Urban Flooding Disaster Risk Assessment Based on Combined Empowerment-Fuzzy Mathematics

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Abstract: Purpose In recent years, flooding disasters have occurred frequently in major cities, in order to improve urban safety and reduce flooding disaster losses. With four urban areas in Zhengzhou City as the research object, it aims to provide a reference basis for the risk management and control of heavy rainfall and flooding disaster in Zhengzhou City. Methods From the four aspects of urban flooding disaster causative factor risk, sensitivity of the breeding environment, vulnerability of the disaster-bearing body and disaster prevention and mitigation capacity, 12 evaluation indicators were selected to construct the Zhengzhou city flood disaster risk assessment system. Based on the hierarchical analysis method (AHP) and entropy weight method (EWM) to get the weights of the combination of indicators, and using fuzzy mathematical analysis method to analyse the risk of urban flooding disaster. Results The assessment results were analysed to conclude that Jinshui District has the highest urban flood risk disaster as high risk, followed by Erqi District, Guancheng District and Zhongyuan District as medium risk, and Huiji District has the lowest risk as low risk. Conclusion Develop a set of flood risk assessment model, and accordingly draw a flood risk coefficient map of Zhengzhou City, and then derive the engineering and non-engineering measures to deal with the flood disaster in Zhengzhou City.

Keywords: Urban flooding; Risk assessment; Hierarchical analysis; Fuzzy mathematical analysis; Entropy weight approach.

1. Introduction

Global climate change has brought about the frequent occurrence of extreme weather events, which has become a key factor restricting rapid economic growth and social stability and harmony. In recent years, extreme rainstorms have occurred in many places in China, such as the '5.22' rainstorm in Guangzhou in 2020, the '7.20' rainstorm in Zhengzhou in 2021, and the '7.31' rainstorm in Beijing-Tianjin-Hebei region in 2023. 'rainstorms' in the Beijing-Tianjin-Hebei region[1]. As a highly destructive natural disaster, it poses a serious threat to the prosperity and development of cities, the life and travelling of residents, and the safety of personal and social property. In recent years, frequent flooding disasters caused by heavy rainfall have occurred in Zhengzhou city, resulting in casualties and property losses. Therefore, it is extremely important to assess the significance of urban flooding disaster.

Foreign research on flood risk assessment is earlier than our country, and in some developed countries, the research on prevention and response measures for meteorological disasters such as heavy rainfall and flooding started earlier, and has achieved the transformation from a single engineering measure to a comprehensive disaster prevention strategy that includes non-engineering measures and modern technology[2]. Benito G [3] and other scholars used the statistical method of historical disaster data to select a number of European countries as the study area, and proposed a flood risk assessment method based on long time series, using big data fusion methods, and analysed the number of 30-50 years.Hategekimana Yves [4] constructed a multi-indicator analytical framework by using the fuzzy hierarchical analysis method, and binary statistical methods .

Domestic scholars' research on flood risk assessment started late, and since the early 1990s, China has made relevant and greater progress. Li Yanfang [5] and others used the historical disaster statistics method to analyse the time-varying characteristics and spatial trends of flooding in the region, and predicted the flooding development trend in the next five years. Cao Jinhu [6] analysed the formation mechanism of waterlogging disaster and system theory to assess the establishment system in Xuzhou urban area. Cao Luodan [7] and others constructed a flood disaster risk assessment model with the help of GIS technology coupled with remote sensing suitable for large-scale regional studies of this feature.

At present, AHP, improved AHP combined with a variety of other evaluation theories can be analysed and evaluated on the urban flooding factors, and in recent years the literature at home and abroad scholars consider the disaster system comprehensively, but the weight of the indicators is subject to subjective factors, so this paper adopts the AHP-EWM integrated weighting method and fuzzy mathematical evaluation theory, evaluates and analyses the impacts of urban flooding disaster risk from four aspects, and constructs the Zhengzhou Risk distribution map of different regions, which provides a powerful decision support tool for urban flood prevention and disaster reduction.

2. Overview of the Study Area and Data Sources

2.1. Overview of the study area

Zhengzhou is situated in the north-central region of Henan Province, at the southern end of the North China Plain, close to the lower basin of the Yellow River. The terrain is generally characterised by high south-west and low north-east, forming a stepped and gradually declining landscape. With the rapid expansion of urban areas, the capacity of urban water systems and drainage facilities to cope with extreme rainfall is still insufficient. In the '7.20' extreme rainfall weather is particularly prominent, water makes the underground tunnel traffic blocked, communication and monitoring equipment damage, property and economic losses are serious [8]. In this paper, we analyse the risk assessment of the five central urban areas of Zhengzhou city, including Erqi District, Jinshui District, Guancheng District, Huiji District and Zhongyuan District.

Figure 1. Regional Distribution Map of Zhengzhou City

2.2. Data sources

①Annual rainfall data and maximum daily rainfall data are mainly obtained from 'China Surface Climate Daily Value Dataset' published by China Meteorological Data Network (CMDN), which collects daily historical precipitation data from 2020 to 2023. ② Elevation and green coverage were obtained from Geospatial Data Cloud (ASTER GDEM 30m×30m); ③ The proportion of old and young population, population density, built-up area density, and economic data of Henan Province in 2022 were obtained from Henan Provincial Statistical Yearbook 2023 (http: //www.henan.gov.cn).

3. Research Method

The risk assessment of urban waterlogging disasters in Zhengzhou is achieved through the following steps: ① Analyze from four aspects and establish an index system for evaluating the risk coefficient of urban waterlogging disasters; ② Determine the weight of each waterlogging influencing factor using the AHP entropy weight mixed evaluation method; ③ The risk of rainstorm and flood disaster is analyzed by using fuzzy mathematical analysis method, and the spatial distribution map is established and corresponding countermeasures are proposed. The research technology roadmap is shown in Figure 2.

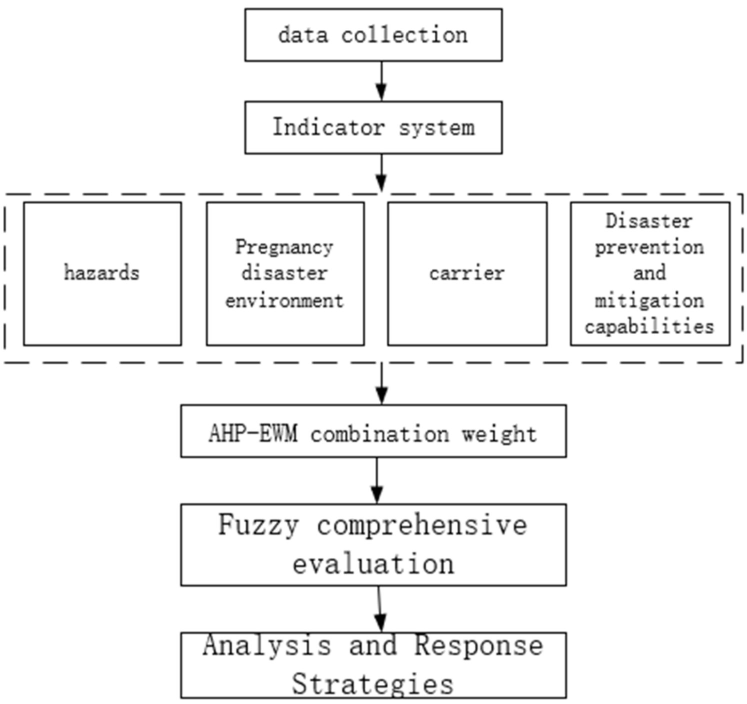

Figure 2. Research Technical Route

3.1. Analytic hierarchy process

The Analytic Hierarchy Process (AHP) is a simple, practical, and easy to calculate and analyze method for comprehensive evaluation of multiple indicators. After being scored by multiple experts and compared with literature, its calculation steps are as follows:

(1) Experts compare the indicators pairwise and construct a judgment matrix R=(A_{ij}) m × n.

(2) Determine the maximum eigenvalue λ_{max} of the judgment matrix R based on the summation method, and its corresponding eigenvector is ω. And normalize the vectors to obtain the corresponding weights for each indicator.

(3) Perform consistency assessment. Calculate the judgment matrix R. If the consistency index CR<0.1, it is considered that R has good consistency, otherwise it needs to be corrected.

3.2. Entropy weight method

Calculate the feature weight P_{ij} of the evaluation object under the indicator, using the formula (1).

$$P_{ij} = \frac{X_{ij}}{\sum_{i=1}^{m} X_{ij}} \quad (1)$$

②Calculate the entropy value E_j of the indicator using formula（2）.

$$E_j = -(\ln m)^{-1} \sum_{i=1}^{m} P_{ij} \ln P_{ij} \quad (2)$$

③ Determine the weight V_j of each indicator using formula(3)

$$V_j = \frac{1-E_j}{\sum_{j=1}^{n} 1-E_j} \quad (3)$$

3.3. Combination weight coefficient

The combination weighting method of Analytic Hierarchy Process and Entropy Weight Method is used to determine the weights of indicators, complementing the advantages of subjective weighting method and objective weighting method. It considers both the subjective experience of experts and the objective authenticity of data, making the obtained indicator weights more scientific and accurate.

$$W_j = \frac{\sqrt{U_j V_j}}{\sum_{j=1}^{n} \sqrt{U_j \bullet V_j}} \quad (4)$$

W_j is the weight of the j indicator factor after integrating two weighting methods. U_j and V_j represent the weight of the j indicator factor under AHP weighting and entropy weighting methods. The combination weight of the indicators is determined according to equation(4).

3.4. Fuzzy comprehensive evaluation method

(1) Determine the factor set U and evaluation set V for the evaluation object

$$U = (u_1, u_2, ..., u_n) \quad (5)$$

$$V = (v_1, v_2, ..., v_m) \quad (6)$$

(2) Determination of Weight

The weights of different influencing factors in the fuzzy comprehensive evaluation process directly affect the evaluation results and comprehensive decision-making.

(3) Determination of membership degree

This article determines the membership degree of the evaluation factors using a membership function.

(4) Constructing a Fuzzy Relationship Matrix

If each factor u_i in the evaluation factor set U belongs to the membership degree r_{ij} of each level v_j, then the membership degree of this factor u_i relative to each level in the evaluation set is

$$R_i = (r_{i1}, r_{i2}, ..., r_{im}) \quad (7)$$

Furthermore, the membership degree set R of all influencing factors in the factor set U is obtained, which is called the fuzzy relationship matrix.

$$R = (r_{ij}) \begin{bmatrix} r_{11} & \cdots & r_{1n} \\ r_{21} & \cdots & r_{2m} \\ \cdots & \cdots & \cdots \\ r_{m1} & \cdots & r_{mn} \end{bmatrix} (i = 1, 2, ..., m \,/\, j = 1, 2, ..., n) \quad (8)$$

(5) Fuzzy comprehensive evaluation

Based on the established comment set and its membership vectors for each indicator, obtain the comprehensive evaluation results corresponding to each indicator.

4. Risk Assessment and Analysis of Waterlogging Disasters in Zhengzhou City

4.1. Establishment of risk assessment system

The main cause of urban waterlogging disasters is rainfall, therefore, when assessing their risk, the primary indicator to consider is rainfall. The disaster prone environment mainly refers to the geographical features of the study area, including key elements such as terrain undulations and green coverage. The disaster bearing body involves multiple levels of society and economy, and requires comprehensive consideration of factors such as population density, building density, and economic development level. Disaster prevention capability, as an important indicator of human ability to respond to disasters, focuses on evaluating the construction level of flood prevention facilities and the effectiveness of flood prevention measures taken. The risk assessment index system for urban waterlogging disasters is shown in Figure 3.

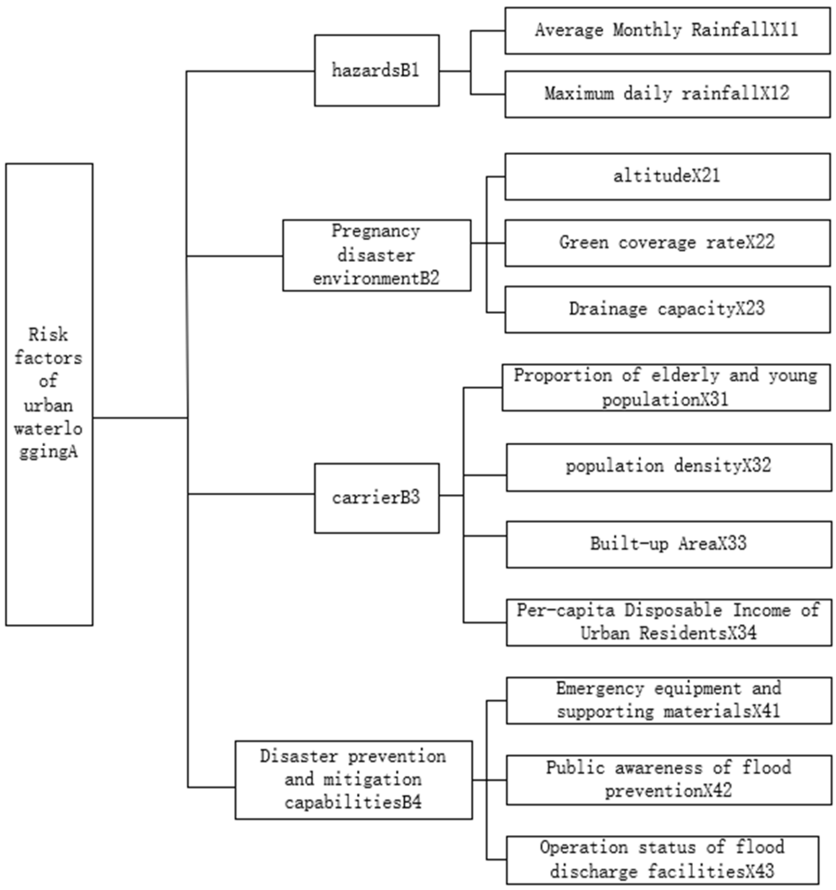

Figure 3. Urban Flooding Disaster Risk Evaluation Indicator System

The evaluation indicators and classification criteria are shown in Table 1.

Table 1. Criteria for dividing evaluation indicators

guideline	Evaluation	Evaluation level			
		low risk	low risk	medium risk	high risk
hazards	Average Monthly Rainfall(mm)	≤500	(500，600]	(600，700)	≥700
	Maximum daily rainfall (mm)	≤50	(50，100]	(100，150)	≥150
Pregnancy disaster environment	altitude(m)	≤90	(90，120]	(120，150)	≥150
	Green coverage rate(%)	≥45	(35，45]	(25，35]	≤10
	Drainage capacity	very strong	stronger	general	weak
carrier	Proportion of elderly and young population(%)	≤25	(20，25]	(25，30)	≥30
	population density (10000 households/km^2)	≤0.25	(0.2，0.25]	(0.25，0.3)	≥0.3
	Built-up Area(square kilometer)	≤60	(60，70]	(70，80)	≥80
	Per-capita Disposable Income of Urban Residents (Ten thousand yuan)	≥5.5	(5，5.5]	(4.5，5]	≤4.5
Disaster prevention and mitigation capabilities	Emergency equipment and supporting materials	Abundant	relatively abundant	average	not abundant
	Public awareness of flood prevention	very strong	stronger	general	weak
	Operation status of flood discharge facilities	Normal operation	basically normal operation	some facilities are operating normally	unable to operate normally

4.2. Indicator weighting

(1) By using the Analytic Hierarchy Process (AHP) in the subjective weighting method to assign weights, and comparing the Delphi method with literature data, hierarchical weighting is carried out from three parts: constructing the hierarchical structure model, determining the matrix and testing, and calculating the results.

Based on the factors affecting urban waterlogging selected in Figure 3, establish judgment matrices for adjacent layers, calculate the weights of the judgment matrices to obtain the eigenvectors and corresponding parameters of each judgment matrix, and conduct consistency tests to ensure that the judgment matrices meet overall consistency. According to the comprehensive analysis of the vector matrices of the judgment matrix, the weight analysis results of each factor are shown in Table 2:

Table 2. Weight of each indicator under the Analytic Hierarchy Process (AHP)

guideline	weight	Evaluation	weight
hazards	0.2087	X11	0.1565
		X12	0.1545
Pregnancy disaster environment	0.2113	X21	0.1123
		X22	0.1036
		X23	0.0983
carrier	0.265	X31	0.0669
		X32	0.0659
		X33	0.0623
		X34	0.0522
Disaster prevention and mitigation capabilities	0.315	X41	0.0429
		X42	0.0429
		X43	0.0417

(2) The entropy weighting method (EWM) in the objective weighting method is used to assign weights as shown in Table 3.

Table 3. Weight of each indicator under entropy weight method

guideline	Evaluation	weight
hazards	X11	0.0672
	X12	0.1908
Pregnancy disaster environment	X21	0.0550
	X22	0.0851
	X23	0.0535
carrier	X31	0.0496
	X32	0.0972
	X33	0.0767
	X34	0.0911
Disaster prevention and mitigation capabilities	X41	0.0725
	X42	0.1108
	X43	0.0505

(3) Determine the comprehensive weights as shown in Table 4.

Table 4. Comprehensive weigh

guideline	Evaluation	weight
hazards	X11	0.3428
	X12	0.5740
Pregnancy disaster environment	X21	0.2627
	X22	0.3139
	X23	0.2424
carrier	X31	0.1926
	X32	0.2676
	X33	0.2311
	X34	0.2305
Disaster prevention and mitigation capabilities	X41	0.1864
	X42	0.2305
	X43	0.1534

4.3. Comprehensive evaluation

Based on relevant information and the actual situation in the region, the evaluation indicators are divided into four safety levels, with an evaluation set of V={I, II, III, IV}, representing low risk, low risk, medium risk, and high risk respectively. Quantitative indicators are quantified using measured values, while qualitative indicators are quantified using a scoring system.

There are many types and forms of membership functions, and a corresponding membership function should be established based on the different influencing characteristics of each factor. Perform uniform calculation on each indicator, and the indicator calculation is as follows:

The positive indicator calculation formula is:

$$A(x)=\begin{cases} 1, & x \geq a_1 \\ 0.6+0.4\dfrac{x-a_2}{a_1-a_2}, & a_2 \leq x < a_1 \\ 0.6\dfrac{x-a_3}{a_2-a_3}, & a_3 \leq x < a_2 \\ 0, & x \leq a_3 \end{cases} \tag{9}$$

The calculation formula for the negative indicator is:

$$A(x)=\begin{cases} 1, & x \leq a_1 \\ 0.6+0.4\dfrac{a_2-x}{a_2-a_1}, & a_1 \leq x < a_2 \\ 0.6\dfrac{a_3-x}{a_3-a_2}, & a_2 \leq x < a_3 \\ 0, & x \geq a_3 \end{cases} \tag{10}$$

Substitute quantitative indicators and qualitative indicators after quantitative analysis into the membership function.

The comprehensive weight result is denoted as the weight matrix W, multiplied by the membership matrix X, and the evaluation result is denoted as the membership vector Q. The flood disaster risk assessment results for each district in the main urban area of Zhengzhou city are obtained. The evaluation results of Zhengzhou city center are shown in Table 5. The four levels of high risk, medium risk, low risk, and low risk are divided into 2, 1.75, and 1.5. The hazard level of the disaster causing factors, sensitivity of the disaster inducing factors, vulnerability of the carrying body, disaster prevention and reduction capability, and the final evaluation results and corresponding levels are shown in Table 5. According to the table, the following conclusion can be drawn: Jinshui District has the highest risk level, at the "high risk" level, followed by Zhongyuan District, Erqi District, and Guancheng District, which are at the "medium risk" level. Huiji District has the lowest risk level, at the "low risk" level.

Table 5. Evaluation Results of Zhengzhou Central Urban Area

Zhengzhou city center area	risk of disaster causing factors	sensitivity of disaster prone factors	vulnerability of carrying bodies	disaster prevention and mitigation capabilities	risk level
Zhongyuan District	0.4252	0.3631	0.6986	0.3510	1.8379 (III)
Jinshui District	0.9168	0.3199	0.6022	0.3377	2.1766 (IV)
Erqi District	0.6906	0.4563	0.4603	0.3898	1.9969 (III)
Guancheng District	0.47156	0.3940	0.7679	0.3440	1.9775 (III)
Huiji District	0	0.355366	0.521696	0.389027	1.2661 (I)

5. Risk Analysis and Response Strategies for Urban Waterlogging Disasters in Central Zhengzhou City

5.1. Risk analysis of urban waterlogging disasters in the center of Zhengzhou city

Summarizing the four aspects of the risk of disaster causing factors, sensitivity of disaster inducing factors, vulnerability of carrying factors, and disaster prevention and reduction capabilities in the central urban area of Zhengzhou, the risk analysis chart of waterlogging disasters in the central urban area of Zhengzhou can be obtained as shown in Figure 4. Through the analysis chart, it can be concluded that there is a large difference in the risk of disaster causing factors among the five central urban areas of Zhengzhou, while the sensitivity of disaster inducing factors and the risk of disaster prevention and reduction capabilities for waterlogging disasters are relatively small, both at a moderate level. The vulnerability risk of the carrying factors for flood disasters in the five central urban areas is generally high.

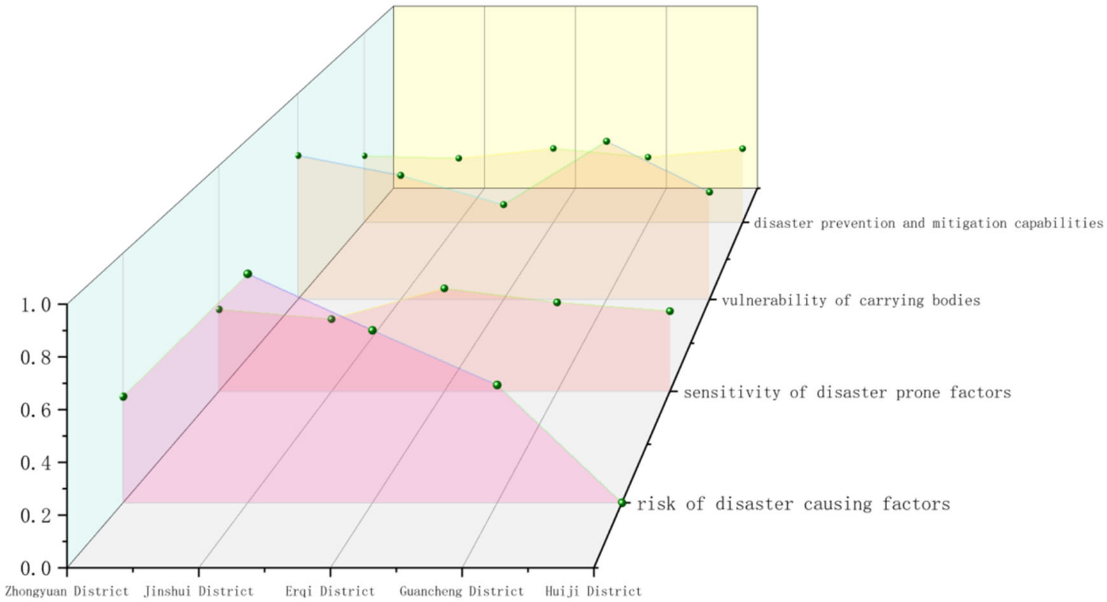

Figure 4. Risk analysis map of waterlogging disasters in the central urban area of Zhengzhou

(1) Hazard analysis of disaster causing factors

In terms of disaster causing factors, Jinshui District has the highest risk level, while Erqi District has a higher risk level. In 2023, the average monthly precipitation in Jinshui District reached 136mm, while in Erqi District it was 87mm. The average monthly precipitation in Zhongyuan District, Guancheng District, and Huiji District was relatively low. Due to the influence of urban heat island effect, the rainfall in the urban area of Zhengzhou city shows a relatively large amount in the central part, and the vast majority of precipitation is distributed from June to September [9].

(2) Sensitivity analysis of pregnancy disaster factors

In terms of the sensitivity of disaster pregnant factors, Erqi District has a slightly higher risk level, while the other four districts have similar risk levels. Because the four districts are located in the center of Zhengzhou, and Zhengzhou City is located in the south of North China Plain, the terrain is flat, and the urbanization level of these four districts is similar, they have similar risk levels in terms of the sensitivity of disaster pregnant factors. In terms of altitude, Erqi District is the central urban area of Zhengzhou, the capital city of Henan Province. Compared with other districts, it has a higher proportion of impermeable area and lower vegetation coverage, making it the most vulnerable to disaster factors.

(3) Vulnerability analysis of bearing body

In terms of carrying capacity vulnerability, the risk level in Guancheng District is relatively high, followed by Zhongyuan District and Jinshui District. The three districts of Guancheng District, Zhongyuan District, and Jinshui District have high population density, dense building density, dense urban road network density, and high per capita GDP, and a large number of enterprises and universities are stationed here. Compared to other regions, when waterlogging disasters occur, the three urban areas suffer relatively greater losses, so the risk level of the carrier is relatively high.

(4) Analysis of Disaster Prevention and Reduction Capability

In terms of disaster prevention and mitigation capabilities, the risk levels of Zhongyuan District, Jinshui District, Erqi District, Guancheng District, and Huiji District are relatively similar, all at a medium to low level. The development plan of Zhengzhou city is not mainly based on the traditional circular development model, but adopts a multi center and clustered spatial development structure. This development model avoids excessive concentration of resources in a single area, making the infrastructure and medical resources in various regions of Zhengzhou city more equitable, thereby effectively increasing the city's ability to resist risks. The key to urban drainage is the Dongfeng Canal and its tributaries Jinshui River and Xiong'er River flowing through Jinshui District, which carry the key task of flood control and elimination in the central urban area of Zhengzhou[10]. According to the investigation of the "7.20" rainstorm, the drainage pipe network was overloaded in a short time. And combined with the upstream river channel for flood discharge, the water level of Jialu River and Dongfeng Canal sharply increased, making it difficult to discharge the accumulated water smoothly.

5.2. Response strategies for urban waterlogging disasters in the central city of Zhengzhou

Engineering measures.

(1) Increase urban green space area

Increasing the green space area can not only enhance the natural rainwater regulation and storage capacity, effectively reduce the amount of rainwater directly discharged into the drainage system, but also slow down the flow rate of rainwater in densely vegetated areas, thereby reducing the speed and total amount of surface runoff formed by rainwater. As of the end of 2021, the total green area in the built-up areas of Zhengzhou City reached 246.17 million square meters, with green coverage rate, green coverage rate, and per capita park green area reaching 36.74%, 41.63%, and 15.26 square meters, respectively[11].

(2) Strengthen the construction of drainage facilities

The Jialu River is the main flood storage tank in Zhengzhou City, responsible for the important task of discharging floods. All the rivers and canals in the urban area ultimately discharge their floodwaters into the Jialu River. The water storage capacity of Jialu River cannot meet the actual drainage needs of the city[12]. As of 2019, the density of drainage pipelines in the built-up area of Zhengzhou City was only 7.97km/km2, which is below the national average of 8.82km/km2 and ranks 398th among cities in China[13]. So it is necessary to further improve the drainage capacity of Zhengzhou City, control the depth and scope of water accumulation, reduce disaster losses, promote normal urban operation, and ensure sustainable urban development.

(3) Constructing emergency shelters

In response to emergency situations such as severe urban waterlogging, mountain floods and geological disasters, Zhengzhou has established multiple flood prevention emergency shelters to ensure the safety of the public. As of 2022, the Zhengzhou Flood Control and Drought Relief Headquarters has collected a total of 2889 flood control emergency shelters, including 1663 flood control dedicated emergency shelters and 1226 temporary flood control emergency shelters[14]. As a safe haven for the public in the event of waterlogging, emergency shelters can effectively reduce the casualties of residents in extreme weather conditions.

Non engineering measures.

(1) Strengthen monitoring and early warning work

The flood prevention plan of Zhengzhou City is divided into four levels from low to high based on the severity and impact scope of flood disasters, namely level IV, level III, level II, and level I. The indicator system and technical means of risk assessment, monitoring and early warning in Zhengzhou should be gradually improved. At the same time, the simulation monitoring and early warning mechanism should be improved. Relevant hydrological models should be used to simulate the regional scenarios, build a regional rainstorm waterlogging model, and improve the accuracy and timeliness of waterlogging early warning.

(2) Establish sound relevant laws, regulations, and policies

Sound laws, regulations, and policies are important guarantees for preventing urban waterlogging. Developing overall requirements, work principles, work objectives, and systems for the governance of urban waterlogging, as well as various measures for the construction of urban drainage and flood prevention engineering systems, can effectively mobilize social resources, promote cooperation among the government, various sectors of society, and citizens, and jointly build a scientific, comprehensive, and efficient waterlogging prevention system, thereby significantly reducing the risk of waterlogging disasters.

(3) Enhancing citizens' awareness of flood prevention

Enhancing awareness of flood prevention is the primary step in preventing and mitigating waterlogging disasters. Enhancing awareness of flood prevention is not only related to personal safety, but also an important cornerstone for building a safe and resilient society. Citizens should actively learn about flood prevention knowledge, master necessary disaster prevention and mitigation skills, and ensure that they can respond quickly and accurately when disasters occur, thereby reducing personal and property safety risks.

6. Summary

(1) In response to the waterlogging disaster in Zhengzhou City, a risk assessment system was constructed based on 12 evaluation indicators selected from four aspects: the risk of disaster causing factors, the sensitivity of disaster prone environments, the vulnerability of disaster bearing bodies, and the ability to prevent and reduce disasters. The weight determination of risk zoning indicators is achieved through the Analytic Hierarchy Process and weighting method, which maximizes the balance between subjective judgments and objective facts on the evaluation results, further enhancing the rationality and scientificity of the comprehensive evaluation results in risk zoning.

(2) The risk zoning results indicate that Jinshui District has the highest risk of urban waterlogging disasters as high risk, followed by Erqi District, Guancheng District, and Zhongyuan District as medium risk, and Huiji District has the lowest risk as low risk. Analyze the risk levels of the four centers separately and provide some suggestions for flood prevention and mitigation in Zhengzhou city.

(3) Propose strategies for dealing with waterlogging disasters from both engineering and non engineering perspectives. In the face of extreme rainstorm weather, problems such as uncoordinated flood drainage between water systems and blocked drainage network are exposed. Therefore, in terms of engineering measures, increasing green space area, strengthening drainage facilities construction, and building emergency shelters; In terms of non engineering measures, strengthen the assessment, monitoring and early warning of waterlogging risks, improve relevant laws, regulations and policies, and enhance citizens' awareness of waterlogging prevention.

Conflicts of Interest

Acknowledgements

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