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Original Research

Environmental Vulnerability Assessment of Rainstorm Waterlogging Disaster in Underground Railway

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Abstract

During the rainy season, heavy rainfall will lead to urban waterlogging disasters, which have a great impact on the environment. In addition, the continuous flood disaster has seriously affected the operation and safety of urban subways and the living environment of human beings. After the flood disaster, the underground railway and its surrounding environment are highly vulnerable systems with strong uncertainty, ambiguity, and complexity. Therefore, it is the key issue to perform an environmental vulnerability assessment of the rainstorm waterlogging disaster in urban rail transit for environmental estimation and emergency decision-making. Based on a large amount of literature research and environmental assessment experience, the index system for rainstorm waterlogging environmental vulnerability assessment has been constructed, which includes 5 secondary indexes and 25 tertiary indexes. Moreover, the entropy weight theory is improved, and the matter-element theory is optimized to construct the environmental vulnerability assessment model of the rainstorm waterlogging disaster. The Nanning Metro Line 1 is analyzed as a typical case study. The results show that the new environmental vulnerability assessment model is perfect for case studies, and the evaluation result is level III. Furthermore, the application results of the environmental vulnerability assessment show that the main influencing factors are emergency training drills and crisis response learning. Overall, this assessment method can be extended to similar applications of environmental vulnerability assessment in flood disasters.

Keywords: underground railway, matter-element theory, heavy rain and waterlogging, environmental vulnerability assessment, entropy weight method

Introduction

Heavy rainfall is easy to cause urban waterlogging, which brings great challenges to the safe operation of the city. In recent years, with the development of subways, the construction of urban underground engineering has brought great convenience to urban traffic and has become an indicator of urban sustainability [1]. However, the underground depth of the subway is generally 10~30 meters, and since the entrance and exit of pedestrians are set through the subway station, it is extremely easy to overflow water in rainy weather. For example, in 2005, continuous torrential rains caused flooding in Shanghai, China, which in turn led to the suspension of Shanghai

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Metro Line 1 for a long time. In 2016, heavy rains in Beijing paralyzed five subway lines, seriously affecting the normal operation of the city. Thus, the emergency management and decision-making of urban subway operations are full of complexity and challenges. When rainwater swarms into a subway station, the most critical step to carrying out emergency rescue is to assess the flood's environmental vulnerability and solve the most unfavorable factors under the complex system. Therefore, how to scientifically and reasonably evaluate and control waterlogging and flood prevention in underground spaces such as the subway has become a key issue to be solved in urban operation safety.

Based on the development of the related concepts of frequent urban subway flood disasters, natural disasters, and urban infrastructure environmental vulnerability, many researchers have begun to study the environmental vulnerability of subway operations and rainstorm waterlogging [2-5]. However, at present, most studies still focus on the traditional evaluation methods for the operational safety of subway stations and the environmental vulnerability of rainstorm waterlogging, such as scenario simulation methods [6, 7], TOPSIS models [8, 9], projection pursuit methods [10], analytic hierarchy process (AHP) analysis methods [11, 12], and other traditional assessment methods [13, 14]. The decision evaluation of complex systems is still rough, in particular; the achievements in quantitative research are very limited. Therefore, the environmental vulnerability assessment of subway operations needs further in-depth study, which is also the basis for carrying out targeted control.

In view of the problems existing in complex system evaluation and the current environmental vulnerability assessment of rainstorm waterlogging in subway stations, this research takes Nanning Metro Line 1 as an example to establish a safety evaluation index system of evaluation indicators. On this basis, the mathematical model of environmental vulnerability assessment was established by using entropy weight and matter element theory, and the environmental vulnerability level of the subway operation function was evaluated.

Methods

Matter-element theory, proposed by Chinese scholar Cai Wen, can effectively evaluate complex multi-factor research objects and select important parameters and indicators, according to the actual situation, and the selected factors and indicators are not restricted [15]. This method can transform each evaluation index into a compatible problem. By establishing the matter-element model and improving the weight assignment method, more objective and practical conclusions can be obtained, which can provide an effective reference for managers and decision-makers [16-18]. Therefore, it can be used in the environmental vulnerability assessment of rainstorm waterlogging in subway stations and urban subway operation management.

Determine the Weight of Evaluation Indicators

Entropy theory [19] originated from information science and has been widely used in index evaluation and weight determination [20, 21]. According to the characteristics of entropy, the smaller the entropy value, the greater the weight [22]. The main process of determining the weight of the entropy value method can be divided into the following five steps:

(1) Construction of an evaluation matrix

Firstly, according to the index data of the evaluation object, a set of the participating data matrix is established. The matrix of is, denoted as $P=[x_{01},x_{02}...x_{0n}]$, where the data of the rating index is the mean value of the evaluation results of the indicators by experts, namely:

$$x_{0j}=\frac{\sum_{k=1}^{l}x_{kj}}{10l} \qquad j=1,2,......,n \tag{1}$$

Secondly, the benchmark evaluation matrix Q is constructed according to the security level nodes $m-1$.

$$Q=\begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \dots & \dots & \dots & \dots \\ x_{m-1,1} & x_{m-1,2} & \dots & x_{m-1,n} \end{bmatrix} \tag{2}$$

Where m represents the evaluation level and n represents the number of evaluation indicators.

Then, the constructed evaluation data matrix P and the security level node construction benchmark evaluation matrix Q are constructed into a decision matrix X.

$$X=\begin{bmatrix} x_{01} & x_{02} & \dots & x_{0_n} \\ x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \dots & \dots & \dots & \dots \\ x_{m-1,1} & x_{m-1,2} & \dots & x_{m-1,n} \end{bmatrix} \tag{3}$$

(2) Standardization processing of the decision matrix.

The normalization matrix $X=(x_{ij})_{m\times n}$ is obtained by transforming the decision matrix $Y=(y_{ij})_{m\times n}$ with a linear proportional transformation method.

$$y_{ij}=\frac{x_{ij}}{\sum_{i=1}^{m}x_{ij}} \tag{4}$$

(3) Calculate the entropy value of the index.

$$e_j=-\lambda\sum_{i=1}^{m}y_{ij}\ln y_{ij} \tag{5}$$

Among them $\lambda=1/\ln m$,

(4) Calculate the difference coefficient of indicators.

$$u_j=1-e_j \tag{6}$$

(5) Use the entropy value method to give weight to the index and the weight vector of the index. $W = (w_1, w_2, ..., w_n)$

$$W = \frac{u_j}{\sum_{j=1}^{n} u_j} \tag{7}$$

Determine the Classical Domain and Node Domain

Set the environmental vulnerability level domain of things to be evaluated Z:

$$Z = (z_1, z_2, z_3 \cdots z_n) \tag{8}$$

Select the feature set of environmental vulnerability according to the comprehensive consideration of various factors in the actual situation:

$$C = (c_1, c_2, c_3 \cdots c_n) \tag{9}$$

Assuming that the environmental vulnerability assessment of a certain thing N is carried out and there are characteristic factors affecting the environmental vulnerability level of the thing, then the environmental vulnerability of the thing can be described by a dimensional matter element:

$$R = (N, C, V) = \begin{Bmatrix} N & c_1 & v_1 \\ & c_2 & v_2 \\ & \vdots & \vdots \\ & c_n & v_n \end{Bmatrix} \tag{10}$$

In the formula: N -- things to be evaluated:

C -- Characteristics of environmental vulnerability factors affecting things;

V -- Quantity value corresponding to the characteristics of environmental vulnerability factors.

The classical domain matter element of the object to be evaluated can be obtained as follows:

$$R_{ot} = (N_{ot}, C, x_{oti}) = \begin{Bmatrix} N_{ot} & c_1 & x_{ot1} \\ & c_2 & x_{ot2} \\ & \vdots & \vdots \\ & c_n & x_{otn} \end{Bmatrix} = \begin{Bmatrix} N_{ot} & c_1 & (a_{ot1}, b_{ot1}) \\ & c_2 & (a_{ot2}, b_{ot2}) \\ & \vdots & \vdots \\ & c_n & (a_{otn}, b_{otn}) \end{Bmatrix} \tag{11}$$

Where: $N_o t$-- Things to be evaluated are divided into T grades;

x_{oti}-- Quantity value range determined by characteristic factor c.

The node domain can be expressed as:

$$R_p = (N_p, C, X_p) = \begin{Bmatrix} N_p & c_1 & x_{p1} \\ & c_2 & x_{p2} \\ & \vdots & \vdots \\ & c_n & x_{pn} \end{Bmatrix} = \begin{Bmatrix} N_p & c_1 & (a_{p1}, b_{p1}) \\ & c_2 & (a_{p2}, b_{p2}) \\ & \vdots & \vdots \\ & c_n & (a_{pn}, b_{pn}) \end{Bmatrix} \tag{12}$$

Where: N_p-- individuals of environmental vulnerability level;

X_p-- The value range of characteristic factor C in the corresponding environmental vulnerability level.

Determine the Matter-Element to be Evaluated

According to the collected data and materials, the actual value of various characteristic factors corresponding to the object to be evaluated can be obtained, namely:

$$R = (N, C, x_n) = \begin{Bmatrix} N & c_1 & x_1 \\ & c_2 & x_2 \\ & \vdots & \vdots \\ & c_n & x_n \end{Bmatrix} \tag{13}$$

Where: x_n-- The quantitative value corresponding to the characteristic factor, namely the specific value obtained from the practice.

Determine the Correlation Degree of Each Environmental Vulnerability Level

The correlation degree of the i_{th} characteristic factor of the object to be evaluated with respect to environmental vulnerability level Z can be obtained by the following equation:

$$k_t(x_i) = \begin{cases} \dfrac{-\rho(x_i, x_{oti})}{|x_{oti}|} & if, \rho(x_i, x_{pi}) - \rho(x_i, x_{oti}) = 0 \\ \dfrac{\rho(x_i, x_{oti})}{\rho(x_i, x_{pi}) - \rho(x_i, x_{oti})} & if, \rho(x_i, x_{pi}) - \rho(x_i, x_{oti}) \neq 0 \end{cases} \tag{14}$$

Among them:

$$\rho(x_i, x_{oti}) = \left| x_i - \frac{1}{2}(a_{0ti} + b_{oti}) \right| - \frac{1}{2}(b_{oti} - a_{oti}) \tag{15}$$

$$\rho(x_i, x_{pi}) = \left| x_i - \frac{1}{2}(a_{pi} + b_{pi}) \right| - \frac{1}{2}(b_{pi} - a_{pi}) \tag{16}$$

$$|x_{oti}| = |a_{oti} - b_{oti}| \tag{17}$$

According to the definition of matter distance, $\rho(x_i, x_{oti})$ is the distance between the actual value of the characteristic factor c of the environmental vulnerability assessment object and the classical domain, $\rho(x_i, x_{pi})$ is the distance between the actual value of the characteristic factor c of the environmental vulnerability assessment object and the node domain. $|x_{oti}|$ represents the classical domain interval $x_{oti} = (a_{oti}, b_{oti})$ mode.

Determine the Environmental Vulnerability Level and Assign Points

The weight coefficient w_j can be obtained by combining the entropy weight method (1) ~ (7), and the correlation degree $k_t(x_i)$ of an environmental vulnerability factor concerning grade can be obtained according to the correlation degree formulas (14) ~ (17), and the correlation degree $K_t(N)$ of the object concerning grade can be obtained:

$$K_t(N) = \sum w_j k_t(x_i) \tag{18}$$

Environmental Vulnerability Assessment Index System

In this paper, based on the research and analysis of rainstorm waterlogging control in subway stations at home and abroad, combined with the relevant regulations of subway operation and management in China and the effective identification of environmental vulnerability by

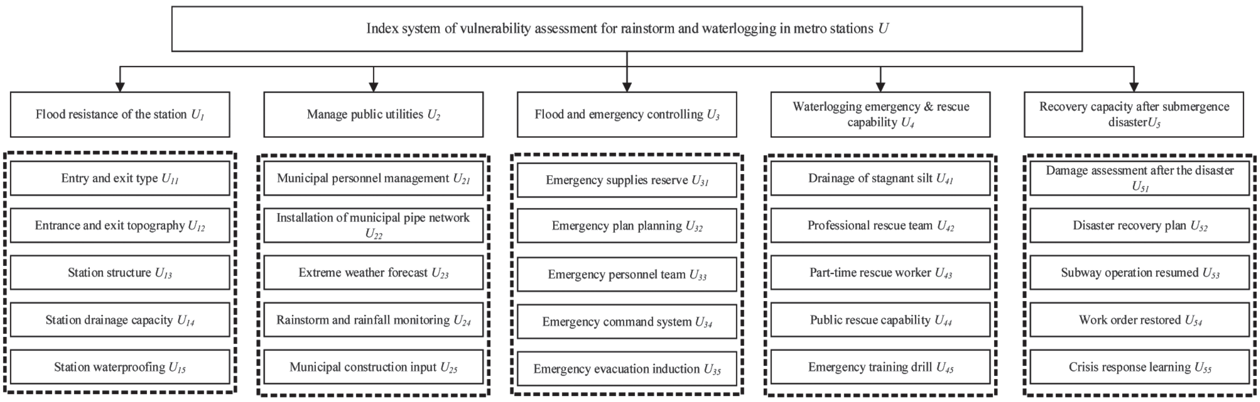

Fig. 1. Environmental vulnerability assessment index system.

industry experts, a complete index system for evaluating the environmental vulnerability of rainstorm waterlogging in subway stations is established, which is divided into five grades and 25 third-level indicators (Fig. 1).

In this paper, on the basis of referring to a large number of pieces of subway operation environmental vulnerability assessment literature [23-25], combined with the subway safety evaluation standard [26, 27], as well as subway station operation and management experience in dealing with sudden rainstorms, the acceptance criteria are divided into four levels (Table 1).

Table 1. Environmental vulnerability classification.

Level	Statement
I	Serious impact on the safety of the subway operation, the ability to resist heavy rain is extremely low.
II	Affects the safe operation of the subway, and the ability to resist the rainstorm is low.
III	It has a certain impact on subway operations and can withstand a certain degree of rain.
IV	It does not influence subway operations and can better resist heavy rainfall.

Table 2. Quantitative range of indicators.

Index number	High	Higher	Medium	Low
U_{11}	Open the [60 ~ 70]	Half-open [70-80]	With a canopy [80-90]	Enclosed [90-100]
U_{12}	A bad [60 ~ 70]	General [70-80]	Better [80-90]	Good [90-100]
U_{13}	The [60 ~ 70]	Medium [70-80]	Good [80-90]	Optimal [90-100]
U_{14}	The [60 ~ 70]	Medium [70-80]	Good [80-90]	Optimal [90-100]
U_{15}	The [60 ~ 70]	Medium [70-80]	Good [80-90]	Optimal [90-100]
U_{21}	The [60 ~ 70]	Medium [70-80]	Good [80-90]	Optimal [90-100]
U_{22}	Very few [60 ~ 70]	Less [70-80]	More [80-90]	Often [90-100]
U_{23}	The [60 ~ 70]	Medium [70-80]	Good [80-90]	Optimal [90-100]
U_{24}	Less [60 ~ 70]	Less [70-80]	More [80-90]	Often [90-100]
U_{25}	Less [60 ~ 70]	Less [70-80]	More [80-90]	Often [90-100]
U_{31}	Less [60 ~ 70]	Less [70-80]	More [80-90]	Enough [90-100]
U_{32}	Poor [50 ~ 70]	General [70-80]	Better [80-90]	Good [90-100]
U_{33}	Poor [50 ~ 70]	General [70-80]	Better [80-90]	Good [90-100]
U_{34}	Poor [50 ~ 70]	General [70-80]	Better [80-90]	Good [90-100]
U_{35}	Poor [50 ~ 70]	General [70-80]	Better [80-90]	Good [90-100]
U_{41}	Poor [10 ~ 70]	General [70-80]	Better [80-90]	Good [90-100]
U_{42}	Poor [10 ~ 70]	General [70-80]	Better [80-90]	Good [90-100]
U_{43}	Poor [10 ~ 70]	General [70-80]	Better [80-90]	Good [90-100]
U_{44}	Poor [10 ~ 70]	General [70-80]	Better [80-90]	Good [90-100]
U_{45}	Less [10 ~ 70]	General [70-80]	More [80-90]	Often [90-100]
U_{51}	Unreasonable [10 ~ 70]	General [70-80]	More reasonable [80-90]	Reasonable [90-100]
U_{52}	Unreasonable [10 ~ 70]	General [70-80]	More reasonable [80-90]	Reasonable [90-100]
U_{53}	Poor [10 ~ 70]	General [70-80]	Better [80-90]	Good [90-100]
U_{54}	Poor [10 ~ 70]	General [70-80]	Better [80-90]	Good [90-100]
U_{55}	Poor [10 ~ 70]	General [70-80]	Better [80-90]	Good [90-100]

According to Table 1 above, the single factor method was used to analyze, and the values of each grade Z and its environmental vulnerability were obtained.

$$Z = (z_1, z_2, z_3, z_4) = (high \quad higer \quad medium \quad low)$$

Determine the Environmental Vulnerability Level Domain

According to the operation data and the existing literature [28-30], the quantitative range of each index of rainstorm waterlogging environmental vulnerability assessment of subway stationa under single-factor conditions can be obtained (Table 2).

Results and Discussion

A Case Study

Nanzhiyuan Station is the penultimate station of Nanning Metro Line 1, connecting Pengfei Road Station in front and Shibu Station in the rear. The station is an island-style, two-story underground structure that runs along Xuxue West Road. There are three entrances and exits along University West Road to meet the operational requirements. The main passengers at Nanzhiyuan Station are from Nanning Vocational and Technical College, Nanning Municipal Party School of Guangxi Zhuang Autonomous Region, and Guangxi University for Nationalities. If the station is paralyzed or closed, the movement of people and safety will be seriously affected. Nanning City is located in a subtropical area with abundant precipitation, while Nanzhiyuan Station is located in the low-lying Xixiangtang area of Nanning City, near which there are large reservoirs and many small lakes. The geographical location determines whether the area is easy to cause waterlogging. In addition, there is also construction land near Nanzhiyuan Station. When the passenger flow is dense, it is easy to form a catchment area and then pour into the subway station, eventually leading to the shutdown of the subway.

Determine the Weight of Evaluation Indicators

According to the established evaluation index system, as shown in Fig. 1 and Table 2, a number of experts were invited to score the 25 indicators that affect the environmental vulnerability of rainstorm waterlogging in the station, and experts were invited to evaluate and score. On this basis, the original score matrix was constructed, and the score matrix was obtained.

$$S = \begin{bmatrix} 85\ 86\ 96\ 87\ 88\ 83\ 72\ 85\ 88\ 86\ 88\ 82\ 89\ 97\ 98 \ldots \\ 77\ 69\ 79\ 80\ 88\ 70\ 76\ 77\ 89\ 88 \end{bmatrix}$$

The normalization of the result is processed so that the range of the assigned data is $(0, 1)$, and the normalized matrix S' is obtained.

$$S' = \begin{bmatrix} 0.266 & 0.269 & 0.300 & 0.272 & 0.275 & 0.259 & 0.225 & 0.266 \\ 0.261 & 0.234 & 0.268 & 0.271 & 0.298 & 0.237 & 0.258 & 0.261 \end{bmatrix}$$

$$\begin{matrix} 0.275 & 0.269 & 0.279 & 0.260 & 0.283 & 0.308 & 0.311 \ldots \\ 0.302 & 0.298 \end{matrix}$$

Then build the entropy method model:

(1) Invite experts to evaluate and score, and build the original score matrix accordingly;
(2) The evaluation matrix and the node value of the environmental vulnerability level are composed of the decision matrix X;
(3) The normalized matrix Y is obtained by using Equation (4).
(4) Calculate the entropy value and weight of each index one by one.

The decision matrix X is as follows:

$$X = \begin{bmatrix} 0.266 & 0.269 & 0.300 & 0.272 & 0.275 & 0.259 & 0.225 & 0.266 & 0.275 & 0.269 & 0.279 & 0.260 \\ 0.203 & 0.203 & 0.203 & 0.203 & 0.203 & 0.203 & 0.203 & 0.203 & 0.203 & 0.203 & 0.190 & 0.190 \\ 0.234 & 0.234 & 0.234 & 0.234 & 0.234 & 0.234 & 0.234 & 0.234 & 0.234 & 0.234 & 0.238 & 0.238 \\ 0.266 & 0.266 & 0.266 & 0.266 & 0.266 & 0.266 & 0.266 & 0.266 & 0.266 & 0.266 & 0.270 & 0.270 \\ 0.297 & 0.297 & 0.297 & 0.297 & 0.297 & 0.297 & 0.297 & 0.297 & 0.297 & 0.297 & 0.302 & 0.302 \end{bmatrix}$$

$$\begin{matrix} 0.283 & 0.308 & 0.311 & 0.261 & 0.234 & 0.268 & 0.271 & 0.298 & 0.237 & 0.258 & 0.261 & 0.302 & 0.298 \\ 0.190 & 0.190 & 0.190 & 0.136 & 0.136 & 0.136 & 0.136 & 0.136 & 0.136 & 0.136 & 0.136 & 0.136 & 0.136 \\ 0.238 & 0.238 & 0.238 & 0.254 & 0.254 & 0.254 & 0.254 & 0.254 & 0.254 & 0.254 & 0.254 & 0.254 & 0.254 \\ 0.270 & 0.270 & 0.270 & 0.288 & 0.288 & 0.288 & 0.288 & 0.288 & 0.288 & 0.288 & 0.288 & 0.288 & 0.288 \\ 0.302 & 0.302 & 0.302 & 0.322 & 0.322 & 0.322 & 0.322 & 0.322 & 0.322 & 0.322 & 0.322 & 0.322 & 0.322 \end{matrix}$$

(4) The importance of evaluation indexes can be obtained by calculating and sorting the entropy values in sequence from Equations (5) to (7). The results are shown in Table 3.

Table 3. Index weights.

Indicators	Weight	Indicators	Weight	Indicators	Weight	Indicators	Weight	Indicators	Weight
U_{11}	0.0250	U_{21}	0.0352	U_{31}	0.0250	U_{41}	0.0352	U_{51}	0.0352
U_{12}	0.0254	U_{22}	0.0346	U_{32}	0.0254	U_{42}	0.0346	U_{52}	0.0346
U_{13}	0.0314	U_{23}	0.0346	U_{33}	0.0314	U_{43}	0.0346	U_{53}	0.0346
U_{14}	0.0254	U_{24}	0.0423	U_{34}	0.0254	U_{44}	0.0423	U_{54}	0.0423
U_{15}	0.0254	U_{25}	0.1109	U_{35}	0.0254	U_{45}	0.1109	U_{55}	0.1109

Environmental Vulnerability Assessment

According to the different causes of environmental vulnerability that may be involved and the experts' scoring matrix, the matter element to be evaluated can be:

$$R_{U_1}=\begin{Bmatrix} N & c_{U_{11}} & 85 \\ & c_{U_{12}} & 86 \\ & c_{U_{13}} & 96 \\ & c_{U_{14}} & 87 \\ & c_{U_{15}} & 88 \end{Bmatrix} R_{U_2}=\begin{Bmatrix} N & c_{U_{21}} & 83 \\ & c_{U_{22}} & 72 \\ & c_{U_{23}} & 85 \\ & c_{U_{24}} & 88 \\ & c_{U_{25}} & 86 \end{Bmatrix} R_{U_3}=\begin{Bmatrix} N & c_{U_{31}} & 88 \\ & c_{U_{32}} & 82 \\ & c_{U_{33}} & 89 \\ & c_{U_{34}} & 97 \\ & c_{U_{35}} & 98 \end{Bmatrix} R_{U_4}$$

$$=\begin{Bmatrix} N & c_{U_{41}} & 77 \\ & c_{U_{42}} & 69 \\ & c_{U_{43}} & 79 \\ & c_{U_{44}} & 80 \\ & c_{U_{45}} & 88 \end{Bmatrix} R_{U_5}=\begin{Bmatrix} N & c_{U_{51}} & 70 \\ & c_{U_{52}} & 76 \\ & c_{U_{53}} & 77 \\ & c_{U_{54}} & 89 \\ & c_{U_{55}} & 88 \end{Bmatrix}$$

According to the formula (14) ~ (17) of correlation degree, the correlation degree of environmental vulnerability grade in various situations is obtained through calculation.

$$k_t(x_i)=\begin{bmatrix} -0.500 & -0.533 & -0.867 & -0.567 & -0.600 & -0.433 & -0.143 & -0.500 & -0.600 & -0.533 & -0.600 & -0.400 & -0.633.... \\ -0.900 & -0.933 & -0.233 & 0.017 & -0.300 & -0.333 & -0.600 & 0.000 & -0.200 & -0.233 & -0.633 & -0.600 & \\ -0.250 & -0.300 & -0.800 & -0.350 & -0.400 & -0.150 & 0.200 & -0.250 & -0.400 & -0.300 & -0.400 & -0.100 & -0.450.... \\ -0.850 & -0.900 & 0.300 & -0.031 & 0.100 & 0.000 & -0.400 & 0.000 & 0.400 & 0.300 & -0.450 & -0.400 & \\ 0.500 & 0.400 & -0.600 & 0.300 & 0.200 & 0.300 & -0.400 & 0.500 & 0.200 & 0.400 & 0.200 & 0.200 & 0.100... \\ -0.700 & -0.800 & -0.115 & -0.262 & -0.045 & 0.000 & 0.200 & -0.250 & -0.143 & -0.115 & 0.100 & 0.200 & \\ -0.250 & -0.222 & 0.400 & -0.188 & -0.143 & -0.292 & -0.600 & -0.250 & -0.143 & -0.222 & -0.143 & -0.308 & -0.083... \\ 0.300 & 0.200 & -0.361 & -0.404 & -0.344 & -0.333 & -0.143 & -0.400 & -0.368 & -0.361 & -0.083 & -0.143 & \end{bmatrix}^T$$

According to Equation (18), the correlation degree of each environmental vulnerability level can be calculated as follows:

$$K_t\ N = \sum w_i k_t\ x_i =$$
$$[-0.402\ \ -0.141\ \ -0.035\ \ -0.234]$$

In the matter evaluation theory, the smaller the difference between 0 and $|K_t(N)|$, the higher the probability corresponding to the environmental vulnerability rating at this level. Therefore, according to the above calculation, the rainstorm waterlogging environmental vulnerability assessment of Nanning Metro Line 1 subway station is medium grade, that is $|K_4(N)|=0.035$, environmental vulnerability is III, which accords with the actual situation.

Conclusions

Urban subway operation in extreme weather is a high-risk and high-environmental vulnerability work with strong uncertainty and ambiguity. This is a typical problem of complex system operation and decision analysis. Therefore, using reasonable and effective methods to assess and control the environmental vulnerability of urban subway rainstorm waterlogging under extreme weather conditions is of great significance to the operation and public safety of the whole city. In this paper, the environmental vulnerability of rainstorm waterlogging in urban subways is evaluated by the combination of the entropy weight method and property theory. The main conclusions are as follows:

- Based on the investigation and analysis of domestic and foreign urban subway operation and flood prevention and control, the causes of waterlogging environmental vulnerability in urban subway stations were identified, and a complete index system of waterlogging environmental vulnerability assessment in urban subway stations was established. According to the relevant norms and existing literature, the quantitative range of each index of waterlogging environmental vulnerability assessment of subway stations under a single factor is obtained.
- Based on the matter-element theory, a quantitative assessment model of urban subway station waterlogging environmental vulnerability was established, and an evaluation index system was established based on subway operation practice and system engineering complexity considerations. The entropy weight method was introduced to improve the calculation method, which makes the calculation results more objective.
- Through the case study of the station on Nanning Metro Line 1, the entropy method was used to evaluate the environmental vulnerability of the station to rainstorms and extreme weather. The evaluation results are consistent with the actual situation of III, and the reliability evaluation model is further verified.
- The improved matter-element evaluation method can effectively reduce the influence of subjective factors, and the evaluation result is more objective, scientific, and reliable. This method can be applied to the evaluation of similar complex systems.

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Conflict of Interest

The authors declare no conflict of interest.

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