adaptation.

The contributions of this paper are as follows. First, given the continually growing concerns about natural disasters (Lyu et al. 2019a, b), a resilience perspective to metro stations in the context of the rainstorm disaster can effectively advance the literature on disaster prevention and mitigation management. Second, a multi-dimension, a multi-method evaluation framework is proposed. In particular, the development of the social perspective dimension and the application of the cloud model in metro resilience are both bold attempts and significant explorations. Third, suggestions are beneficial to increase public knowledge of how to deal with the devastation caused by rainstorm disasters in metropolitan areas and the planning and design of the metro's upcoming construction.

2 Methodology

This study combines the ordered binary comparison, entropy weight, and cloud models to develop the resilience assessment model. The ordered binary comparison method and entropy weight method are used to calculate the weights of factors. The cloud model is used to realize the comprehensive resilience evaluation.

2.1 Ordered binary comparison method

In the subjective weighting methods, the criteria weights and the alternatives' scores mainly depend on the decision makers' judgements and preferences via pairwise comparisons, the potential uncertainty of which is considered the prime disadvantage of the subjective methods (Sahoo et al. 2016; Sitorus and Brito-Parada 2022). As a subjective weighting method, the ordered binary comparison method combines qualitative ranking and quantitative scaling, aiming to distinguish the importance of factors by repeatedly comparing every two factors to identify the ranks and weights of factors. The method can effectively solve the problem of fuzzy set category, and the specific steps are as follows (Xu 2018):

Step 1. Establishment of scaling matrix based on importance.

Assume a set of factors to be compared in the system, shown as $D = \{d_1, d_2, d_3, \cdots, d_m\}$, where d_i represents i - th factor, $i = 1, 2, \cdots, m$. Then, the importance degree can be measured by comparing one factor to another in the D. If d_k is more important than d_l, $e_{kl} = 1$ and $elk = 0$. When the importance of d_k is equal to d_l, $e_{kl} = 0.5$ and $e_{lk} = 0.5$. Similarly, if d_k is less important than d_l, $e_{kl} = 0$ and $e_{lk} = 1$. Among them, $kl = 1, 2, \cdots, m$. According to the comparison results, the scaling matrix based on importance can be expressed as:

$$E = \begin{bmatrix} e_{11} & e_{12} & \cdots & e_{1m} \\ e_{21} & e_{22} & \cdots & e_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ e_{m1} & e_{m2} & \cdots & e_{mm} \end{bmatrix} = \left(e_{kl}\right) m \times m \tag{1}$$

Step 2. Consistency check of scaling matrix.

Suppose thinking contradictions exist in binary comparison of the importance of factors, the consistency check of the scaling matrix should be raised, that is, $e_{hk} > e_{hl}$ while $e_{lk} > e_{kl}$, and $e_{hk} < e_{hl}$ while $e_{lk} < e_{kl}$, and if e_{hk}=e_{hl}, e_{lk}=e_{kl}= 0.5. If the scaling matrix fails the consistency check, in that case, there is a contradiction in the thinking process of judgement, and the scaling matrix needs to be adjusted until the consistency check is met.

Step 3. Judgement of importance level.

By summing the elements in each row of the scaling matrix that passed the consistency check, the importance level can be proposed based on the size of the values.

Step 4. Determination of factor weight.

Fuzziness is essential for humans to make binary comparisons of things using empirical knowledge. Therefore, this study introduces tone operators, fuzzy scale values, and membership values to calculate the weights in Table 1.

As is shown in Table 1, tone operators are divided into ten categories. In contrast, a tone operator corresponds to two membership values. According to the importance level, a weight vector can be carried out by comparing the relationship of tone operator between the most critical factor and others and transforming to relative membership values. After normalizing, the weight vector can be expressed as $w = \{w_1, w_2, \cdots, w_m\}$ eventually.

2.2 Entropy weight method

The entropy weight method is an objective weighting method that utilizes the amount of information provided by the entropy value to determine the weight of each factor. In information theory, entropy measures the degree of disorder in the system while extracting helpful information from the data. Therefore, according to the idea of entropy, the amount and quality of the information in the process determine the accuracy and reliability of the decision-making. In the process of identifying weights, a larger difference in the values of a factor means a more significant amount of information, which represents that the factor deserves a higher weight (Liu and Lin, 2019; Yan et al. 2021). Conversely, a smaller difference means less information, representing a lower weight. The method has been widely applied to analyse problems in the city system (Shen et al. 2016; Huang et al. 2018; Yan et al. 2021). The specific steps are as follows (Li et al. 2020; Yan et al. 2021):

Step 1. Establishment of a data matrix.

Assume that there are m research objects and n factors so that the data matrix can be expressed as:

$$Y = \begin{bmatrix} y_{11} & y_{12} & \cdots & y_{1n} \\ y_{21} & y_{22} & \cdots & y_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ y_{m1} & y_{m2} & \cdots & y_{mn} \end{bmatrix} \tag{2}$$

Table 1 Correspondence between tone operators, fuzzy scale values and membership values

Tone operator	Fuzzy scale value	Membership value	Tone operator	Fuzzy scale value	Membership value
As well	0.500	1.000	Fully	0.800	0.250
	0.525	0.905		0.825	0.212
A little	0.550	0.818	Highly	0.850	0.176
	0.575	0.739		0.875	0.143
Slightly	0.600	0.667	Completely	0.900	0.111
	0.625	0.600		0.925	0.081
Relatively	0.650	0.538	Extremely	0.950	0.053
	0.675	0.481		0.975	0.026
Obviously	0.700	0.429	Unmatched	1.000	0.000

where y_{ij} represents the data value of the j - th factor in the i - th research object.
Step 2. Normalization of all data.

The evaluation factors are divided into positive factors and negative factors. For those positive factors, a larger value indicates a better performance. The normalized value can be calculated as follows:

$$y'_{ij} = \frac{y_{ij} - \min(y_j)}{\max(y_j) - \min(y_j)} \tag{3}$$

For those negative factors, a smaller value indicates a better performance. The normalized value can be calculated as follows:

$$y'_{ij} = \frac{\max(y_j) - y_{ij}}{\max(y_j) - \min(y_j)} \tag{4}$$

where $\min(y_j)$ and $\max(y_j)$ are the minimum value and maximum value for the factor j.
Step 3. Calculation of the entropy weight.

As for the evaluation matrix after normalization, firstly, the contribution value of each factor in each object should be calculated as follows:

$$p_{ij} = \frac{y'_{ij}}{\sum_{i=1}^{m} y'_{ij}} \tag{5}$$

Then, based on contribution values, the entropy value for each factor can be calculated as follows:

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^{m} p_{ij} \ln p_{ij} \tag{6}$$

Finally, the entropy weight of each factor can be calculated as follows:

$$\omega_j = \frac{1 - e_j}{n - \sum_{j=1}^{n} e_j} \tag{7}$$

2.3 Cloud model

As an important communication tool, natural language contains too many uncertainties in human's daily life, such as "good-looking", "excellent", and other words. Different people have different opinions on this type of expression. Therefore, to describe this type of language more clearly, the cloud model was proposed to realize the transformation between qualitative concepts and quantitative values (Xie et al. 2021). The cloud model has been widely used to evaluate natural disasters and city systems (Xie et al. 2021, Wang et al. 2021, Zhou et al. 2021a). This study briefly introduces the definition, digital characteristics, and cloud generator of the cloud model.

2.3.1 Definition of cloud model

Assuming that U is a quantitative domain represented by exact values, and C is a qualitative concept on U. x, the quantitative value is a random implementation of the qualitative concept C, and $x \in U$. A random number $\mu(x)$ is the membership degree of C in x, and $\mu(x) \in [0,1]$, with a stable tendency, that is, $\mu(x) : U \rightarrow [0,1]$, $\forall x \in U$, $x \rightarrow \mu(x)$. The distribution of x on the domain U is called cloud, and the random number $\mu(x)$ represents certainties of C in x.

2.3.2 Digital characteristics of cloud model

The digital characteristics of the cloud reflect the quantitative characteristics of the qualitative concept. Therefore, the characteristics of the concept expressed by the cloud model can be reflected by the digital characteristics of the cloud, namely expectation, entropy, and hyper-entropy, which can be expressed as C(Ex,En,He).

Expectation (Ex): the most representative point of the qualitative in domain is the central value.

Entropy (En): the measurement of the degree of uncertainty of qualitative concepts and representative of the probability and ambiguity of qualitative concepts, which can symbolize the degree of dispersion of the qualitative concept and reflect the qualitative concept cloud drop's value range the domain.

Hyper-entropy (He): the measurement of the uncertainty of entropy, that is, the entropy of entropy, representing the degree of dispersion of all cloud droplets.

2.3.3 Cloud generator of cloud model

A cloud generator is an important tool to realize the conversion between the digital characteristics of the cloud and the cloud drop and between the qualitative concept and the quantitative value. According to the different generation conditions, the cloud generator is divided into three categories: forward, reverse, and conditional. And conditional cloud generator can be divided into X-condition and Y-condition cloud generators. This study mainly uses the forward and X-condition cloud generators in the subsequent empirical analysis process, explaining the forward and the X-condition cloud generator.

The forward cloud generator is a mapping from qualitative concepts to quantitative values. When the cloud's digital characteristics are known, inputting digital characteristics and the number of cloud droplets, the coordinates of each cloud droplet in the number domain, and the degree of certainty that each cloud droplet represents a concept, are outputted, as is shown in Fig. 1.

The algorithm of the forward cloud generator is as follows (Wang et al. 2021):

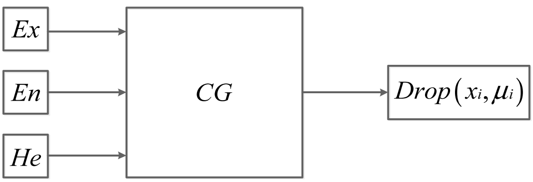

Fig. 1 Forward cloud generator

(a) an average random number E'_{ni} is generated with E_n as the expectation and He^2 as the standard deviation, that is, $E'_{ni} = NORM(En, He^2)$.
(b) an average random number x_i is generated with Ex as the expectation and E'^2_{ni} as the standard deviation, that is, $x_i = NORM(E_n, E'^2_{ni})$.
(c) The membership is calculated by $\mu_i = e^{-\frac{(x_i - Ex)^2}{2E'^2_{ni}}}$.
(d) $drop(x_i, \mu_i)$ generated is a cloud drop in the domain, and x_i is the value after transforming from qualitative concept, and μ_i is the value of the membership of x_i.
(e) Repeat steps a) to e) until N cloud droplets are produced.

The X-condition cloud generator is a cloud generator in which all cloud droplets are finally distributed on the vertical line of the cloud by setting the condition in the domain. That is $x = x_0$ when the digital characteristics of the cloud are known, as shown in Fig. 2.

The algorithm of the X-condition is as follows:

(a) an average random number E'_{ni} is generated with En as the expectation and He^2 as the standard deviation, that is, $E'_{ni} = NORM(En, He^2)$.
(b) The membership is calculated by $\mu_i = e^{-\frac{(x_0 - Ex)^2}{2En'^2_i}}$.
(c) Generate cloud drops corresponding to a specific value x_o, that is, $drop(x_0, \mu_i)$.

3 Development of resilience assessment model

3.1 Selection resilience factors of metro stations

Currently, there is no uniform standard for the dimensional classification of resilience. For the metro system, Liu et al. (2020b) constructed an evaluation index system containing defence, recovery and adaptive to assess the waterlogging disaster resilience capability. Lyu et al. (2020) conducted an inundation risk assessment of the metro system from hazard, exposure and vulnerability dimensions. Xu and Chopra (2022) proposed a four-stage resilience cycle, including preparedness, robustness, recoverability and adaptation, to develop resilience analysis. In other related fields, such as urban resilience and transportation resilience, Chen et al. (2020) put forward that urban resilience should be considered from dimensions of resistance, adaptability and recovery. Hoterová and Chovančíková (2021) pointed out that robustness, recoverability and adaptability were the critical elements of resilience in the transportation infrastructure system.

Therefore, this study defines resilience as resistance, recovery, and adaptation. So, in this study, factors affecting the resilience of metro stations under rainstorm disasters

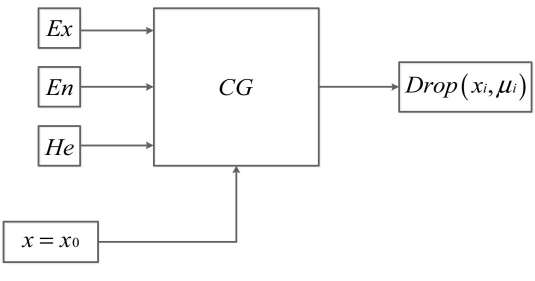

Fig. 2 X-condition cloud generator

from dimensions of resistance, recovery, and adaptation are selected. Based on the review of the existing literature involving resilience indicators (Lyu et al. 2018, 2019a, 2020; Wu et al. 2020; Wang et al. 2019; Quan et al. 2011; Zhu et al. 2018), resilience factors under the three dimensions are identified.

Resistance can be considered as the ability to resist or defend against damage from waterlogging caused by extremely heavy rainfall through the metro system's engineering facilities and the metro station's external environment. The engineering facilities and external environment have direct and indirect impacts on the metro's drainage capacity under rainstorms, further affecting the resilience of the metro system. Therefore, six factors type of exit (X1), the step height of exit (X2), drainage capacity of metro station (X3), the elevation of metro station (X4), slope of metro station (X5) and municipal drainage capacity (X6) are selected in the dimension of resistance.

The recovery process usually contains two scopes, i.e., reorganizing and maximizing the use of internal assets and importing external resources (Xu and Chopra, 2022). This research mainly considers external resources, e.g., external rescue from the central government, neighbouring provinces or the international community (Chen et al. 2020). Therefore, recovery in this research is defined as the ability to rescue the metro system and help it return to its original state after waterlogging caused by extremely heavy rainfall from a social perspective. Considering that population, economy and infrastructure are the main elements in the socioeconomic system, eight factors gross domestic product (X7), Per capital disposable income of urban residents (X8), general public budgetary expenditure (X9), investment in fixed assets (X10), resident population (X11), employment of on-post urban non-private units (X12), medical, technical personnel (X13) and the number of health care institutions (X14) are proposed in the dimension of recovery.

Adaptation is the objective ability of that relative department of the metro system to adapt to the rainstorm disaster in terms of emergency equipment and emergency plans when facing waterlogging caused by extremely heavy rainfall. Therefore, six factors completeness of pre-disaster system plans (X15), completeness of emergency plans in disasters (X16), completeness of post-disaster learning programs (X17), integrity of monitoring and warning equipment (X18), the integrity of emergency supplies and equipment (X19) and integrity of disaster assessment equipment (X20) are selected in the dimension of adaptation.

The total 20 factors are shown in Table 2.

3.2 Construction Resilience Assessment Model Based on Cloud Model

Based on the above methods and factors, an assessment resilience model of metro stations is constructed, as shown in Fig. 3.

From Fig. 3, the assessment of the resilience of metro stations mainly involves four steps:

(1) Through scoring by experts and collecting objective data, the evaluation data of factors from dimensions of resistance, recovery and adaptation can be obtained to form the data matrix of resilience assessment.
(2) Based on the data matrix, all weights can be calculated using the binary comparison and entropy weight methods to form the weight matrix.

Table 2 Factors affecting Metro resilience under rainstorms

Target	Dimension	Factor	Unit	Direction
Metro resilience	Resistance	Type of exit (X1)	–	+
		The step height of exit (X2)	–	+
		Drainage capacity of the metro station (X3)	–	+
		Elevation of metro station (X4)	–	+
		The slope of the metro station (X5)	–	+
		Municipal drainage capacity (X6)	–	+
	Recovery	Gross domestic product (X7)	10,000 CNY	+
		Per capital disposable income of urban residents (X8)	CNY	+
		General public budgetary expenditure (X9)	10,000 CNY	+
		Investment in fixed assets (X10)	10,000CNY	+
		Resident population (X11)	10,000 persons	-
		Employment of on-post urban non-private units (X12)	10,000 persons	+
		Medical, technical personnel (X13)	Person	+
		Number of health care institutions (X14)	Unit	+
	Adaptation	Completeness of pre-disaster system plans (X15)	–	+
		Completeness of emergency plans in disasters (X16)	–	+
		Completeness of post-disaster learning programs (X17)	–	+
		Integrity of monitoring and warning equipment (X18)	–	+
		Integrity of emergency supplies and equipment (X19)	–	+
		Integrity of disaster assessment equipment (X20)	–	+

(3) Based on the concept and connotation of the cloud model, the digital characteristics of the cloud and the theoretical basis of the cloud generator, the steps of calculation of the membership matrix of factors can be carried out as follows:

(a) A comment set contains five levels which are low level (I), lower level (II), medium level (III), higher level (IV) and high level (V), which are raised to evaluate the resilience of the metro stations.
(b) According to the level division of the comment set, this model identifies the level interval and digital characteristics of factors based on the data matrix. Taking a positive factor as an example, the maximum and minimum values are taken as the *Ex* of the level of V and I, respectively. The middle values of the level intervals are taken as the *Ex* of the level of II, III, and IV. Moreover, 1/2.355 times the level interval distance is proposed as the *En*, and a practical value of 0.1 is taken as the *He*.
(c) Input the data matrix into an X-condition generator. The membership matrix can be obtained from all the factors.

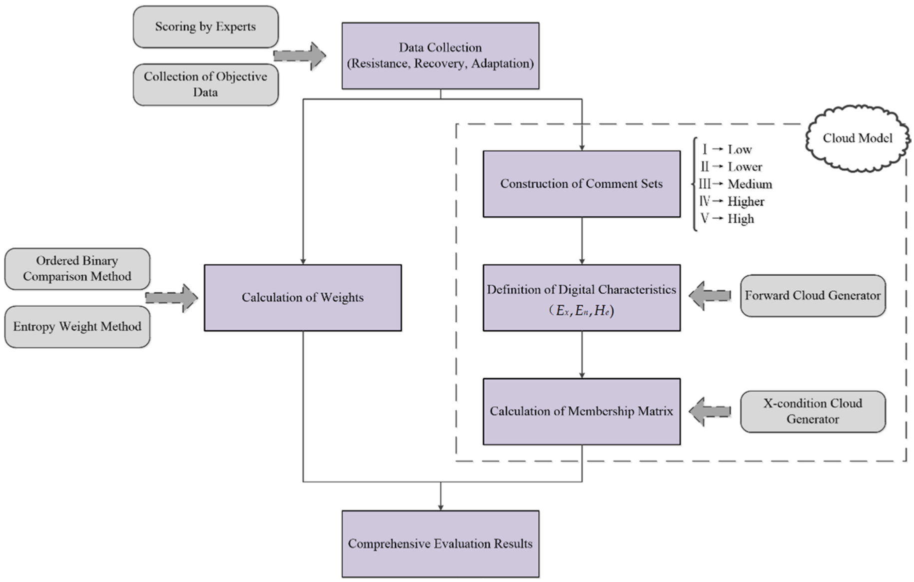

Fig. 3 Assessment resilience model of metro stations

(4) By multiplying the weight matrix and the membership matrix, the membership values of the five levels from the view of an object can be calculated to assess the resilience of the metro system under a rainstorm, referring to the comment set.

4 Case study

4.1 Research objects

Chongqing's metro system in China is selected as a case study to demonstrate the assessment of the model's application. The first line of the Chongqing metro system was opened for operation on June 18, 2005. As of January 2021, 9 metro lines were opened for operation, with 369.56 km and 190 stations. Meanwhile, in 2020, the total passenger traffic of Chongqing in the metro system reached 1.042 million, with average daily passenger traffic of 2.855 million and maximum passenger traffic of 3.872 million. The line network diagram of the Chongqing Metro System is shown in Fig. 4.

Comprehensively considering the number of interchange lines, the passenger flow, and the links to other transportation modes, 13 metro stations involving seven districts and eight metro lines are selected for further analysis, as shown in Table 3.

4.2 Research data

The data in this study were mainly acquired from experts' scores or publicly available data. In the dimension of resistance and adaptation, the data of X2, X4 and X5 seem to be accessible but private, and others are qualitative and unavailable. In addition, there are multiple exits in a certain metro station, and data of different exits are not at the

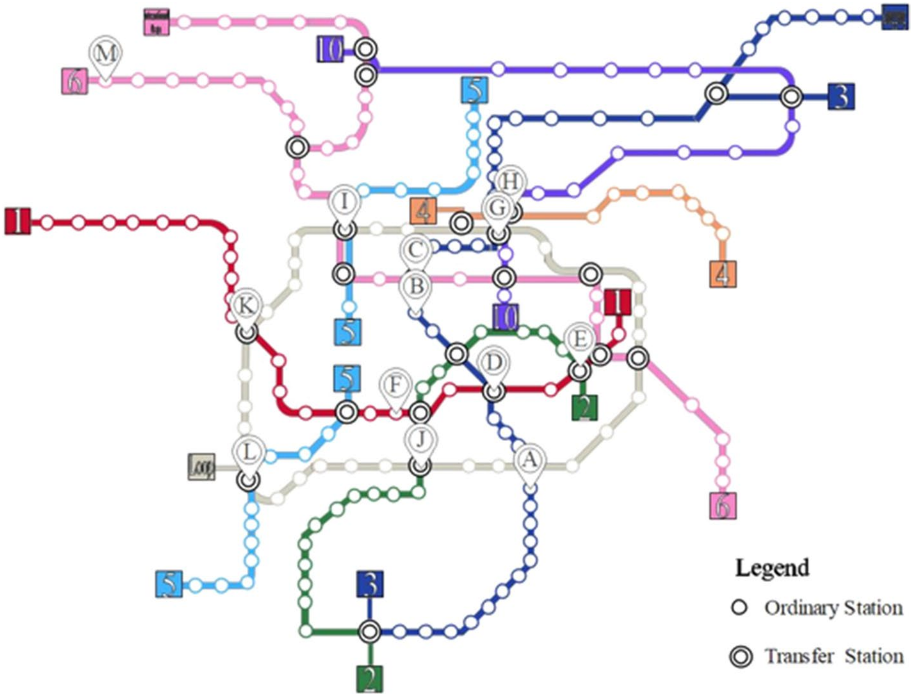

Fig. 4 The line network diagram of the Chongqing metro system

Table 3 Research objects

Station	District	Line
Nanping Station (A in Fig. 4)	Nanan District	Line 3
Guanyinqiao Station (B in Fig. 4)	Jiangbei District	Line 3
Hongqihegou Station (C in Fig. 4)	Jiangbei District	Line 3, Line 6
Lianglukou Station (D in Fig. 4)	Yuzhong District	Line 1, Line 3
Jiaochangkou Station (E in Fig. 4)	Yuzhong District	Line 1, Line 2
Shiyoulu Station (F in Fig. 4)	Yuzhong District	Line 1
Chongqing North Station South Square (G in Fig. 4)	Yubei District	Line 3, Line 10, Loop Line
Chongqing North Station North Square (H in Fig. 4)	Yubei District	Line 4, Line 10
Ranjiaba Station (I in Fig. 4)	Yubei District	Line 5, Line 6, Loop Line
Xiejiawan Station (J in Fig. 4)	Jiulongpo District	Loop Line
Shapingba Station (K in Fig. 4)	Shapingba District	Line 1, Loop Line
Chongqing West Station (L in Fig. 4)	Shapingba District	Line 5, Loop Line
Beibei Station (M in Fig. 4)	Beibei District	Line 6

same level, even a huge difference, so determining the uniform criteria is another complex issue. Considering the principles of comprehensive evaluation and issues above, three experts are invited to score 1–5 on the 12 factors, and 1–5 represent extremely bad, poor, medium, well, and excellent, respectively, in resistance and adaptation, and the profile information of experts are shown in Table 4.

In the dimension of recovery, the public data on all the factors can be obtained from *Chongqing Statistical Yearbook 2020*. Details of the scoring data and public data are shown in Appendix A.

4.3 Calculation results

4.3.1 Calculation results of weights

According to steps (1) and (2) in the assessment model, the weights of factors in the dimension of resistance and adaptation are calculated by using an ordered binary comparison combining experts' suggestions and the weights of factors in the recovery dimension by using the entropy weight method as shown in Table 5.

From Table 5, dimensions of resistance, recovery and adaptation account for 1/3, respectively. In the dimension of resistance, the type of exit stands first. The drainage capacity of the metro station and municipal drainage capacity is located at the end, with values of 0.068 and 0.050. Moreover, the value of the other three factors is 0.055, lying in a position of medium importance. In the dimension of recovery, the average weight of eight factors is 0.042, and the maximum weight and minimum weight belong to investment in fixed assets and gross domestic product, respectively, whose values are 0.061 and 0.025. As for the other six factors, the weights of per capital disposable income of urban residents and the number of health care institutions are higher than the average weight. The weights of the other four factors are lower than the average weight. Among six factors in the dimension of adaptation, the weight of completeness of pre-disaster system plans and monitoring and warning equipment integrity is 0.048. The weight of the other four factors is 0.059.

4.3.2 Calculation results of resilience level

After calculating the weights, based on step (3) in the assessment model, the comment set of resilience, the level interval and digital characteristics of factors are carried out. Taking positive factors, including the type of exit from the dimension of resistance, the gross domestic product from the dimension of recovery, completeness of pre-disaster system plans from the dimension of adaptation, and negative factor resident population from recovery as the example, the digital characteristics can be calculated, as shown in Table 6.

Table 4 Profile information of experts

Expert	Occupation	Education	Work experience	Employer
A	Station manager	Master's degree	9 years	Chongqing Rail Transit (Group) Co., Ltd., Chongqing, China
B	Station operator	Bachelor's degree	8 years	Chongqing Rail Transit (Group) Co., Ltd., Chongqing, China
C	Professor	Doctoral degree	12 years	Chongqing University, China

Table 5 Weights of factors

Dimension	Weight	Code of factor	Weight
Resistance	1/3	X1	0.068
		X2	0.055
		X3	0.050
		X4	0.055
		X5	0.055
		X6	0.050
Recovery	1/3	X7	0.025
		X8	0.042
		X9	0.031
		X10	0.061
		X11	0.039
		X12	0.040
		X13	0.038
		X14	0.056
Adaptation	1/3	X15	0.048
		X16	0.059
		X17	0.059
		X18	0.048
		X19	0.059
		X20	0.059

From Table 6, the digital characteristics of the type of exit and completeness of pre-disaster system plans can be expressed as I (1.000, 0.425, 0.100), II (2.000, 0.425, 0.100), III (3.000, 0.425, 0.100), IV (4.000, 0.425, 0.100), V (5.000, 0.425, 0.100). The digital characteristics of the gross domestic product can be represented as I (524,980, 1,906,311, 0.100), II (5,014,343, 1,906,311, 0.100), III (9,503,706, 1,906,311, 0.100), IV (13,993,068, 1,906,311, 0.100), V (18,482,431, 1,906,311, 0.100), and the one of the resident population can be expressed as I (168.350, 15.902, 0.100), II (130.900, 15.902, 0.100), III (93.450, 15.902, 0.100), IV (56.000, 15.902, 0.100), V (18.550, 15.902, 0.100).

According to the digital characteristics, the normal cloud diagram of the type of exit, gross domestic product, completeness of pre-disaster system plans and negative factor resident population can be drawn out using matlab2017, shown in Fig. 5.

Based on the X-condition cloud generator, taking Nanping Station as the example, the membership results of all the factors in the Nanping Station can be calculated using matlab2017, shown in Table 7. The specific algorithm procedures are shown in Appendix B.

From Table 7, among all the factors, the type of exit takes the maximum membership value of 0.7012 in level V, so the type of exit belongs to level V of resilience. Similarly, per capital disposable income of urban residents, the completeness of post-disaster learning programs, and the integrity of emergency supplies and equipment belong to the resilience level V of resilience. Furthermore, the step height of the exit, the slope of the metro station, the completeness of pre-disaster system plans, the completeness of emergency plans in disasters, the integrity of monitoring and warning equipment and the integrity of disaster assessment equipment belong to the level IV of resilience. The metro station's drainage capacity, the metro station's elevation, gross domestic product, general public budgetary

Table 6 Digital characteristics of factors

Type of exit (X1)					
Level	I	II	III	IV	V
Interval	[1,1.5)	[1.5,2.5)	[2.5,3. 5)	[3.5,4.5)	[4.5,5]
Ex	1	2	3	4	5
En	0.425	0.425	0.425	0.425	0.425
He	0.1	0.1	0.1	0.1	0.1
Gross domestic product (X7)					
Level	I	II	III	IV	V
Interval	[524980,2,769,661)	[2769661,7,259,024)	[7259024,11,748,387)	[11748387,16,237,750)	[16237750,18482431]
Ex	524,980	5,014,343	9,503,706	13,993,068	18,482,431
En	1,906,311	1,906,311	1,906,311	1,906,311	1,906,311
He	0.100	0.100	0.100	0.100	0.100
Resident population (X11)					
Level	I	II	III	IV	V
Interval	[168.35,149.625)	[149.625,112.175)	[112.175,74.725)	[74.725,37.275)	[37.275,18.55]
Ex	168.350	130.900	93.450	56.000	18.550
En	15.902	15.902	15.902	15.902	15.902
He	0.100	0.100	0.100	0.100	0.100
Completeness of pre-disaster system plans (X15)					
Level	I	II	III	IV	V
Interval	[1,1.5)	[1.5,2.5)	[2.5,3. 5)	[3.5,4.5)	[4.5,5]
Ex	1.000	2.000	3.000	4.000	5.000
En	0.425	0.425	0.425	0.425	0.425
He	0.100	0.100	0.100	0.100	0.100

expenditure, and resident population belong to the level III of resilience. The rest of the factors belong to the level II of resilience, which means a lower level of resilience.

According to step (4) in the assessment model, the membership values of the five levels of all the stations can be calculated by multiplying the weight matrix and the membership matrix. The specific membership results of all the stations are shown in Table 8.

From Table 8, the membership values of Nanping Station are 0.0193, 0.2244, 0.2601, 0.3599 and 0.2072 in the levels I to V. Due to the maximum value in level IV, the comprehensive level of resilience of Nanping Station belongs to the level IV, that is, a higher level of resilience. Based on the above, the comprehensive level of resilience of Guanyinqiao Station, Lianglukou Station, Shiyoulu Station, Chongqing North Station, North Square, Ranjiaba Station, and Xiejiawan Station also belongs to the level IV. The comprehensive level of resilience of Hongqihegou Station, Jiaochangkou Station, Chongqing North Station South Square, Shapingba Station, Chongqing West Station, and Beibei Station belongs to the level III, which represents a medium level of resilience.

4.4 Discussion

The 13 metro stations above belong to level III and level IV, respectively. It can be concluded that all the stations reach a medium or higher level of resilience. For further analysis of the resilience level of metro stations, this study raises the radar chart to reflect the comparison between comprehensive resilience level and resilience level in three dimensions of resistance, recovery and adaptation in all the stations by using origin2017, shown in Figs. 6, 7 and 8.

4.4.1 Resistance level

The comparison between the comprehensive resilience level and resistance level among 13 metro stations is carried out in Fig. 6.

From Fig. 6, Shiyoulu Station, Ranjiaba Station, and Xiejiawan Station are at the level of IV, showing high resistance to rainstorm disasters. Nanping Station, Hongqihegou Station, Chongqing North Station South Square, Chongqing North Station North Square, Shapingba Station, Chongqing West Station and Beibei Station are at level III of resistance, presenting a moderate level to rainstorm disasters. However, Guanyinqiao Station, Lianglukou Station, and Jiaochangkou Station's resistance levels only reach level II, indicating a limited capacity to withstand rainstorm catastrophes. From the perspective of engineering facilities, considering differences in standards for early construction, most exits remain open with no step heights in Lianglukou Station and Jiaochangkou Station, which significantly contribute to the weak resistance to the rainstorm. In addition, the lack of municipal drainage capacity is prominent in the three metro stations, pulling down the resistance level. From the perspective of the external environment, given the characteristics of a mountainous city (Liu et al. 2017), the elevation and slope of metro stations vary greatly, and Guanyinqiao Station performs worst in the elevation dimension. Furthermore, the resistance levels of the 13 metros are all lower than or equal to their overall resilience levels, indicating the promotion of space to resilience.

The various circumstances of metro stations should be considered while making recommendations for resilience improvement in the dimension of resistance. For the established stations, the optimization for the stations, for example, adding a roof while the exit is open, allocating more drainage facilities for the emergency of flooding in metro stations

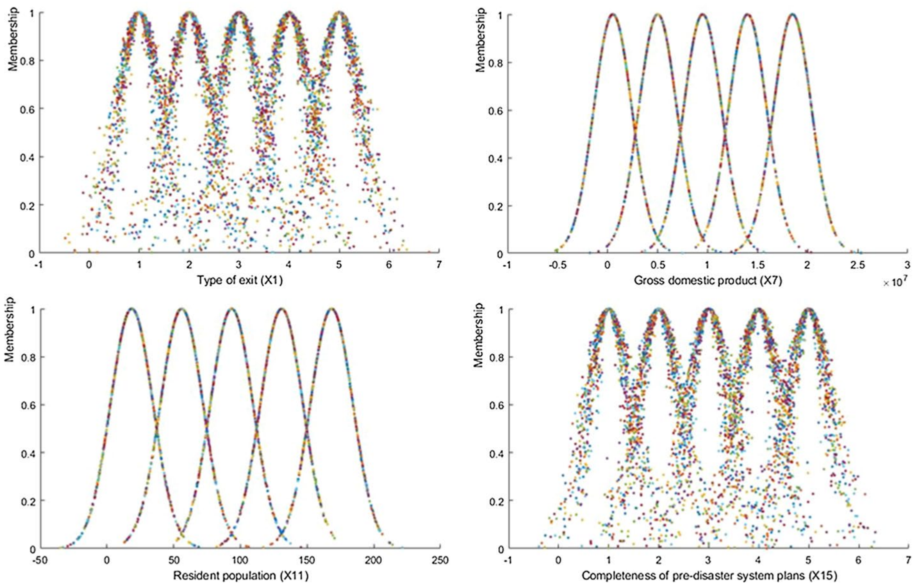

Fig. 5 Normal cloud diagram

Table 7 Results of membership in Nanping station

Level	I	II	III	IV	V
X1	0.0000	0.0000	0.0036	0.2865	0.7012
X2	0.0000	0.0035	0.2865	0.7050	0.0192
X3	0.0006	0.0827	1.0000	0.0834	0.0006
X4	0.0001	0.0188	0.7023	0.2887	0.0037
X5	0.0000	0.0036	0.2878	0.7048	0.0189
X6	0.2866	0.7037	0.0190	0.0001	0.0000
X7	0.0008	0.3691	0.6410	0.0043	0.0000
X8	0.0000	0.0000	0.0012	0.4276	0.5753
X9	0.0000	0.0048	0.6609	0.3521	0.0007
X10	0.0476	0.9936	0.0810	0.0000	0.0000
X11	0.0000	0.0567	0.9992	0.0687	0.0000
X12	0.0283	0.9512	0.1251	0.0001	0.0000
X13	0.0115	0.8188	0.2268	0.0002	0.0000
X14	0.0076	0.7448	0.2837	0.0004	0.0000
X15	0.0000	0.0006	0.0822	1.0000	0.0822
X16	0.0000	0.0006	0.0833	1.0000	0.0839
X17	0.0000	0.0000	0.0006	0.0837	1.0000
X18	0.0000	0.0037	0.2851	0.7024	0.0191
X19	0.0000	0.0000	0.0006	0.0826	1.0000
X20	0.0000	0.0006	0.0841	1.0000	0.0828

and increasing the drainage capacity of the ground surface around the metro stations can be adopted appropriately (Aoki et al. 2016; Lyu et al. 2019c). In terms of stations under construction currently or that have not yet started construction, the resilience assessment of metro stations can effectively guide their design work to improve the resilience level from the dimension of resistance, such as increasing the step height of exiting stations and using more potent drainage systems, etc. (Zhu et al. 2018; Lyu et al. 2018). It is recommended that flood awareness be raised to mitigation management, not relying only on flood defence structures (Lyu et al. 2020).

4.4.2 Recovery level

The recovery level depends on the socioeconomic level of the district where metro stations locate. The comparison between comprehensive resilience and recovery levels in 13 metro stations is carried out in Fig. 7.

Figure 7 shows Lianglukou Station, Jiaochangkou Station, Shiyoulu Station, Chongqing North Station South Square, Chongqing North Station North Square and Ranjiaba Station are all at level V, indicating an excellent recovery ability to rainstorm disasters. Guanyinqiao Station, Hongqihegou Station, Xiejiawan Station, Shapingba Station, and Chongqing West Station present a moderate recovery to rainstorms at level III of recovery. Only Nanping Station and Beibei Station are located in level II, a comparatively lower level relevant to the Districts' socioeconomic status. In Nanan District, the gross domestic product, employment of on-post urban non-private units, and medical and technical personnel all perform far below average, while other socioeconomic indices are slightly above average. Due to its geographical differences (Wei et al. 2022), Beibei District's economic and social growth has lagged behind that of the other eight districts, negatively impacting its capacity for recovery directly.

Population and income have always been key factors that need to be considered for metro construction (Chen et al. 2021b) and metro recovery (Chen et al. 2020). Therefore, Chongqing should improve urban socioeconomic development following relevant policy documents to achieve the sustainable development of metro and even urban systems such

Table 8 Resilience level of stations

Metro station	I	II	III	IV	V	Level
Nanping Station	0.0193	0.2244	0.2601	0.3599	0.2072	IV
Guanyinqiao Station	0.0283	0.2811	0.2584	0.2863	0.2079	IV
Hongqihegou Station	0.0155	0.2662	0.3328	0.2841	0.1977	III
Lianglukou Station	0.1609	0.286	0.0916	0.2878	0.2575	IV
Jiaochangkou Station	0.1025	0.2179	0.3069	0.2174	0.2502	III
Shiyoulu Station	0.0675	0.199	0.1644	0.3985	0.2577	IV
Chongqing North Station South Square	0.0454	0.145	0.3664	0.2808	0.2421	III
Chongqing North Station North Square	0.0406	0.0714	0.299	0.4173	0.252	IV
Ranjiaba Station	0.046	0.152	0.1745	0.4128	0.278	IV
Xiejiawan Station	0.0062	0.1686	0.2562	0.3637	0.266	IV
Shapingba Station	0.0684	0.1292	0.4025	0.3233	0.1731	III
Chongqing West Station	0.1104	0.1696	0.3476	0.2548	0.1911	III
Beibei Station	0.0476	0.3074	0.3259	0.2638	0.1325	III

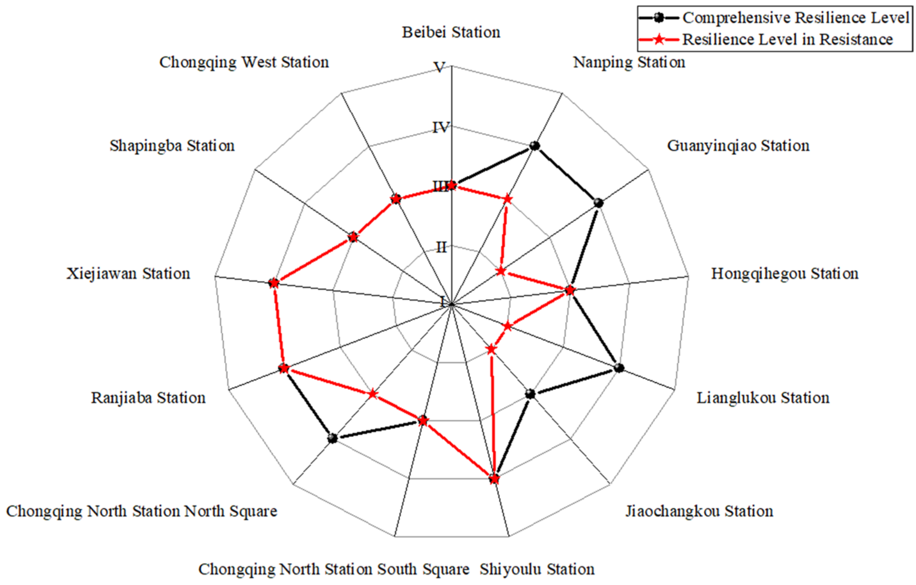

Fig. 6 Comprehensive resilience level and resistance level

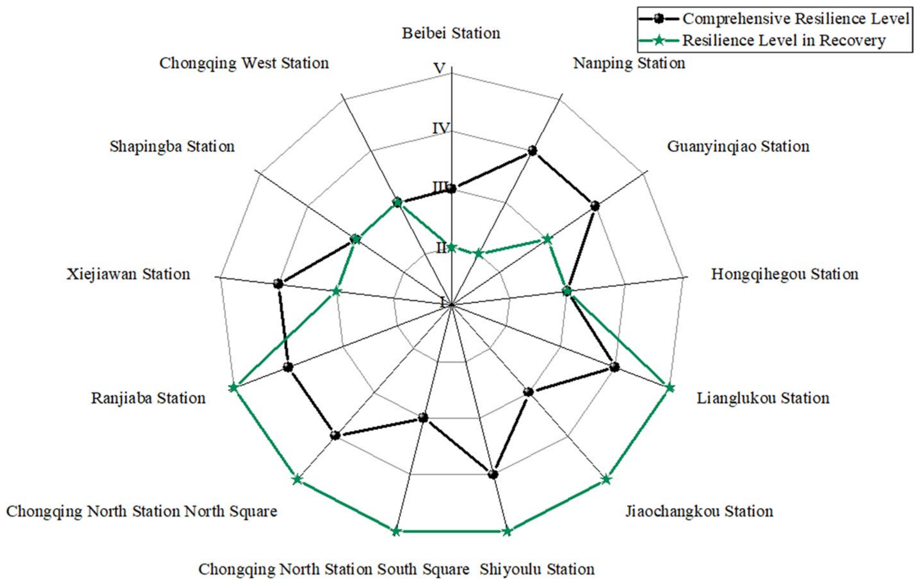

Fig. 7 Comparison between comprehensive resilience level and recovery level

as the implementation of strategic emerging industrial cluster, development of modern mountain-based high-efficiency agriculture, construction of 5G essential networks, the establishment of talent team, improvement of public emergency ability, etc. (Li et al. 2021; Yang et al. 2020; Li et al. 2021; Ruan et al. 2021).

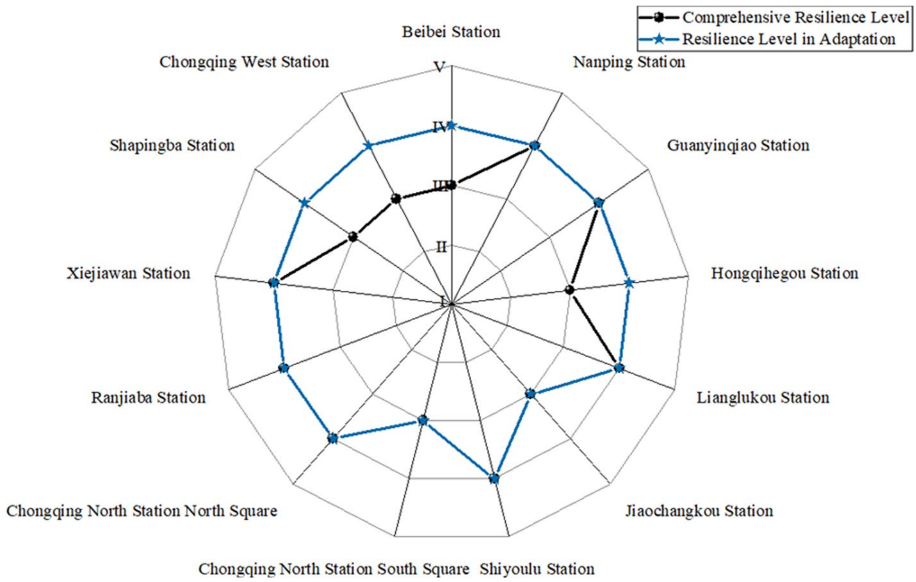

Fig. 8 Comparison between comprehensive resilience level and adaptation level

4.4.3 Adaptation level

The comparison between comprehensive resilience and adaptation levels in 13 metro stations is carried out in Fig. 8.

As shown in Fig. 8, except for Jiaochangkou Station and Chongqing North Station South Square on level III, all the other stations situated on the level IV present decent performance in the dimension of adaptation. Additionally, the adaptation levels of the 13 metro stations are all higher than or equal to their overall resilience levels, confirming satisfactory performance.

For the improvement of adaptation levels, such as drainage capacity and metro depth, following the relevant requirements of disaster prevention and control management in the whole process (Mercado et al. 2020; Lyu et al. 2020; Wu et al. 2020), should be considered for emergency plans based on the condition of every station. In terms of emergency equipment, departments should implement the availability of emergency equipment such as monitoring and warning equipment, emergency materials and equipment, and disaster assessment equipment as soon as possible, following relevant management requirements. In addition, disaster warning and learning have become indispensable and significant parts of disaster management in the information age. Establishing a mechanism containing dynamic warning, material allocation, and deep learning linkage will be the direction of defending against rainstorms for metro stations (Zhu et al. 2018).

5 Conclusion

The safe operation of the metro system will still be threatened by rainstorm disaster in the future. Assessment resilience results of metro stations are imperative for supporting strategy implementation against the rainstorm disaster. In this study, the ordered binary comparison method, entropy weight method, and cloud model have combined to establish an assessment model of metro stations' resilience level. The case study of the Chongqing metro system in China demonstrates that the assessment model can effectively evaluate the resilience level of metro stations and can be used in other infrastructures under natural disasters for resilience assessment. From the results of this study, the resilience of metro stations under rainstorms can be evaluated from three dimensions of resistance, recovery and adaptation, which represent engineering facilities and external environment, national economy and social development, emergency plans and emergency equipment, respectively. In addition, a recommendation can be proposed to instruct the improvement of the resilience of metro stations through empirical analysis to add value to the development of the metro system. Also acknowledged is the need to increase public awareness of the dangers of a rainstorm in order to attain sustainable prevention rather than relying solely on the engineering structure, social assistance and emergency preparedness.

The limitations of this research are mainly concluded as follows: (1) The development of indicator systems lacks a common standard in the literature of metro resilience to rainstorms currently, and this work has not yet been fully acknowledged for its bold exploration of indicator systems. (2) Due to restrictions on data collecting, only 13 Chongqing metro stations were chosen as research subjects. As a result, the results appear to be occasional in several ways. This research team's further research agenda is to explore metro resilience to different disasters and the relationship between disasters to effectively realize disaster prevention and mitigation management.

Appendix A: Original data

See Tables 9, 10 and 11.

Table 9 Original data in resistance

Codes of Factors	X1			X2			X3			X4			X5			X6		
Nanping Station	4	5	5	3	3	5	2	3	4	2	4	4	3	4	4	1	2	2
Guanyinqiao Station	3	4	4	1	3	4	3	3	4	1	2	2	2	2	2	1	2	4
Hongqihegou Station	2	3	4	1	2	3	3	4	4	3	3	3	2	3	3	1	2	3
Lianglukou Station	1	2	2	1	1	2	2	3	3	2	2	2	2	2	2	1	1	2
Jiaochangkou Station	3	4	5	1	1	2	2	2	3	2	3	3	2	3	4	1	2	3
Shiyoulu Station	3	4	4	3	4	4	4	4	4	2	2	2	2	2	2	3	3	3
Chongqing North Station South Square	3	4	4	1	2	3	3	3	4	3	4	4	2	2	3	2	3	3
Chongqing North Station North Square	3	4	4	3	3	3	3	3	3	3	4	4	2	2	3	3	3	4
Ranjiaba Station	3	4	4	2	2	3	4	4	4	3	4	4	2	2	2	2	2	3
Xiejiawan Station	4	4	5	3	3	3	4	5	5	4	5	5	2	2	2	4	4	5
Shapingba Station	1	1	1	3	3	3	4	4	4	3	3	3	3	3	3	2	3	3
Chongqing West Station	3	3	4	3	3	3	3	3	3	2	2	2	1	1	1	1	1	1
Beibei Station	3	3	4	2	3	4	3	3	3	2	2	3	1	2	2	2	2	2

Table 10 Original data in recovery

Codes of factors	X7	X8	X9	X10	X11	X12	X13	X14
Nanping Station	7,705,829	41,105.03186	982,572	4,666,991.574	92.8	14.06	7860	533
Guanyinqiao Station	12,400,715	42,885.99092	1,003,620	4,629,081.794	90.28	19.91	11,198	446
Hongqihegou Station	12,400,715	42,885.99092	1,003,620	4,629,081.794	90.28	19.91	11,198	446
Lianglukou Station	13,013,485	44,209.0034	742,789	1,751,360.541	66.24	46.53	22,283	391
Jiaochangkou Station	13,013,485	44,209.0034	742,789	1,751,360.541	66.24	46.53	22,283	391
Shiyoulu Station	13,013,485	44,209.0034	742,789	1,751,360.541	66.24	46.53	22,283	391
Chongqing North Station South Square	18,482,431	38,756.18842	1,198,721	15,995,395.51	168.35	39.84	9482	702
Chongqing North Station North Square	18,482,431	38,756.18842	1,198,721	15,995,395.51	168.35	39.84	9482	702
Ranjiaba Station	18,482,431	38,756.18842	1,198,721	15,995,395.51	168.35	39.84	9482	702
Xiejiawan Station	14,628,804	41,568.43644	1,021,341	6,256,632.54	123.3	15	11,731	768
Shapingba Station	9,767,809	40,894.23378	1,043,649	6,320,306.667	116.5	16.9	12,044	677
Chongqing West Station	9,767,809	40,894.23378	1,043,649	6,320,306.667	116.5	16.9	12,044	677
Beibei Station	6,059,446	38,384.05373	671,876	8,682,643.34	81.6	9.5	5698	378

Table 11 Original data in adaptation

Codes of factors	X15			X16			X17			X18			X19			X20		
Nanping Station	4	4	4	4	4	4	5	5	5	3	4	4	5	5	5	4	4	4
Guanyinqiao Station	4	4	5	4	4	4	5	5	5	4	4	5	5	5	5	4	4	5
Hongqihegou Station	4	4	5	4	4	4	5	5	5	3	4	5	5	5	5	4	4	5
Lianglukou Station	4	4	4	4	4	4	5	5	5	4	4	4	5	5	5	4	4	4
Jiaochangkou Station	3	3	3	4	4	4	5	5	5	3	3	3	5	5	5	3	3	3
Shiyoulu Station	3	4	4	4	4	4	5	5	5	3	4	4	5	5	5	4	4	4
Chongqing North Station South Square	3	3	3	4	4	4	5	5	5	3	3	3	5	5	5	3	3	3
Chongqing North Station North Square	3	4	4	4	4	4	5	5	5	4	4	4	5	5	5	4	4	4
Ranjiaba Station	3	4	4	4	4	4	5	5	5	4	4	5	5	5	5	4	4	5
Xiejiawan Station	4	3	4	4	4	4	5	5	5	4	3	4	5	5	5	4	3	4
Shapingba Station	4	4	5	4	4	4	5	5	5	4	4	4	5	5	5	4	4	4
Chongqing West Station	4	4	5	4	4	4	5	5	5	4	4	5	5	5	5	4	4	5
Beibei Station	3	4	4	4	4	4	5	5	5	3	4	4	5	5	5	3	4	4

Appendix B: algorithm procedures

Appendix B: Algorithm Procedures

```
clc;

clear;

close all;

data = xlsread('data');

m = size(data,2);

n = 13;

output = [];

for j = 1:m

    for i = 1:n

        x0 = data(i, j);

        Ex = data(23:27,j);

        En = data(28,j);

        M = zeros(1,size(Ex,1));

        for k = 1:size(Ex)

            [drop] = xcloud(Ex(k),En,0.1,x0,10000);

              M(k)= mean(drop(2,:));

        end

        output(i,:,j) = M;

    end

end

output
```

Author's contribution The authors confirm their contribution to the manuscript as follows: LJ and YZ were involved in study conception and design; LJ, YZ, and XH were involved in data collection; YZ, YW, and YZ were involved in analysis and interpretation of results; LJ and YZ were involved in manuscript preparation. All authors reviewed the results and approved the final version of the manuscript. The authors do not have any conflicts of interest to declare.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval The authors certify that this manuscript is original and has not been published and will not be submitted elsewhere for publication while being considered by Natural Hazards. And the study is not split up into several parts to increase the quantity of submissions and submitted to various journals or to one journal over time. No data have been fabricated or manipulated (including images) to support the conclusions. No data, text, or theories by others are presented as if they were our own.

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