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Enhancing the resilience of road networks to flooding

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Enhancing the resilience of road networks to flooding

Purpose – This paper aims to clarify the resistance degree of group road logistics to flood disaster resilience. It measures the resilience of group road logistics by establishing network structure model. The purpose of this study is to improve the resilience of road logistics to flood risk.
Design/methodology/approach – This paper adopts Delphi method to collect data, interviews mainly flood management experts and supply chain risk management experts, and then analyzes the data through the network structure model combined with Interpretative structure model (ISM) and analytical network process (ANP).
Findings – The results show that flood frequency and drainage systems are the main factors affecting the resilience of road transport logistics in urban areas. These research results provide useful guidance for the effective planning and design of urban road construction and infrastructure.
Research limitations/implications – However, the main factors affecting the resilience of road transport logistics are likely to change with the development of factors such as climate, economy, and environment. Therefore, in future work, our research will focus on the further application of this evaluation method.
Practical implications – The results show that the impact of flooding on the four dimensions of road logistics resilience varies. This shows that in deciding what intervention measures are to be taken to improve the resilience of the road network to flooding, various measures need to be considered.
Originality/value – This paper addresses a clear need to study how to build models to improve the resilience of road logistics in flood risk.
Keywords: ISM-ANP model; Resilience; Road transport logistics; flooding
Article Type: Research paper

1. Introduction

The logistics associated with our urban road network refers to the route systems within the entire road transportation network. Road networks are vital to trade, business and communities and represent a key component of the transportation system and therefore the associated logistics. Extreme events caused by natural hazards such as severe flooding can cause incalculable losses to the transportation of goods [1,2]. The construction of new road networks is positively related to economic development and social growth, especially in developing countries. This helps to meet people's daily commuting needs and the increasing demand for the transportation of goods. However, this expansion and enhanced land use increases the vulnerability of flood-prone areas, which leads urban planners to confront difficult decisions involved in constructing large-scale road networks. Therefore, improving the resilience of transportation networks to destructive events has a positive impact on society. The resilience of the transportation system depends on the ability of a network to maintain functionality following initial interruption (i.e. robustness) and then to quickly restore performance (i.e. speed), with the latter attracting much less attention than robustness [4,5]. Although there is no consensus on the precise definition of resilience today [6,7], different views and methodological approaches have been generated within its scope [8-10]. However, there is a consensus in the scientific community that resilience includes two principal aspects: response and recovery. Resilience has also been applied to various fields of natural hazards, including disaster management such as floods, earthquakes, hurricanes, and fires [11-13]. Hence, the concept of resilience is important towards understanding roads and the risks they are exposed to as part of the transportation network. In response to concerns about the frequency and severity of natural hazards and extreme events, the concepts of road resilience, logistics and planning have received increasing attention in the field of emergency management in recent years. The international academic and policy circles have also recognized the need to strengthen the resilience of our road networks [2,14-16].

Enhancing resilience is an effective way to reduce the impact of extreme events on the road networks and minimize interruptions to the overall transportation network, thus improving logistics. However, even when road networks are being designed, risk reduction and vulnerability are often not prominent issues leaving them vulnerable to extreme events [17,18,19]. Therefore, as research efforts shift from reducing vulnerability to improving resilience of the road network, the concepts of adaptability and resilience have become increasingly prominent in the process [20]. The ability of roads to resist flooding has gradually received more attention and development. However, even if these hazards are recognized, risk reduction and vulnerability often only become prominent issues after these events have occurred [9,21]. Hence, through the lens of resilience theory, the purpose of this study is to identify the factors associated with the resilience of the road transportation network when exposed to flooding and identify means towards improving this.

2. Review of Previous Studies

Figure 1 illustrates the relationship between vulnerability and resilience, and an overview of the performance of a resilient system over time. Starting from the initial stage of normal operations, the performance of the system decreases due to its susceptibility to interference. In the context of road networks, performance refers to the ability of the network to support effective transportation logistics. As the interference continues to spread, it begins to affect the entire system, leading to a further reduction and sometimes failure in performance. The performance levels achieved in the recovery process need to exceed a performance threshold in order to achieve the minimum acceptable performance. Therefore, resilience becomes a function of interruption time and performance changes.

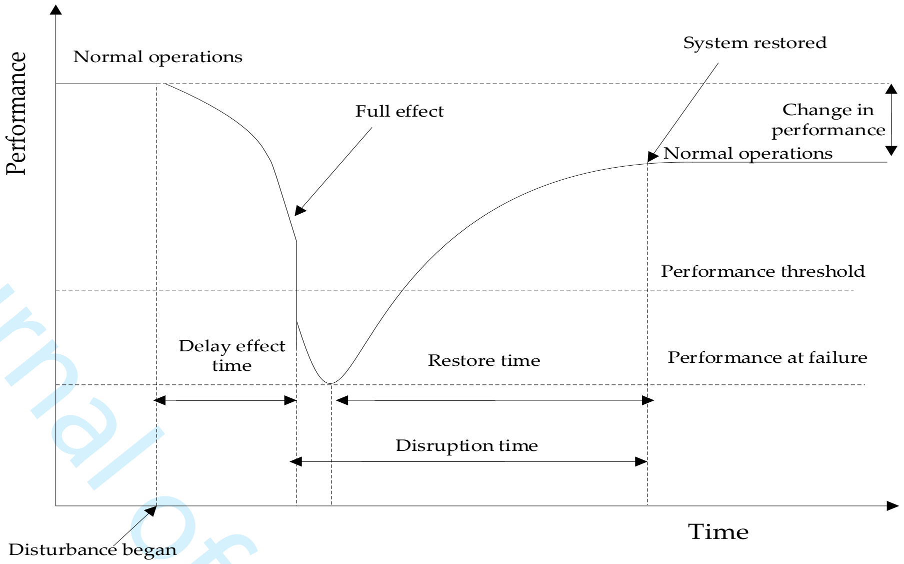


Figure1.Impact of disturbances on a resilient system

Vulnerability describes the characteristics of the road that weakens or limits the ability to withstand threats from inside and outside the boundaries of the road system [22]. Vulnerability can be manifested in any constituent part of the system, including issues concerning the process, operation and management of the system. Unlike fragility, resilience refers to the ability of the system to absorb interference and recover into a fully functional system, with reliability and adaptability. Rapidness and robustness are therefore important characteristics for the resilience of road networks. A resilient road network not only refers to the ability of roads to resist external interference, but also to the ability of roads to mitigate impacts consistent with the expected level of risk [23].Therefore, road resilience not only refers to the ability of roads to resist external interference, but also to the ability to mitigate external interference and maintain level of transportation performance [23].

Measuring the resilience of road networks to external pressures is a complex systemic problem, and hence it is necessary to examine the rationality of various related components and their designs. Several scholars have established frameworks and index systems to measure the resilience of road networks from different viewpoints, including the measurement of road safety standards for flooded roads, the deterioration of road surfaces after floods, and the prediction of road restoration performance [24,25]. This implies that road resilience exhibits three characteristics, namely redundancy, vulnerability and mobility [26]. Subsequently, four dimensions are proposed to measure the resilience of road networks to flooding, namely, natural factors, road factors, structural factors, and social factors [2,20,27].

Zhang proposed a resilience-based framework that integrates network topology, redundancy levels, traffic patterns, structural reliability of network components (ie roads and bridges), and network functions during disaster recovery. These were compared using a common risk mitigation basis to improve the resilience of the transportation network and to mitigate the risks of the road transportation network. These systems have been used to evaluate the resilience at the local road level and have been applied in many road resilience studies [8].

In addition, Kasmalka et al. assessed the importance of resilience by quantifying the risk of flooding to urban road network disruption [28]. Ishibashi used the economic loss and post-disaster function of the road network to quantify risk and resilience. They used the Monte Carlo simulation method to estimate the probability of failure, considering the resilience framework related to fault movement estimation, risk intensity and structural vulnerabilities [29]. The use of quantitative index evaluations has been shown to be a powerful tool for identifying causes of vulnerability to roads and key resilience indexes have been developed [30-32]. As for the hydraulic failures of the channel network caused by the spread of flood water on the road, this has been mainly simulated by algorithmic probability to improve the resistance of the road to flood risk [33-35].

When it comes to economic losses, Gude analyzed the traffic costs caused by road interruptions due to flood propagation, and explored the importance of road networks for the supply chain infrastructure and in providing connectivity [36]. Kenley's location-based thinking provided the basic concepts for effectively coordinating and forecasting passive road maintenance activities, reducing the loss of road assets. Their location-based framework provides a useful basis for the development of collaborative resilience for road networks against flood risks [37].

The use of geographic information systems (GIS) has been shown to be important in the adaptive management of flood risk towards reducing losses and the continuous reduction of risk. GIS data, based on evacuation routes and disaster shelters, has been imported into analysis maps allowing roads to be analyzed. The close correlation between network failures and the impact of potential floods has become a powerful tool for identifying vulnerable roads and risk incidence [38-40].

In China, which as a rapidly developing country with an accelerating rate of urbanization, the impact of floods on road network projects has not been fully considered. This applies especially to those areas with weak, unplanned and unmanaged traffic, and which consequently leads to increased flood risk exposure in these road networks. The assessment of the restoration of the road logistics together with the determination of the main resilience indicators and their importance would provide a useful scientific basis for risk reduction. The distribution and the weighting of these indicators is key to the decision-making and evaluation process [19,31,41]. However, there remains many challenges towards determining the importance of the flood resilience indicators before they can be used to assess the causes of floods and improve the resilience of the road netowrks. This study adopts the use of structural modelling (ISM) combined with analytical network method (ANP), and proposes a structured network model to enhance the resilience of road networks against flooding. The main aims of the study are as follows: i) To determine the resilience index of road networks towards the risk of flooding; ii) to distinguish the relationship between the indicators and identify the weakest links of resilience, and (iii) to propose optimization schemes to improve the resilience of the road network in a targeted manner and towards reducing unnecessary losses and improving overall logistics.

3. Methodology

The interpretative structural model (ISM) allows the internal structure of a system to be revealed by processing known but messy system element relationships [42] and was put forward in 1973 by Warfield. Its basic principle is to decompose the constituent elements of a complex system into several sub elements. Drawing on a combination of theoretical knowledge, practical experience and statistical analysis, the system elements are converted into a multi-level hierarchical structure diagram. The Analytical Network Process (ANP) has evolved from the Analytic Hierarchy Process (AHP), which is used to assign weights to selected dimensions and indicators. The AHP process provides weights to indicators by pair-wising dimensions and indicators without considering interdependent relationships among dimensions. To deal with the uncertainty of interdependency of indicators and complex network relationship of dimensions, ANP can be used to determine the mixed weight [43,44].

In this study, firstly, an evaluation index of the factors affecting the resilience of road networks exposed to flooding was developed, including the direct, indirect and deep-seated fundamental factors. Then, based on the multi-level hierarchical structure obtained, an ANP structure chart was established. Then, the relative weight of each evaluation index was obtained by using the Super Decisions software. The specific principles are shown in Figure 2. Through the combination of ISM and ANP methods, the relationship between the factors affecting the resilience of the road network can be identfied, and corresponding suggestions can be provided to improve the resilience of the road networks according to the strength of the relationship between the factors.

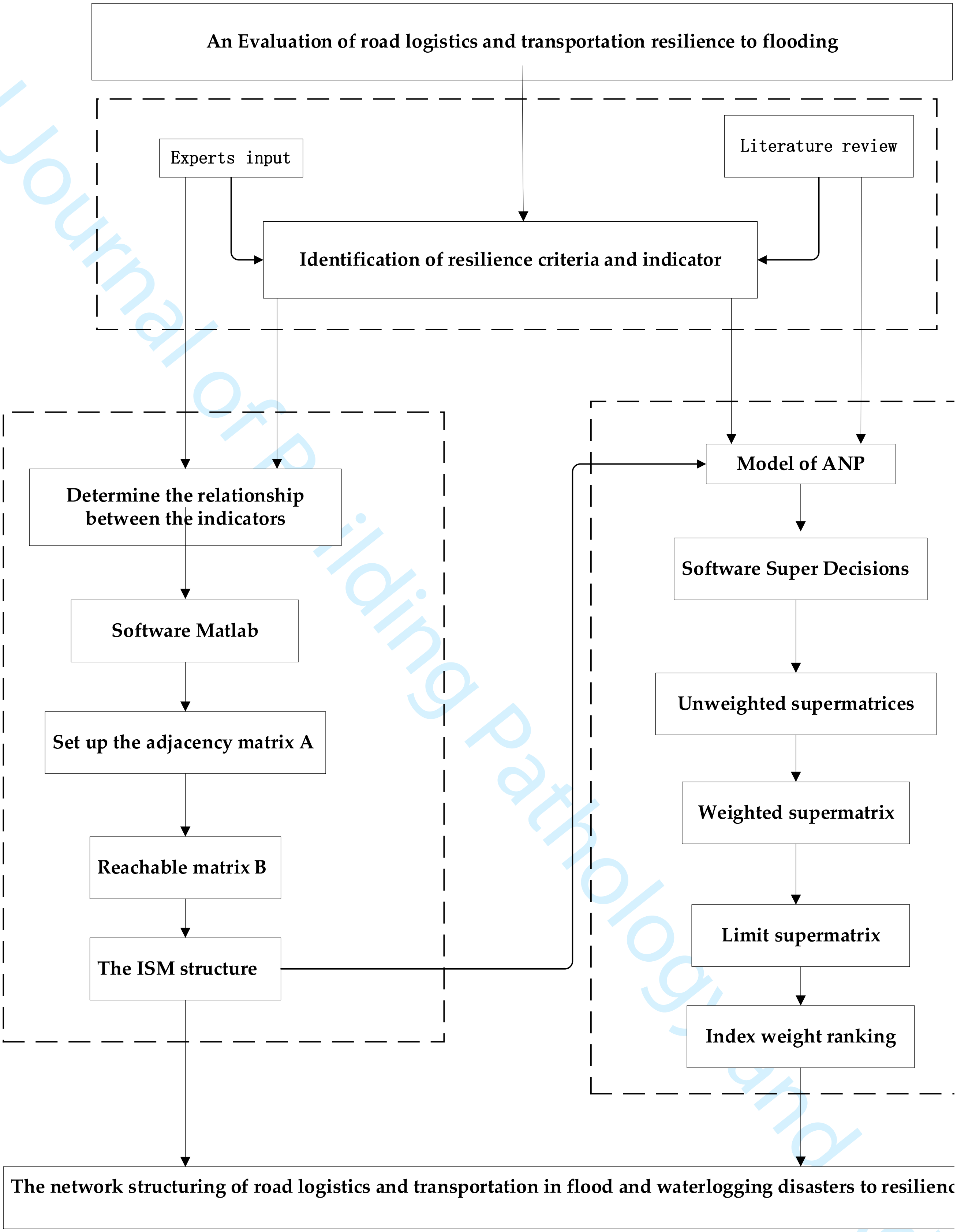

An Evaluation of road logistics and transportation resilience to flooding
Experts input
Literature review
Identification of resilience criteria and indicator
Determine the relationship between the indicators
Software Matlab
Set up the adjacency matrix A
Reachable matrix B
The ISM structure
Model of ANP
Software Super Decisions
Unweighted supermatrices
Weighted supermatrix
Limit supermatrix
Index weight ranking
The network structuring of road logistics and transportation in flood and waterlogging disasters to resilienc

Figure 2. Factor analysis of road logistics and transportation resilience based on ISM-ANP

2.1. ISM method

Step1： Establish adjacency matrix.

The factors found to influence the resilience of road network exposed to flooding are denoted as $S_{1,}S_{2,}$ ...,Sn, n is the quantity of the resilience influencing factors, and S is the set of resilience influencing factors. The directed graph G described as a mathematical formula:

$$G=\{(S,R)\mid S=n,R=m\} \tag{1}$$

Where $S=\{S_1,S_2,\cdots,S_n\}$ and $R=\{(S_i,S_j)\mid S_i,S_j\in Y\}$ The directed graph model describes the interrelationship between the elements of the influencing factors. A directed graph model was created to construct the adjacency matrix and the reachable matrix.

The factors were compared using the Delphi method to attribute scores to represent the degree of influence of each factor, and to establish the adjacency matrix. The relationship between two factors in a directed graph G can be represented by an $n\times n$ adjacency matrix $A=(a_{ij})$.

$$a_{ij}=\begin{cases}1, & (S_i,S_j)\in R\\ 0, & \text{other}\end{cases} \tag{2}$$

Step2：Calculate the reachability matrix B.

The reachable matrix B can be obtained by processing adjacency matrix A with Boolean operation rules.

$$B\equiv(A+I)^{n+1}=(A+I)^{n}\neq\cdots\neq(A+I)^{2}\neq(A+I) \tag{3}$$

The reachability matrix reflects the structural relationship between the influencing factors after continuous influence.

Step3：Decomposition reachability matrix B.

By decomposing the reachable matrix to construct the structure analysis model, an hierarchical structure diagram was established.

2.2. ANP method

ANP has evolved from the Analytic Hierarchy Process (AHP), which is applied to assign weights of the selected dimensions and indicators [45]. AHP determines the weight of indicators by pairing dimensions and indicators without considering the interdependence among dimensions [46]. ANP extends the AHP to address problems with dependence and feedback. This allows for more complex interrelationships among decision elements by replacing a hierarchy in the AHP with a network[38]. The analysis process using ANP is as follows [47-50]:

Step1： Extracting the features of a problem.

This entails carrying out a systematic analysis of the problem to be solved to form element sets and elements, and at the same time determining the independence or influencing relationships between each element. Here, urban flood resilience was broken down into different dimensions, and a robust network was constructed through quantitative correlation analysis.

Step2： Construct a pairwise comparison judgment matrix.

Decision indicators for each dimension were compared pairwise with respect to their importance towards the same dimension, and the dimensions themselves were also compared pairwise regarding their contribution to resilience. The relative importance values were determined by Satty's scale as in AHP (Table 1), and then, the priority vector was calculated.

Table 1. Satty's scale

Scale of importance	Linguistic term	Explanation
1	Equal importance	Two indicators contribute equally to the objective
3	Moderate importance	Judgment slightly favor one indicator over another
5	Strong importance	Judgment strongly favor one indicator over another
7	Very strong	An indicator is favored very strongly over another
9	Extreme strong	An indicator is favored extremely strongly over another
2,4,6,8,		Represents the intermediate value of the above adjacent judgment

Step3： Calculate eigenvalues and eigenvectors.

After completing the integrated comparison matrix, the eigenvector method and formula (5) was used to obtain the eigenvector W.

$$AW = \lambda_{max} W \tag{5}$$

Where λmax is the maximum eigenvalue of the comparison matrix.

Step4： Checking consistency.

Consistency index (CI) and consistency ratio (CR) are calculated.

$$\mathrm{CI} = \frac{\lambda_{\max} - 1}{n - 1} \tag{6}$$

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{7}$$

Where n is the order of the comparison matrix, RI is the average random index based on matrix size. All the comparison matrices are required to pass the test with CR<0.1, otherwise, the problem must be re-examined and corrected into the judgment of the even comparison matrix.

Step5：Initialize supermatrix formation and supermatrix solution.

After the consistency check was completed, under the influence of a single index that meets the consistency, the eigenvectors of each dimension index were integrated into a large matrix, which becomes an unweighted super matrix. A weighted supermatrix is derived by transforming the sums of all columns to unity, and then the weights were calculated by long-term stable weighted values, allowing the weight of the indicator to be obtained.

4. Factors Influencing the resilience of road transport logistics exposed to flooding

3.1 Study area

This study focuses on the city of Wuhan, located in the Hubei Province, China, and located at the confluence of the Yangtze River and Han River a(Figure 3). Wuhan's geographical location and climatic characteristics mean that is exposed to regular severe flooding. According to historical records and in order of peak water level, the city experienced catastrophic flooding in 1954, 1998, 1983, and 2016. Additionally, from June 1 to July 31, 2020, according to the recorded statistics, cumulative rainfall at the Hankou Station reached 962mm, which was 2.5 times the historical average (386mm from 1950 to 2020). The total amount of rainfall from June to July far exceeded normal years, ranking the highest amount of rainfall in history. This caused large areas of the city and many of the major roads to be flooded, leading to the paralysis of the entire traffic network.

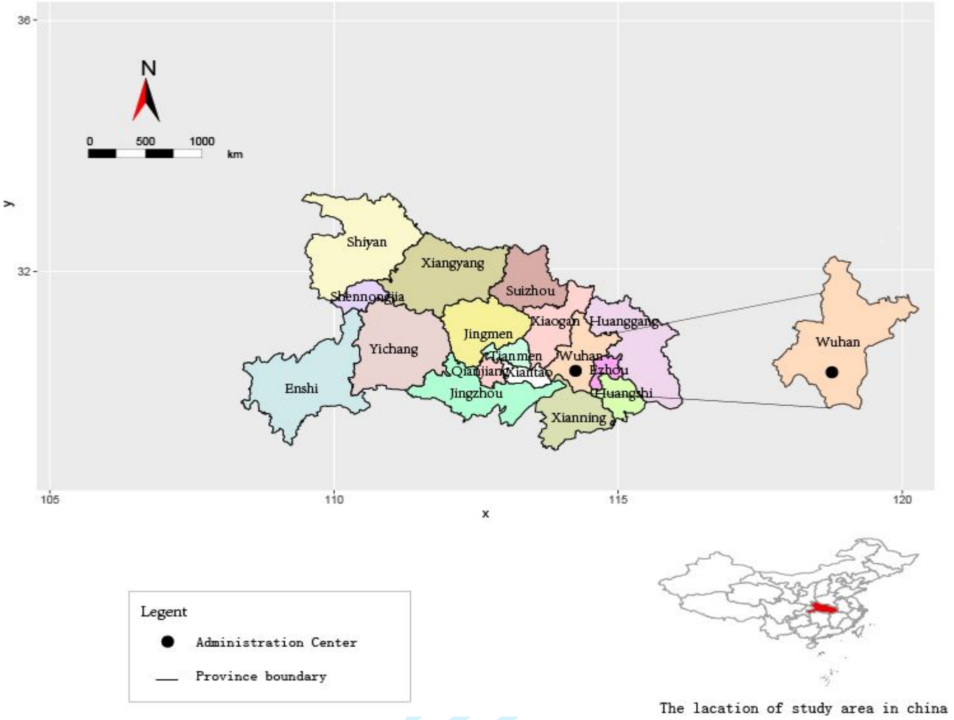


Figure 3. Map of the study area.

3.2 Data Collection

In this study, the Delphi method was used to collect, feedback and modify the opinion of experts, before finally reaching a consensus. In the Delphi method, experts who are not known to each other, were contacted anonymously and invited to participate [51]. According to the research of Winkler and Moser, the effectiveness of the Delphi method depends on the composition of the expert panel. They proposed that there should be a high degree of heterogeneity within the expert panel to avoid grouping opinions [52]. Belton suggested that between 5-20 experts are needed to achieve reliable results, and more experts can be invited if possible. At the same time, their research results revealed that three rounds of investigations are needed to obtain a stable set of opinions [53]. Therefore, for this research, 60 experts were identified for this study. After the first round of the Delphi survey, a total of 45 recoveries were collected, with 75% of the experts answering the questionnaire. After the second and third rounds of the Delphi survey, only 32 participating experts remained. Simultaneously, 81% of expert opinions were concentrated in one category, which verifies that the experts had reached a consensus. The characteristics of the expert panel are shown in Table 2.

Table 2. Expert panel characteristics.

Characteristics		Number
Job Experience	≥10	12
	5~10	20
Job position	Academic	9
	Municipal manager	12

Expertise or research field	Non-governmental organization (NGO)	5
	The road workers	6
	Logistics transport supply chain	2
	Supply chain resilience	4
	Risk management	3
	Flood management	11
	Emergency assistance	12

Through the combined results of the delphi method, 12 factors were found to influence the resilience of road networks exposed to flooding and were selected on the basis of the common framework [2, 20, 27]. These were drawn from the four dimensions of road transport logistics, namely: Natural factors, Road factors, Structural factors, and Social factors, as shown in Table 3[2, 20, 27]. Through three rounds of Delphi surveys, the interactions and weights of the indicators were analyzed. The first round of the Delphi survey was implemented from December 2020 to January 2021, the second round was implemented from January to March 2021, and the third round was implemented from March to April 2021. Satty's 1-9 scale were used to collect expert opinions in the questionnaires and during the interviews. In the first round of the Delphi survey, the questionnaire was sent to the panel members via email. In the second round of the survey, the statistical results of the first round and the revised questionnaire were sent to the experts (the statistical results include the probability distribution and the median). Finally, in the third round of the Delphi survey, the statistical results of the second round and the revised questionnaire were sent to the experts, and their opinions were gained through interviews. After three rounds, the Delphi survey was completed.

Table 3. Factors influencing the resilience of the road network to flooding

Index system of Factors influencing the resilience of the road network to flooding（A）	Criterion Layer	Secondary Indicator Layer	Description
	Natural factors （X1)	Flood frequency S1	Incidence of rainstorm
			Rainfall distribution rate
		Topographic factor S2	Low-lying, mountain road
			The slope of a highway slope
			Flood-prone roads
		Surface infiltration capacity S3	Water permeable brick coverage
			Soil structure
	Road factors(X2)	Road Class S4	Road skill level
			Physical structure level
			Road connection level
		Road drainage system S5	Surface drainage
			The road drainage
			Road under water
		Subgrade protection S6	Repair of drainage channels

			Green belt repair
	Structural factors(X3)	Road network density S7	Design rationality
			Land use efficiency
		Road node flow S8	Traffic capacity
			Characteristics of parking queue
			Characteristics of traffic Conflict
		Road area S9	The width of the road
			Ratio of road area to urban area
	Social factors(X4)	Human factors S10	Road usage
			The population density
		Economic factors S11	Flood prevention road insurance coverage
			Financial input in disaster relief
			Emergency supplies
		Public management factors S12	Road maintenance
			Disaster relief capacity
			Disaster warning

3.3 Key Factors Analysis

Employing the ISM method allowed the data obtained from the questionnaires to be sorted to obtain the relationships between the influencing factors, and the adjacency matrix A was shown in Table. 4.

Tab.4 Adjacency matrix A

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
S1	0	0	0	0	0	0	0	0	0	0	0	0
S2	0	0	0	0	0	0	0	0	0	0	0	0
S3	1	1	0	0	1	0	0	0	0	0	0	0
S4	0	0	0	0	0	0	0	0	0	0	0	0
S5	0	0	0	0	0	0	0	0	0	0	0	0
S6	0	0	0	1	1	0	0	1	0	1	0	0
S7	0	0	0	0	0	0	0	0	0	0	0	0
S8	0	0	0	0	0	0	0	0	0	0	0	0
S9	0	1	1	0	1	0	1	1	0	0	0	0
S10	0	0	0	0	0	0	0	0	0	0	0	0
S11	0	1	1	0	1	1	1	1	1	1	0	0
S12	1	1	1	0	1	1	1	0	0	1	0	0

According to the adjacency matrix, the relationships between the factors was obtained, and the reachability matrix B between indexes was obtained by the Boolean operation, as shown in Table.5.

Table.5 Reachable matrix B

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
S1	1	0	0	0	0	0	0	0	0	0	0	0
S2	0	1	0	0	0	0	0	0	0	0	0	0
S3	1	1	1	0	1	0	0	0	0	0	0	0
S4	0	0	0	1	0	0	0	0	0	0	0	0
S5	0	0	0	0	1	0	0	0	0	0	0	0
S6	0	0	0	1	1	1	0	1	0	1	0	0
S7	0	0	0	0	0	0	1	0	0	0	0	0
S8	0	0	0	0	0	0	0	1	0	0	0	0
S9	1	1	1	0	1	0	1	1	1	0	0	0
S10	0	0	0	0	0	0	0	0	0	1	0	0
S11	1	1	1	1	1	1	1	1	1	1	1	0
S12	1	1	1	1	1	1	1	1	0	1	0	1

By decomposing the reachability matrix B, the multilevel hierarchical interpretation structure model is obtained. The multi-level hierarchical structure model was composed of direct factors in the surface layer, indirect factors in the middle level and fundamental factors in the deep layer, and was obtained using a interpretative structure model (ISM), as shown in Figure 4.

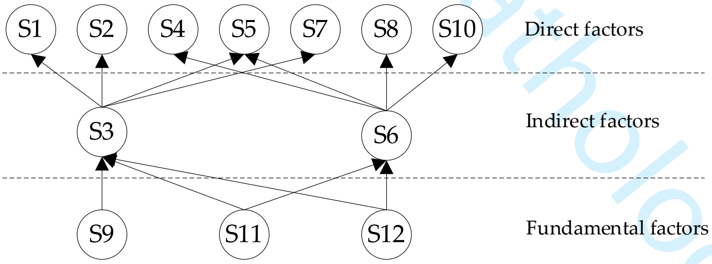


Figure.4. Multi-layer hierarchical diagram of factors influencing road network resilience

The Direct or surface factors include; flood frequency, terrain factors, road grades, road drainage systems, road network density, road node mobility, and human factors. Indirect factors include the infiltration capacity of the ground surface and roadbed protection. These factors also reflect the constraints of the surface influencing factors. The fundamental factors in the lower layer incorporate the extent of the road area, economic factors and public management factors. These reflect the root causes affecting the resilience of the road networks exposed to flooding.

The ANP model is based on the relationship between ISM indicators, as shown in Figure 5. Before calculating the weightlessness supermatrix, a judgment matrix needs to be constructed. After consulting experts, a judgment matrix for pairwise comparison of each indicator was developed, and these judgments were input into the Super Decisions software to calculate weightlessness. The column is based on the sort weight of the element. If there is no effect, the value is 0. Based on the Super Decisions software, the judgment matrix was constructed and calculated in order to check for consistency. Based on the analysis of the network process, the total weight of each factor index was calculated, and the overall normalized weight of the road transport logistics is shown in Table 6. In the next stage, the compatibility super matrix was formed by converging a set of long-term stable weights, which provides the relative importance, as shown in Tables A1 and A2. The super matrix of compatibility after convergence is shown in Table A3.

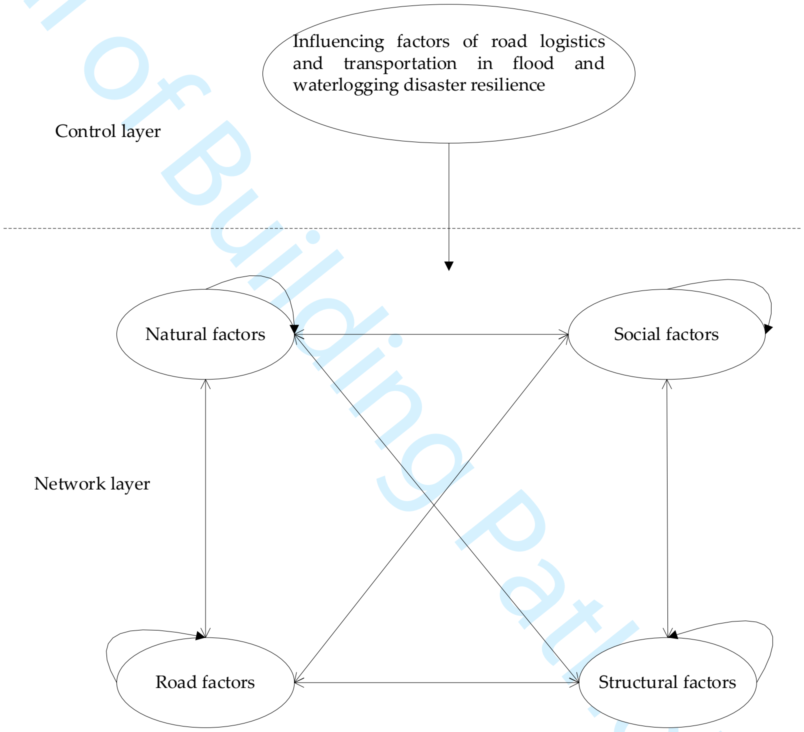


Figure 5 Analytical Network Process model.

Table 6. The index factor weights of the indicator.

Criterion Layer	Secondary Indicator Layer	Score	Total Score
X1	S1	0.20675	0.25752
	S2	0.02788	
	S3	0.02289	
X2	S4	0.06326	0.25499

	S5	0.12848	
	S6	0.06325	
X3	S7	0.05917	0.24795
	S8	0.12264	
	S9	0.06614	
X4	S10	0.0137	0.23955
	S11	0.1128	
	S12	0.11305	

According to the index factor weightings obtained in Table 6, the total weight comparison of each dimension is shown in Figure.6, and the weight ratio of each dimension is shown in Figure 7.

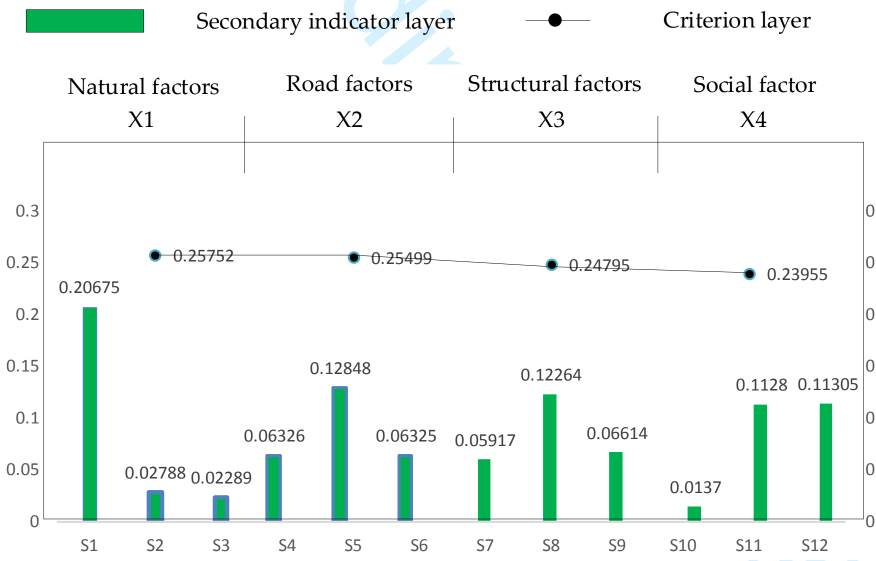
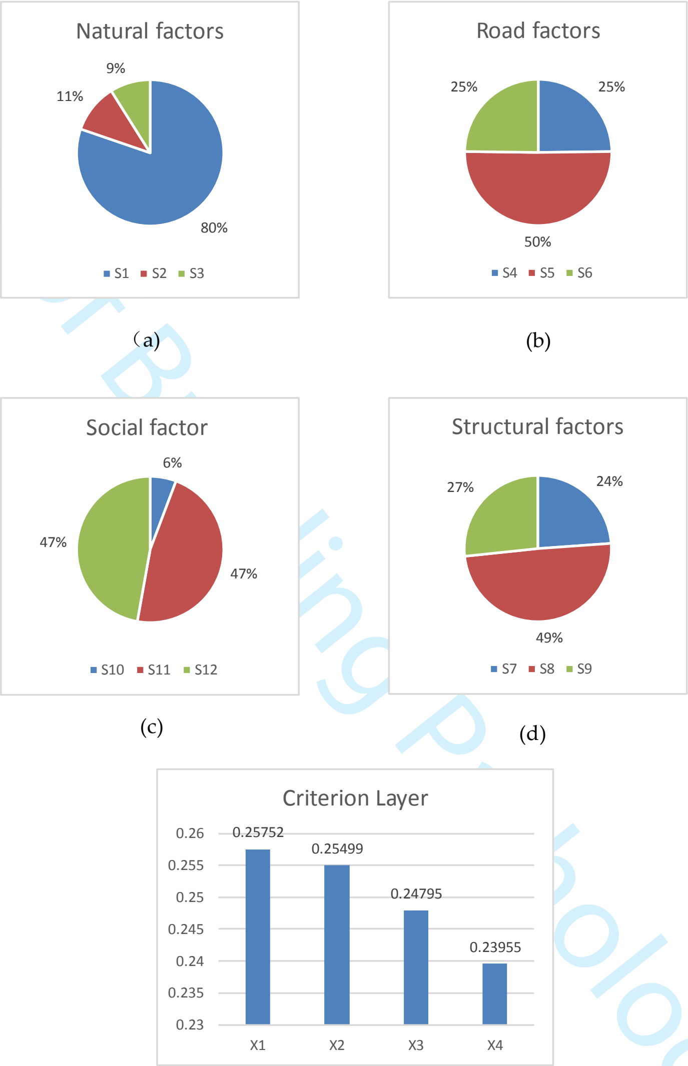


Figure.6. The total weight of factors affecting the resilience of road networks

Figure 6 shows that the most important dimension is the natural factors (X1) with a weight of 0.258, followed by road factors (X2), accounting for 0.255, structural factors (X3), accounting for 0.248, and finally social factors (X4), accounting for 0.240 respectively. In each dimension, the main impacts are flood frequency (S1) 0.207, road drainage system (S5) 0.128, road node liquidity (S8) 0.123, economic factors (S11) 0.113, and public management factors (S12) 0.113. Among these, flood frequency (S1) accounts for the largest proportion, being 0.207. The analysis of the total comparative weight of each index is presented in Figure 7 and Table 6. It can be concluded that there are many factors that affect the resilience of road network exposed to flooding, and the relationship between them is very complicated. The specific analysis of each dimension is shown in Figure 7.



（a) (b)

(c) (d)

(e)

Figure.7. The weight of influencing factors of each dimension

(a) Natural factors dimension; (b) Road factors dimension; (c) Structural factors dimension; (d) Social factors dimension; (e) comparison of each dimension;

Figure.7 shows the weighted ratio of the influencing factors in each dimension, including the comparison of each dimension. Combining the hierarchical relationship of the index factors in the ISM model, it can be seen that these factors directly affect the resilience of road network exposed to flooding. This shows that in the face of flooding, a wide range of issues need to be considered to help improve the ability of urban roads to deal with flood risk. In the dimension of natural factors (X1), the frequency of flood disasters (S1) accounts for the largest proportion, accounting for 80%. Therefore, in the dimension of natural factors, the key is to consider how to accurately predict the location and frequency of flooding and prepare for them in advance. Secondly, the frequency of floods (S1) is also one of the largest weights of all indicators, and is also a direct factor affecting resilience. This highlights the need to avoid building roads in areas where flooding occurs .

In the dimension of road factors (X2), the road drainage system (S5) accounts for up to 50%. The road drainage system includes surface drainage, roadside drainage, and under-road water storage and is considered very important to the resilience of the road network. These drainage systems determine the ability of the road network to resist the effects of flooding and will directly affect the safe passage of vehicles in heavy rain. Road grade (S4) and roadbed protection (S6) account for the same proportion in the road factor (X2) dimension, both being 25%.

In the structural dimension (X3), the road node mobility (S8) accounts for the highest proportion of 49%. The node mobility (S8) is a direct factor that affects the resilience of roads exposed to flooding. The traffic capacity is an important consideration for transportation and reflects the intersection points of roads which are very important for road transport circulation. Hence, traffic volume and capacity are important considerations. Intersection which become impassable will often affect the flow of traffic along multiple roads. Secondly, the road area (S9) and road network density (S7) accounted for 27% and 24%, respectively.

In the dimension of social factors, economic factors and public management factors account for a relatively high proportion, and both are 47%, indicating that these two factors should be carefully considered. Among the indirect factors, the infiltration capacity of the ground surface (S3) and roadbed protection (S6) reflect the importance of urban road management. In general, roadbed protection has a positive impact in the face of heavy rain erosion. This can help to effectively drain and stabilize the soil, thereby improving the resistance of the road to flooding.

Among the basic factors, economic factors (S11) and public management factors (S12) are often ignored because they are only indirectly related to road problems. Studies have shown that public management factors are very important considerations. Effective flood risk management approaches can help speed up the response to flooding events, enable interventions to change the flow of floods, and strengthen road flood control measures thus helping to reduce damage to roads and to speed up recovery and repair. Therefore, when cities face severe flooding events, they should strengthen their investment in public management of urban flood control measures, and increase the flexibility of the entire road transportation system. In addition, economic factors are also one of the important basic factors and include not only the financial investment in disaster relief and the preparation of emergency supplies, but also includes the provision of insurance for roads that are flooded. Insurance can effectively reduce the government's maintenance costs and losses caused by roads damaged by flooding. Therefore, the establishment of a resilient urban road management system requires the government to adopt a comprehensive understanding of the composition of the individual factors that affect the impact of flood events on roads and the location and distribution characteristics of roads, road grade design and flood protection measures. These represent the key considerations and management measures to be considered towards achieving a resilient road network and a robust level of urban logistics.

5. Conclusion

Frequent and severe flooding is known to cause serious loss of life, damage to property, and including major disruption to the logistics and transportation industries. Damage to road networks not only causes serious losses to the logistics industry, but also disrupts the effective and timely delivery of relief supplies. Therefore, the resilience of the road transport network is a key consideration. This study used quantitative methods to study the resilience of road networks exposed to flooding. In order to consider the interaction between flooding events and the resilience of the road network, a structural model has been used to establish a hierarchical structure. The main factors found to influence the resilience of the road network are, flood frequency (s1), road drainage system (s5), road node circulation (s8), and public management factors (s12). These results reveal new insights to the factors affecting the resilience of road networks to flooding and can be used to identify ways of improving resilience. This approach to the assessment of resilience can also be applied to group decision making in the management of logistics and road transportation. The findings can also be used to determine the interdependence between the key factors that affect resilience. Some main conclusions can be drawn as follows.

The model developed in this study combines the analysis network process method and the interpretation structure model, to analyze the relationship between the factors affecting the resilience of road networks exposed to flooding. The development of an explanatory structure model was used to construct a three-level evaluation network which identified the key factors and their hierarchy. Direct factors were found to include flood frequency (S1), topographic factors (S2), road grade (S4), road drainage system (S5), road network density (S7), road node mobility (S8), human factors (S10). Indirect factors included surface infiltration capacity (s3) and roadbed protection (S6); while basic factors included road area (S9), economic factors (S11), and public management factors (S12). These factors reflect the impact of flooding on road networks and help to develop our understanding of the origin and nature of the factors affecting resilience.

The network analysis method was used to calculate the weight of each factor. The frequency of floods (S1) was found to be the main influencing factor accounting for 0.20675, followed by the road drainage system (s5), road node mobility (S8), economic factors (s11), and public management factors (s12). This model represents a comprehensive and systematic identification of measures affecting resilience of the road network when exposed to flooding. Using the mutual influence between evaluation indexes and the importance of each index the causal relationship between influencing factors was determined. This provides a more scientific analysis of the risk management capabilities of the road network in Wuhan in the face of flooding. In addition, this also provides a useful reference for urban road planners.

The indicators were quantified, and the weight of each indicator in each dimension was calculated using the ANP method, enabling the resilience of the road network to be evaluated. The results show that the impact of flooding on the four dimensions of road logistics resilience varies. This shows that in deciding what intervention measures are to be taken to improve the resilience of the road network to flooding, various measures need to be considered and weighted accordingly. In addition, these findings are generally considered applicable to other regions with similar levels of economic development, climatic characteristics, and urban scale. However, the individual factors affecting the resilience of road networks are likely to change with the development of factors such as climate, economy, and environment. Therefore, in future work, research will focus on the further application of this evaluation method. In order to do this, it is necessary to apply this model to establish a framework for road networks exposed to flooding towards helping governments and logistics companies to use predictive analysis techniques to formulate prevention, early warning and mitigation measures.

Appendices

Table A1. Unweighted supermatrix for compatibility before the convergence of dimensions.

	S10	S11	S12	S7	S8	S9	S1	S2	S3	S4	S5	S6
S10	0.03798	0.03968	0.03447	0.03571	0.01892	0.04024	0.01681	0.03472	0.03411	0.04081	0.23316	0.0414
S11	0.47947	0.47859	0.48139	0.47943	0.49234	0.47903	0.49094	0.48199	0.48282	0.47925	0.38372	0.47826
S12	0.48256	0.48173	0.48414	0.48486	0.48874	0.48073	0.49225	0.48329	0.48307	0.47994	0.38312	0.48034
S7	0.27383	0.2672	0.26721	0.26724	0.26725	0.26719	0.26548	0.26702	0.26854	0.03646	0.27104	0.03585
S8	0.47196	0.47218	0.47213	0.47206	0.47204	0.4721	0.4755	0.47218	0.46998	0.63792	0.48187	0.63744
S9	0.2542	0.26063	0.26066	0.2607	0.26071	0.26071	0.25902	0.2608	0.26148	0.32561	0.2471	0.32671
S1	0.82261	0.83178	0.82639	0.80548	0.82928	0.83509	0.82043	0.82973	0.82754	0.8264	0.63785	0.82961
S2	0.09025	0.08473	0.08729	0.10269	0.08586	0.08462	0.0904	0.08552	0.08704	0.08957	0.25221	0.08535
S3	0.08714	0.0835	0.08632	0.09184	0.08485	0.08028	0.08916	0.08475	0.08542	0.08402	0.10994	0.08504
S4	0.25168	0.23304	0.24858	0.25478	0.248	0.25314	0.24804	0.24545	0.25533	0.23742	0.25466	0.25974
S5	0.50005	0.52089	0.50178	0.49978	0.50077	0.4991	0.50162	0.5067	0.49944	0.51545	0.49856	0.49757
S6	0.24828	0.24606	0.24963	0.24544	0.25123	0.24776	0.25035	0.24785	0.24523	0.24713	0.24678	0.24269

Table A2. Weighted supermatrix for compatibility before the convergence of dimensions.

	S10	S11	S12	S7	S8	S9	S1	S2	S3	S4	S5	S6
S10	0.00789	0.00825	0.00717	0.00875	0.00463	0.00986	0.00426	0.0088	0.00865	0.0102	0.05828	0.01035

S11	0.09967	0.09948	0.10006	0.11743	0.1206	0.11734	0.12447	0.1222	0.12241	0.11978	0.09591	0.11954
S12	0.10031	0.10014	0.10064	0.11877	0.11972	0.11775	0.1248	0.12253	0.12247	0.11996	0.09576	0.12006
S7	0.06487	0.06329	0.0633	0.07217	0.07217	0.07216	0.06383	0.0642	0.06457	0.00891	0.06625	0.00876
S8	0.1118	0.11185	0.11184	0.12748	0.12748	0.12749	0.11433	0.11353	0.11301	0.15593	0.11779	0.15582
S9	0.06022	0.06174	0.06175	0.0704	0.07041	0.07041	0.06228	0.06271	0.06287	0.07959	0.0604	0.07986
S1	0.23851	0.24117	0.23961	0.20141	0.20736	0.20882	0.20304	0.20534	0.2048	0.20201	0.15592	0.20279
S2	0.02617	0.02457	0.02531	0.02568	0.02147	0.02116	0.02237	0.02116	0.02154	0.0219	0.06165	0.02086
S3	0.02526	0.02421	0.02503	0.02296	0.02122	0.02007	0.02207	0.02097	0.02114	0.02054	0.02687	0.02079
S4	0.06677	0.06183	0.06595	0.05986	0.05827	0.05947	0.06413	0.06346	0.06601	0.06201	0.06651	0.06784
S5	0.13267	0.1382	0.13313	0.11742	0.11765	0.11726	0.12969	0.13101	0.12913	0.13462	0.13022	0.12996
S6	0.06587	0.06528	0.06623	0.05767	0.05903	0.05821	0.06473	0.06408	0.06341	0.06455	0.06445	0.06339

Table A3. Supermatrix for compatibility after convergence of dimensions.

	S10	S11	S12	S7	S8	S9	S1	S2	S3	S4	S5	S6
S10	0.0137	0.0137	0.0137	0.0137	0.0137	0.0137	0.0137	0.0137	0.0137	0.0137	0.0137	0.0137
S11	0.1128	0.1128	0.1128	0.1128	0.1128	0.1128	0.1128	0.1128	0.1128	0.1128	0.1128	0.1128
S12	0.11305	0.11305	0.11305	0.11305	0.11305	0.11305	0.11305	0.11305	0.11305	0.11305	0.11305	0.11305
S7	0.05917	0.05917	0.05917	0.05917	0.05917	0.05917	0.05917	0.05917	0.05917	0.05917	0.05917	0.05917
S8	0.12264	0.12264	0.12264	0.12264	0.12264	0.12264	0.12264	0.12264	0.12264	0.12264	0.12264	0.12264
S9	0.06614	0.06614	0.06614	0.06614	0.06614	0.06614	0.06614	0.06614	0.06614	0.06614	0.06614	0.06614
S1	0.20675	0.20675	0.20675	0.20675	0.20675	0.20675	0.20675	0.20675	0.20675	0.20675	0.20675	0.20675
S2	0.02788	0.02788	0.02788	0.02788	0.02788	0.02788	0.02788	0.02788	0.02788	0.02788	0.02788	0.02788
S3	0.02289	0.02289	0.02289	0.02289	0.02289	0.02289	0.02289	0.02289	0.02289	0.02289	0.02289	0.02289
S4	0.06326	0.06326	0.06326	0.06326	0.06326	0.06326	0.06326	0.06326	0.06326	0.06326	0.06326	0.06326
S5	0.12848	0.12848	0.12848	0.12848	0.12848	0.12848	0.12848	0.12848	0.12848	0.12848	0.12848	0.12848

S6	0.06325	0.06325	0.06325	0.06325	0.06325	0.06325	0.06325	0.06325	0.06325	0.06325	0.06325	0.06325

AppendixD.

Questionnaire for road logistics and transportation in flood and waterlogging disasters resilience evaluation index.

Dear Experts：

We are conducting a multi-dimensional evaluation study on the resilience of road logistics and transportation in flood and waterlogging disasters in Wuhan. We sincerely invite you to be a consultant on the subject of " Road logistics and transportation in flood and waterlogging disasters resilience evaluation index". Please provide valuable opinions and suggestions for the selection of the index system during your busy schedule. The research group has selected the preliminary indicators through literature induction. The main content of this expert consultation is to evaluate and score the primary indicators in terms of importance.

The purpose of this research is to evaluate the resilience of road logistics and transportation in flood and waterlogging disasters, and select Wuhan for empirical research, and analyze the selected research areas based on the evaluation results and provide reasonable policy recommendations.

If you reply within 10 days, we will be very grateful!

All the members of the research group.

2020/12/1

Directions for the Application Form：

1. The following is the indicator system initially determined in our research. Please rate the importance of the indicators. Each item is divided into 5 levels according to the importance. They are 5=most important, 4=very important, 3=medium important, 2. =not important, 1=least important. Please rate the relative importance of the indicators and tick the corresponding ☐.
2. If you think this indicator is not needed, you can mark "delete" in the edit column.
3. If you think the description of the indicator is incorrect, please modify it in the content modification column.
4. Additional indicators please fill in the blanks.

Primary Indicators	Secondary Indicator Layer	Content Modification	Significance 1 2 3 4 5
Natural factors	Flood frequency （S1）		☐ ☐ ☐ ☐ ☐
	Topographic factor （S2）		☐ ☐ ☐ ☐ ☐

	Surface infiltration capacity （S3）		☐ ☐ ☐ ☐ ☐
Road factors	Road Class （S4）		☐ ☐ ☐ ☐ ☐
	Road drainage system （S5）		☐ ☐ ☐ ☐ ☐
	Subgrade protection （S6）		☐ ☐ ☐ ☐ ☐
Structural factors	Road network density （S7）		☐ ☐ ☐ ☐ ☐
	Road node flow （S8）		☐ ☐ ☐ ☐ ☐
	Road area （S9）		☐ ☐ ☐ ☐ ☐
Social factors	Human factors （S10）		☐ ☐ ☐ ☐ ☐
	Economic factors (S11)		☐ ☐ ☐ ☐ ☐
	Public management factors (S12)		☐ ☐ ☐ ☐ ☐

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