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Research on Structural Toughness of Railway City Network in Yellow River Basin and Case Study of Zhengzhou 7–20 Rainstorm Disaster

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Abstract: With the gradual networking of inter-city relations and the increase in acute impact and chronic stress, the measurement of the resilience of urban network structures is particularly prominent. Based on the construction of the urban network by passenger train trips in the Yellow River Basin, this paper analyzes and assesses the characteristics of the structural resilience of the urban network, and probes into the network resilience and urban response under the circumstances of node failure and line failure in Zhengzhou. The main conclusions are as follows: (1) The urban network in the Yellow River Basin was clearly hierarchical, with a significant spatial distribution of "low in the north and high in the south", and the overall characteristics of "robustness" in small areas and "fragility" in large areas. The network connection forms were diversified and open. The network transmission efficiency was high, and the edge cities depended on the core cities with prominent characteristics, and the risk load of regional core cities rose. (2) The network structure was "robust" as it maintained high operational efficiency and connectivity under random attacks. Under deliberate attacks, the city network operated efficiently with a small increase in connectivity before the 60% threshold, and after the threshold, the overall network started to split into many sub-networks, and the network fragmentation gradually increased until the network collapsed. (3) Zhengzhou node failure and line failure states in the Yellow River Basin urban network were resilient, in the sense that when suffering important nodes and lines going down it could still maintain good network operation efficiency, and the core nodes in the impact of natural disasters could adapt to the destructive nature of the network through the urban network structure self-regulation.

Keywords: railroad urban network; resilience assessment; vulnerability analysis; interference resilience analysis; yellow river basin

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Citation: Xiong, Y.; Tang, H.; Tian, X. Research on Structural Toughness of Railway City Network in Yellow River Basin and Case Study of Zhengzhou 7–20 Rainstorm Disaster. *Sustainability* **2022**, *14*, 12515. https://doi.org/10.3390/su141912515

Academic Editors: Robert Sitzenfrei, Enrico Creaco, Kegong Diao, Christos Makropoulos and Ali Haghighi

Received: 15 September 2022
Accepted: 28 September 2022
Published: 30 September 2022

1. Introduction

With the rapid development of global information technology, inter-city relationships are gradually becoming networked, and production factors are flowing and configured in urban networks, increasing production efficiency. However, uncertainties in urban development can also be transmitted or spread along urban networks, and even have an amplifying effect, causing networked risks as well as regional impacts [1]. The regional urban system is facing rising unknown risks as the forces of globalization, industrialization, and urbanization interact with each other, and local failures of the urban system may cause other parts to fail to function properly under the influence of urban networking, further triggering secondary crises [2]. In order to reduce the impact of urban problems on urban development and residents' lives, and to ensure the safety and stable operation of the urban environment, the ability of regional cities to resist, absorb, and restore their original characteristics and functions has attracted more attention [3].

In the 1970s, the concept of resilience was applied from physics to ecological studies to describe the ability of a system to maintain and recover itself after an external shock [4].

Since then, scholars have further introduced the concept of resilience as a key explanatory factor for economic development after shocks into regional development studies and resilience studies have been expanded [5]. Kendra argued that resilience should include redundancy, the ability to mobilize resources, effective communication, and self-organization [6]. Along with the combination of resilience and city–region networking, the study of resilience thinking into regional space has gradually been developed and has attracted more attention [7–10]. For network structure resilience measurement, Peng defined urban network structure resilience and indicated the regional resilience of urban network spatial structure at different forms or characteristics [11]. In terms of network resilience analysis frameworks, Wei proposed the concept and analysis framework of urban network resilience based on evolutionary resilience from the perspective of negative urban network effects, security, and sustainable development [12]. For the empirical study of network resilience, Wei utilized a multifaceted urban linkage network by measuring the structural resilience of urban networks and proposing corresponding optimization strategies and recommendations [13]. However, most of the existing studies are based on a positive perspective, and not many studies have been conducted on the negative effects of urban networks and the combination of realistic contexts. In recent years, with the era of urban networks overlaid with the rapid advancement of urbanization, the various types of cumulative and emergent risks faced by urban systems are increasing dramatically, and urban network resilience has become an inevitable requirement for robust regional development [14].

Transportation network vulnerability is an important factor affecting network connectivity [15], which reflects both network resilience characteristics and expresses the ways and processes of external attacks on the network [16] and is an important method for urban network resilience research. The quantitative measurement of network resilience and the centralized reflection of resilience characteristics were achieved through the construction of the vulnerability index system and the elimination of nodes, and the research was more concentrated in infrastructure networks such as shipping networks [17,18], railroad networks [19,20], subway networks [21,22], and public transportation networks [23,24]. In general, the existing research on urban network vulnerability is mainly based on the structural toughness of urban networks, and the connotation and framework of urban network toughness research has been initially established, but empirical research on urban network toughness is still relatively scarce and the method is relatively single, while studies on the dynamic toughness and toughness characteristics of the network under continuous blows are relatively rare, so it is necessary to carry out research on dynamic network toughness and characteristics assessment.

The Yellow River Basin is an important geographical unit with a global and strategic role in the regional development of China, and it is also a typical region where the coast and the interior are connected, and the east and the west interact positively [25]. However, the natural lack of river shipping benefits in the Yellow River Basin [26] makes it difficult to form a transportation artery across the entire region, requiring integrated railroad transportation to assume more urban–regional spatial linkages. In the context of the rise of the Yellow River Basin as a national strategy, the importance of using the Yellow River Basin railroad network to carve out the urban network of the basin and to measure the network resilience is particularly important, so it is also feasible to use the railroad network to carve out the urban network. At the same time, the current research scope mainly focuses on provinces and cities, and there are fewer studies on the analysis of urban network resilience in the Yellow River Basin, which has a loose urban structure and weak overall connections [27–29], and the assessment of urban network resilience in the academic community is still in the exploration stage, and no unanimously accepted method has been formed [18], so it is especially necessary to carry out research on urban network resilience within the Yellow River Basin. In view of this, this paper collected the data of passenger trips in the Yellow River Basin in 2021, constructed the network matrix of cities in the basin, measured the network resilience through an overall network resilience assessment model, drew on the vulnerability perspective, conducted a computer simulation of attacks to assess the vulnerability of the urban network structure in the Yellow River Basin, and conducted an anti-disruption performance assessment. Taking the failure of the 7·20 Rainstorm Disaster in Zhengzhou as an example, this paper analyzed the impact of urban node failure and line failure on urban network resilience and proposes an optimization strategy of urban network resilience in order to provide a theoretical reference for urban network resilience optimization.

The applied innovations and contributions of this paper are as follows: (1) It further enriches the study of urban network resilience based on railroad trips and provides a Chinese watershed case, which helps to provide a reference for better exploration of urban network resilience in the watershed. (2) From the perspective of the structural resilience of urban networks, we analyzed the optimization measures that may be helpful in the case of urban network response to emergencies in the context of natural disasters that hit the important nodes of urban networks.

2. Methods and Data Source

2.1. Study Area Overview

Based on the natural basin of the Yellow River, the study area was defined as the eight provincial administrative regions of Qinghai, Gansu, Ningxia Hui Autonomous Region, Inner Mongolia, Shanxi, Shaanxi, Henan, and Shandong provinces, through which the Yellow River flows, with prefecture-level cities (states and leagues) as the smallest study unit, taking into account the integrity of the study geographical unit, regional development, and direct correlation with the Yellow River [30]. Among them, Gannan Tibetan Autonomous Prefecture, Hainan Tibetan Autonomous Prefecture, Guoluo Tibetan Autonomous Prefecture, Yushu Tibetan Autonomous Prefecture, Linxia Hui Autonomous Prefecture, Gannan Tibetan Autonomous Prefecture, Xilingol Meng, Alashan Meng, and Tongchuan City have not opened railroads. The four eastern leagues of Inner Mongolia are naturally closely connected with the northeastern region and were not included in the scope of the study area. Sichuan province is included in the Yangtze River Economic Belt, and the Yellow River flows in Sichuan province only through the Aba Tibetan and Qiang Autonomous Prefecture and the Ganzi Tibetan Autonomous Prefecture, which has less influence. Finally, 80 prefecture-level cities (states and leagues) with a total area of about 1,439,800 km^2 were identified in the Yellow River Basin (Figure 1).

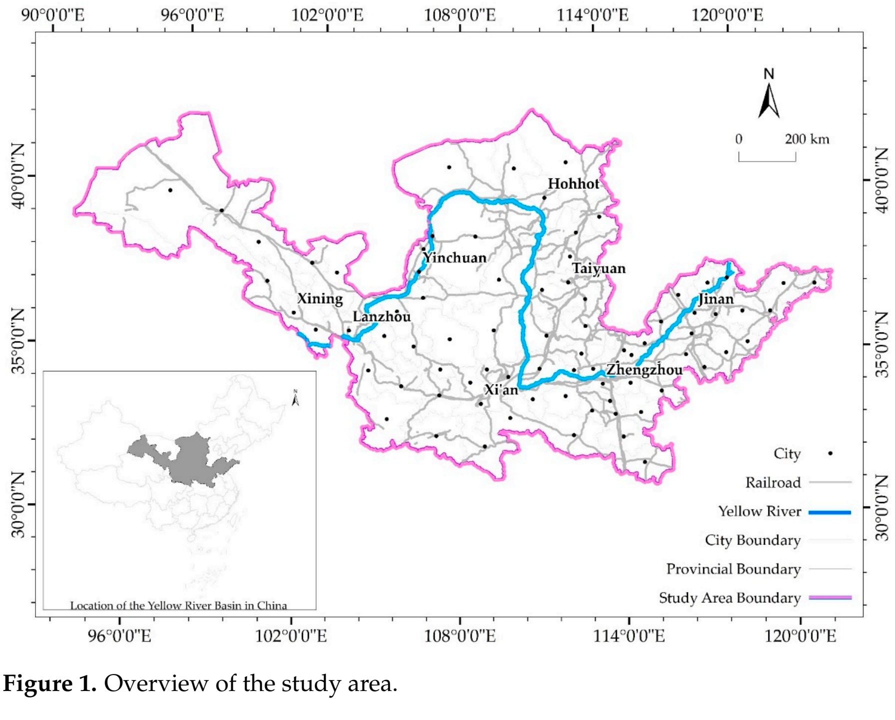

Figure 1. Overview of the study area.

2.2. Data Source

The study data used railroad passenger trips to portray regional urban spatial connections to characterize the urban network in the Yellow River Basin. Data from 2021 were mainly obtained from the 12306 website. Due to the security settings of the website, it was difficult to obtain all the data at one time node. This paper used multi-threaded, IP proxy pool crawler technology to collect the April train data from the 12306 website (https://www.12306.cn/index/ accessed on 15 April 2021). The collected data were first screened and eliminated from stations in the same city, replaced railroad stations with city names and generated city pairs in the study area, which was followed by data cleaning, and manual verification and correction through random sampling and cross-checking to ensure the accuracy and scientific quality of the data acquisition. The data collection and collation in this paper was conducted through the Python language.

2.3. Methods

2.3.1. Urban Network Resilience Characteristics Indicators

With reference to the research results of Peng Chong et al. [31], the network hierarchy, network matchability, network transmissibility, and network agglomeration were selected to measure and assess the resilience of urban networks in the Yellow River Basin according to the general principle of being able to portray the resilience characteristics of static urban network topological relationships and being able to reflect the self-organization and coordination ability of the overall network (Table 1).

Table 1. Urban network structure resilience index.

Measurement Level	Indicator Description	Formula	
Network hierarchy	Reflects the level of city nodes in the network	$WK_i = C \times \left(RK_i^*\right)^a$	C is a constant. RK_i^* is the bitwise ranking of node i. a is the slope of the degree distribution curve. WK_i denotes the weighted degree of node i.
Network matchability	Reflects the degree of correlation between nodes in the network	$\overline{WK_i} = D + bWK_i$ $\overline{WK_i} = \frac{1}{K_i} \sum\limits_{i \in G_i} W_k$	D is a constant, b is the number of degrees off-contact. W_k is the k degree-weighted degree of city i's neighbors. $\overline{WK_i}$ denotes the average weighted degree value of node i's neighboring nodes.
Network transmissibility	Reflects the network's ability to transmit various types of factor flows and global operational capacity	$L = \frac{1}{1/2n(n+1)} \sum\limits_{i>i} d_{ij}$	d_{ij} denotes the average distance between node i and node j. L denotes the average path length.
Network agglomeration	Reflects the tendency towards network agglomeration characteristics; the higher the clustering coefficient, the higher the degree of regional integration	$C = \frac{1}{n \sum_i^n 2E/k_i(k_i-1)}$	n denotes the number of city nodes. k_i denotes the number of neighboring cities of node i. E denotes the actual number of edges generated by node i with neighboring cities. C denotes the network clustering coefficient.

2.3.2. Urban Network Resilience Assessment Metrics

Urban network vulnerability refers to the extent to which the network is affected when it is subjected to external shocks. Using computer simulations, external shocks to urban networks can be classified into random and deliberate attacks. Random attacks can be understood as the degree of impact on the network in the case of sudden and accidental events that cannot be predicted, such as earthquakes and flash floods. Deliberate attacks can be understood as the degree of impact on the network in the case of attacks such as planned military operations or terrorist attacks. Drawing on vulnerability-related metrics [32], six metrics were selected as the assessment system in this paper: network average, isolated node proportion, maximum connected subgraph relative size, network efficiency, aggregation coefficient, and average path length (Table 2).

Table 2. Urban network vulnerability assessment indicators.

Measurement Level	Indicator Description	Formula	
Average degree	When the network suffers from supply, the number of city nodes and the number of edges change, and the greater the change in average degree, the more fragile the network is.	$K = \frac{1}{N}\sum\limits_{i=1}^{N} K_i$	K_i is the degree of node i. K denotes the network average degree.
Percentage of isolated nodes	Reflecting the attack on the network, a node may be disconnected from other nodes, which may make the surrounding nodes become isolated, thus affecting the size and connectivity of the whole network.	$\Delta N = \left(1 - \frac{N^*}{N}\right)$	N and N^* are the number of isolated nodes before and after the attack. ΔN indicates the proportion of isolated nodes.
Maximum connected subgraph relative size	Indicates the size of the nodes that can be contacted when the network is attacked, reflecting the extent to which the network is compromised.	$G = \frac{P^\star}{P}$	P and $P^\star$ denote the number of nodes in the maximum connected subgraph after the network suffers a before-and-after attack. G denotes the maximum connected subgraph relative size.
Network efficiency	Reflects how easy it is for cities to transit through the network, with higher values indicating better connectivity.	$E = \frac{\sum_{\mathrm{i}=1}^{\mathrm{N}}\sum_{\mathrm{j}=1(\mathrm{i}\neq\mathrm{j})}^{\mathrm{N}} H_{ij}}{N(N-1)}$	n indicates the number of city nodes. H_{ij} denotes the reciprocal of the distance d_{ij}. E indicates city network efficiency.
Closeness centrality	The inverse of the sum of the weighted shortest paths from a node to all other nodes multiplied by the number of other nodes.	$C_i = \frac{n-1}{\sum_{j=1.j\neq i}^{n} d_{ij}}$	d_{ij} denotes the shortest path length between any two nodes in the network. C_i denotes the closeness centrality.
Betweenness centrality	The number of weighted shortest paths between all node pairs through a given node.	$B_i = \frac{\sum_{k\neq i\neq j}\frac{m_{ki}(i)}{m_{kj}}}{\sum_{i=1}^{n}\sum\frac{m_{kj}(i)}{m_{kj}}}$	m_{kj} denotes the weighted path between two nodes. $m_{kj}(i)$ denotes the number of times two nodes pass through node i. B_i denotes the betweenness centrality.

The urban network anti-interference performance analysis refers to the fact that the failure of a node in the urban network will affect the remaining nodes to find the connection of the remaining nodes, and there will be a certain self-regulation ability of the remaining nodes, and this ability is defined as the anti-interference performance. Nodes in the network transmissibility conversion function will be in the case of other node failures to produce different degrees of attenuation, and its minimum function value corresponds to the maximum anti-interference state. In general, the greater the magnitude of node function variation, the weaker the immunity to interference.

3. Results

3.1. Structural Resilience Characteristics of Urban Networks

3.1.1. Network Hierarchy

From the network hierarchy, the cities with the highest level were mainly located at the transportation arteries, which are comprehensive transmission hubs that also undertake the agglomeration and diffusion of factors, such as Zhengzhou, Xi'an and Lanzhou located on the Longhai Passenger Line, forming an east–west connected belt pattern. Jinan and Qingdao relied on the Jiaotian–Jinan Railway to form a skeleton of connection within the Shandong Peninsula. From the perspective of the overall watershed, the low values were scattered in the city and showed a spatial distribution of "low in the north and high in the south" in the watershed, with the characteristics of "robust" in small areas and "vulnerable" in large areas highlighted. The upper and middle Yellow River region and the Hexi Corridor region contained the third and fourth level of provincial capitals, and the low degree cities mostly focused on exchange and interaction with the provincial capital core cities, and the non-robustness of the provincial capitals tended to lead to increased local network vulnerability and an increased possibility of interruption or failure of transmission links via railroads (Figure 2).

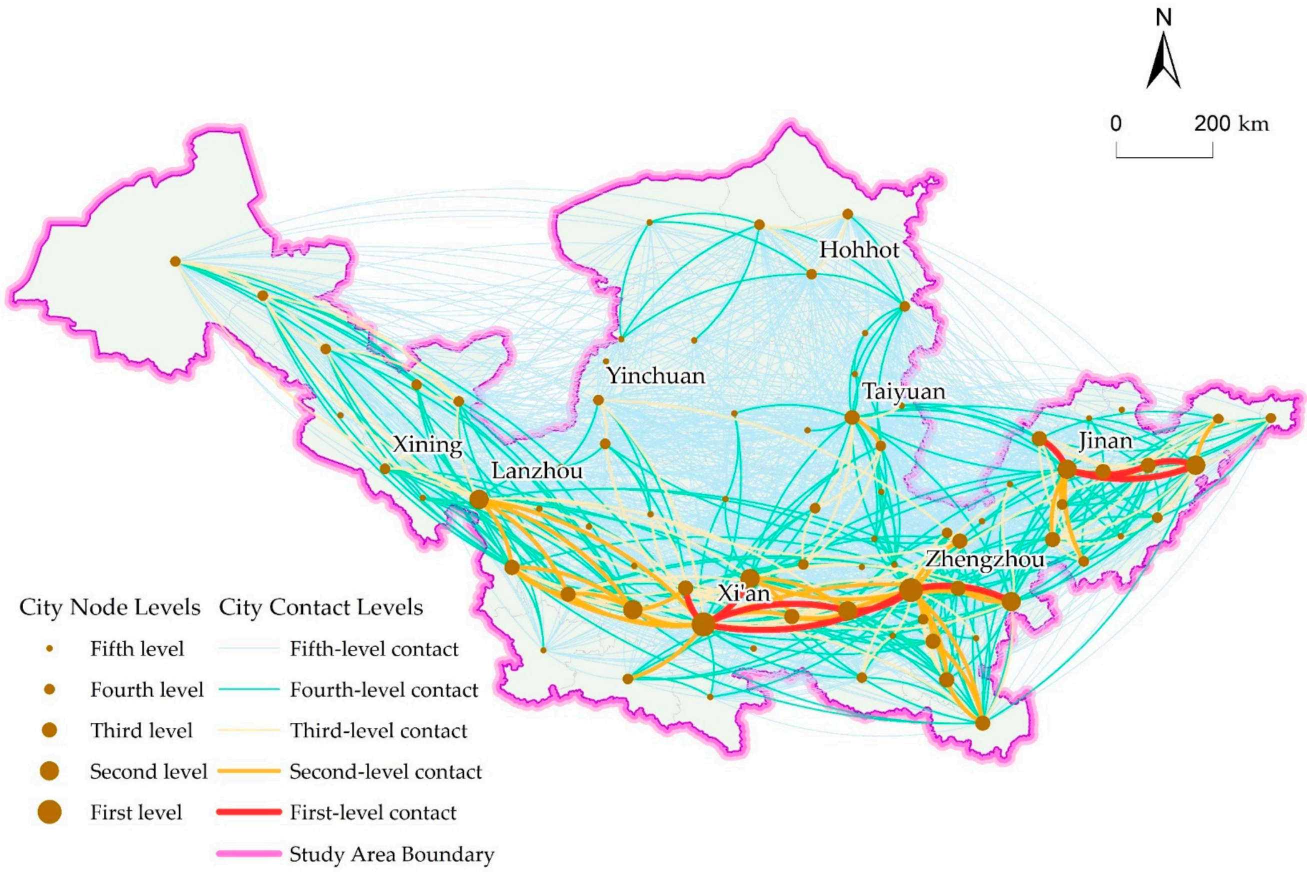

Figure 2. The spatial pattern of urban networks in the 2021 Yellow River Basin; an overview of the study area.

The absolute value of the fitted slope was 0.9839, using the nodal degree of cities in the Yellow River Basin fitted with the city rank order, which indicated that the urban network in the Yellow River Basin had significant hierarchical characteristics, reflecting that the core cities had a strong ability to communicate with and control the surrounding areas. The fitted curve had an overall power-law distribution and an obvious long-tail effect, indicating that the non-homogeneity of cities in the region was obvious, the core cities were prominent, the low-grade cities were obviously dependent on the high-grade cities in the network, and a more closed "weak outside and strong inside" pattern was easily formed.

3.1.2. Network Matchability

From the spatial distribution pattern of the average weighted degree of neighbor nodes, the average weighted degree of neighbor nodes in higher-level cities was lower, while the average weighted degree of lower neighbor nodes was distributed around higher-level cities in a fan-shaped distribution spatial pattern, indicating that there were more communication and interaction opportunities between the lower-level city nodes and higher neighbor nodes with average weighted degree nodes. Although the number of lower and lower neighbor nodes with average weighted degree nodes was smaller, the more obvious spatial difference could give more convenience and options for inter-city transmission links (Figure 3).

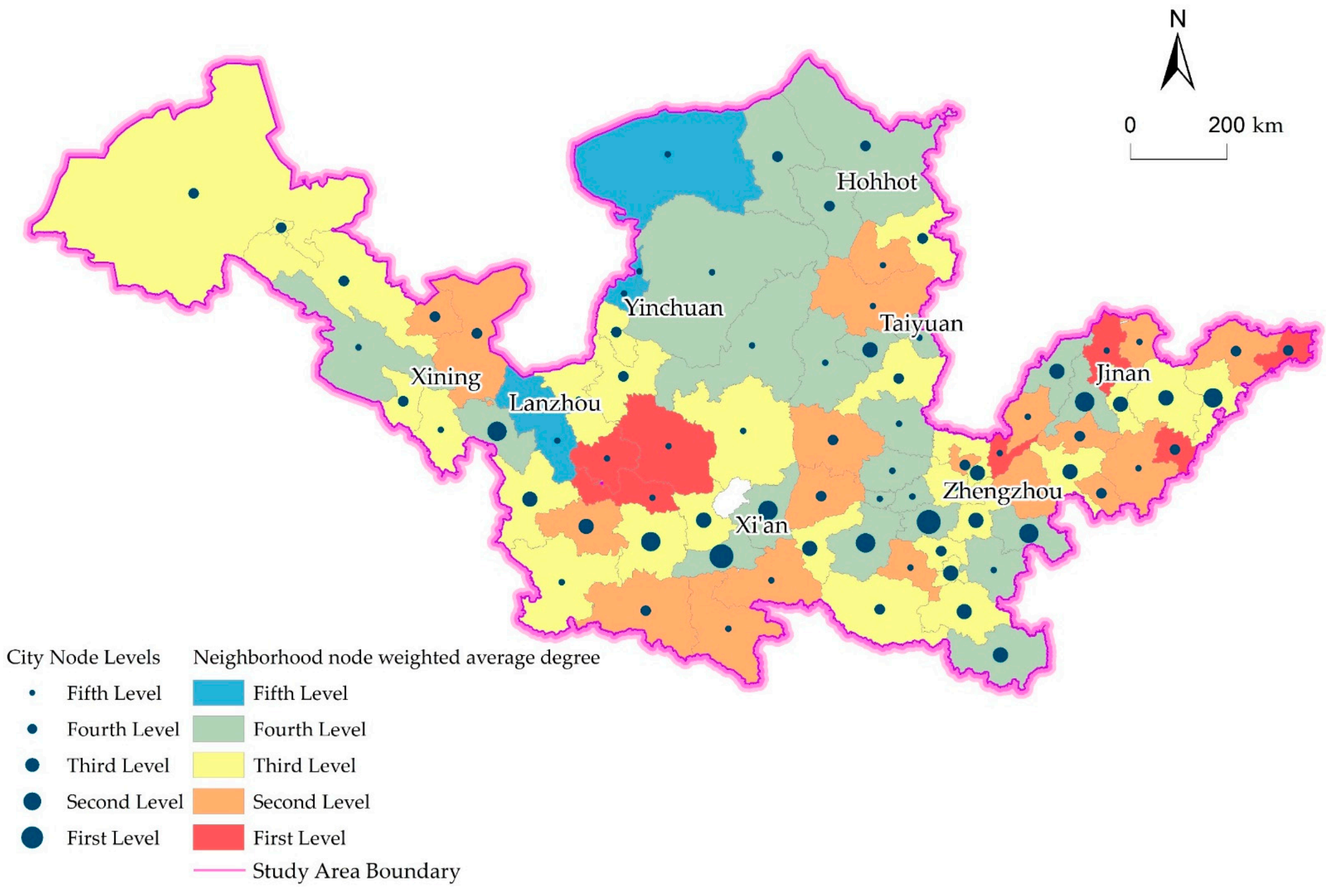

Figure 3. Spatial distribution of the average weighted degree of neighboring nodes in the Yellow River Basin in 2021.

By measuring the weighted degree of the neighboring nodes of the cities in the Yellow River Basin, the network degree correlation coefficient was −0.0519. The city network had the obvious characteristics of heterogeneous matching resilience, weak cohesion of the network structure, and a negative correlation between neighboring nodes, indicating that the path connection form was more diversified, and the network structure was more open, which was conducive to the improvement of network structure resilience. The large national comprehensive transmission hubs of Zhengzhou, Xi'an, Lanzhou and other cities combined with their location advantages, by radiation driven by the surrounding areas of the city, or by maintaining a good interactive relationship with cross-regional hub cities to undertake inter-city flow function, had the overall trend of good flattening.

3.1.3. Network Transmissibility

By calculating the topological paths between all city pairs in the Yellow River Basin, the global average path length of the urban network in the Yellow River Basin was 1.48, which indicated that the transfer efficiency between the cities in the region was high, and the exchange and interaction between the cities in the whole region could be achieved almost within two transit times. Further, the city topology network analysis showed that 1675 city pairs could be directly connected in the region, accounting for 53.01%, and 1445 city pairs needed to transit once to achieve connection, accounting for 45.73%. The total connection efficiency of 98.73% reflected the high accessibility and diffusion of the Yellow River Basin city network, and the network was conducive to the transfer and exchange of factor flows between cities. In addition, 1.27% of the cities had low transmissibility efficiency, requiring two transit times to achieve inter-city interconnection. Such cities are more dependent on provincial capitals and comprehensive transmission hubs, which can easily cause paralysis in such cities when local network disruptions or interruptions occur and may affect the resilience of urban networks.

3.1.4. Network Agglomeration

By measuring the agglomeration coefficient of all cities in the Yellow River Basin, the overall average agglomeration coefficient of the network was 0.76, indicating that the agglomeration effect and small-world effect of the city network were significant, reflecting to a certain extent the closer interconnection between cities. From the agglomeration coefficient of each city, the overall coefficient ranged from 0.60 to 1.0, among which the agglomeration coefficients of Haibei and Dongying were 1. Comparing the weighted degree values of 19 and 23 of the two cities, it indicated to a certain extent that the phenomenon of attachment to high-circulation cities existed in the two cities, and the low interaction opportunities between these types of cities may lead to an insufficient agglomeration effect in these types of cities. The top three cities with the highest weighted degree were Zhengzhou, Xi’an, and Jinan, and the corresponding agglomeration coefficients were 0.60, 0.61, and 0.67, respectively, indicating that the provincial capitals were not well connected with each other, further confirming the one-way connection between the core cities and the peripheral cities. Taken together, the low agglomeration coefficients of integrated hub cities and provincial capitals reflected the global connectivity characteristics of network openness, which could promote an overall network association effect and enhance the structural resilience of the overall network.

3.2. Urban Network Structure Resilience Assessment

3.2.1. Vulnerability Assessment

The network resilience characteristics were explored by using a computer simulation to simulate random attacks and deliberate attacks on the urban networks in the Yellow River Basin using Python programming with scaled node deletion. The changes in the six characteristic values of network average degree, isolated node proportion, agglomeration coefficient, average path length, network efficiency, and relative size of maximum connectivity subgraph when the urban network is attacked were calculated and used in the vulnerability analysis of the urban network in the Yellow River Basin (Figure 4).

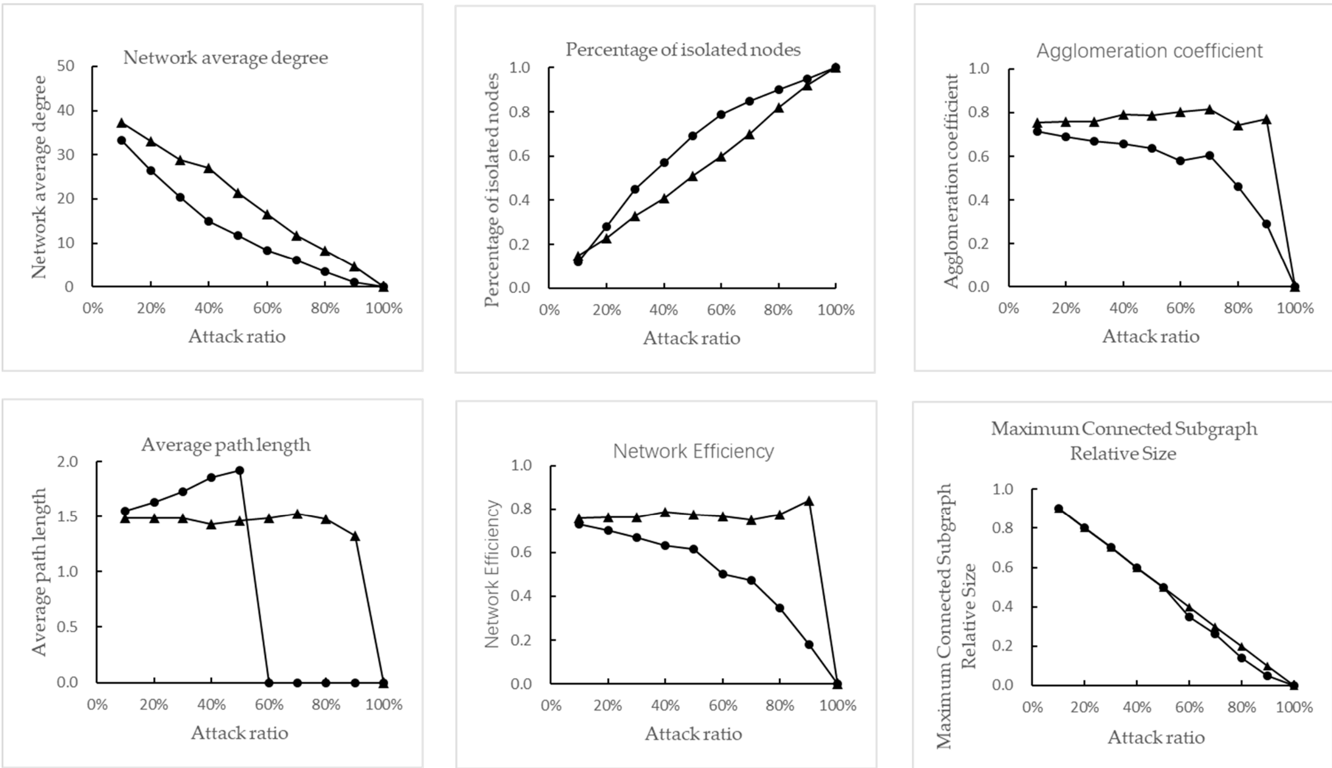

Figure 4. The variation in network eigenvalues under random attack and deliberate attack. -▲- Deliberate attacks; -●- random attacks.

Under random attacks, the average density of the network and the relative size of the maximum connectivity subgraph showed a linear decreasing trend with the increase in the attack proportion. The clustering coefficient and the network efficiency changed in a similar trend, where both experienced a period of smooth and slow decline, and then showed a steep decline when the proportion of random attacks was greater than about 60%. The average path length showed a fluctuating decreasing trend under random attacks. The proportion of isolated nodes in the overall linear and smooth increase under random attack indicated that the proportion of isolated city nodes gradually increased after the attacked nodes lost connection with other nodes, and the overall change in city network was stable. Overall, the urban network in the Yellow River Basin performed more robustly under a random attack.

Under a deliberate attack, the average degree of the network first decreased significantly with the attack proportion, and then the decreasing trend slowed down after reaching the critical point, and the target of the attack before the critical value was mainly the hub-type height-value node city, which undertook the main bridging intermediary function in the network. The attack proportion of the isolated nodes first increased significantly, and then the increase tended to be stable, indicating that the isolated nodes were strongly dependent on the hub height-value city. The average path length in the network and network connectivity was inversely proportional; the shorter the path, the better the connectivity. The average path length changed the most. The average path length under a deliberate attack first increased slightly, and then showed a precipitous decline when the attack proportion reached about 60%, indicating that the network connectivity deteriorated rapidly and dropped directly to a value of 0, and the overall network was in a paralyzed state. Correspondingly, the agglomeration coefficient, network efficiency, and the relative size of the maximum connectivity subgraph increased in decline after the attack proportion reached the 60% threshold, and the overall network began to split into many subnetworks with a high degree of network fragmentation. With the increase in the attack proportion, the network basically collapsed until the completely isolated state.

3.2.2. Anti-Interference Performance Assessment

The closeness centrality of a city network node indicates the indirect accessibility of the city node in the network, reflecting the radiation capability of the node. The betweenness centrality indicates the transmit and articulation function of the nodes in the network, reflecting the transmit function of the nodes. From the anti-interference performance analysis, it can be concluded that the overall anti-interference performance of the network was more balanced. By arranging the nodes in ascending order according to the anti-interference index, it was found that the rate of change in the transit function anti-interference performance index was 0.0698, which was 8.5 times higher than that of the radiation function, indicating that the difference in the transit function anti-interference performance of the urban nodes was greater compared with that of the radiation function (Figure 5) (Table 3).

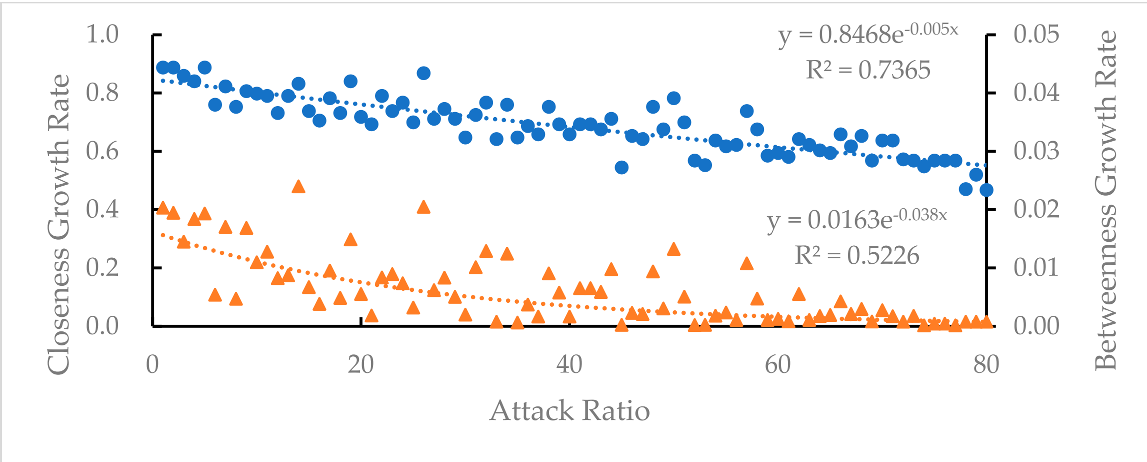

Figure 5. The measure index of anti-jamming of city network. -▲- Betweenness centrality; -●- closeness centrality.

Table 3. Classification of anti-jamming performance of the urban network in the Yellow River Basin.

	Radiation Function Anti-Interference Performance	**Transit Function Anti-Interference Performance**
First level	Zhengzhou, Xi'an, Shangqiu, Taiyuan, Weinan, Luoyang, Xinyang, Lanzhou, Jinan, Dezhou.	Dezhou, Jinan, Luoyang, Shangqiu, Xi'an, Zhengzhou, Taiyuan, Lanzhou.
Second level	Xianyang, Kaifeng, Baoji, Luohe, Nanyang, Sanmenxia, Hohhot, Zhumadian, Baotou, Qingdao, Yangquan, Yinchuan, Weifang, Xinxiang, Datong, Anyang, Dingxi, Zibo, Jining.	Baoji, Anyang, Yinchuan, Yangquan, Sanmenxia, Xining, Ulanqab, Datong, Xianyang, Baotou, Kaifeng, Hohhot, Nanyang, Weinan, Xinyang.
Third level	Ulanqab, Xuchang, Xining, Jinzhong, Tai'an, Tianshui, Pingdingshan, Zaozhuang, Zhangye, Jiayuguan, Wuzhong, Yantai, Hebi, Jiuquan, Zhongwei, Wuwei, Binzhou, Linfen, Yuncheng.	Binzhou, Weifang, Zhongwei, Jining, Tai'an, Pingdingshan, Qingdao, Haidong, Xuchang, Wuzhong, Jiuquan, Jinzhong, Zhangye, Jiayuguan, Dingxi, Zhumadian, Zibo, Xinxiang, Luohe.
Fourth level	Yulin, Heze, Hanzhong, Weihai, Haidong, Liaocheng, Rizhao, Lvliang, Jinchang, Ankang, Xinzhou, Shuozhou, Longnan, Shangluo, Yan'an, Bayannur, Changzhi.	Linfen, Yuncheng, Ankang, Yan'an, Baiyin, Jinchang, Yantai, Bayannur, Hanzhong, Liaocheng, Shangluo, Heze, Longnan, Lvliang, Yulin, Wuwei, Zaozhuang, Hebi, Tianshui.
Fifth level	Jiaozuo, Jincheng, Erdos, Baiyin, Wuhai, Pingliang, Guyuan, Linyi, Puyang, Qingyang, Shizuishan, Zhoukou, Jiyuan, Haibei, Dongying.	Puyang, Shizuishan, Linyi, Qingyang, Zhoukou, Pingliang, Guyuan, Weihai, Rizhao, Erdos, Jiyuan, Haibei, Dongying, Wuhai, Jincheng, Xinzhou, Shuozhou, Jiaozuo, Changzhi.

In the node radiation function anti-interference performance measurement, the cities in the first level included the Zhengzhou, Xi'an, Taiyuan Lanzhou, and Jinan provincial capital cities, but also included the Yellow River Basin backbone Longhai Line of Luoyang, Shangqiu, Weinan, and Xinyang, and the Jiaoji Railway of Dezhou and other comprehensive transmission hub cities; this level of city node radiation function had the strongest anti-interference performance. In addition to the three provincial capitals of Hohhot, Yinchuan, and Xining, the rest of the cities in the second tier were all local hub cities, and the anti-interference performance of the radiation function was further weakened. In the node transit function anti-interference performance measurement, Zhengzhou, Xi'an, Lanzhou, Jinan, and other cities were always ranked in the first tier with strong anti-interference performance. Xinyang and Weinan dropped to the second tier of the transit function, and the nodes of the cities in each tier were in the maximum interference state more evenly (Table 3).

In a comprehensive view, combined with the node radiation function anti-interference performance and transit function anti-interference performance measurement, Zhengzhou, Xi'an, Lanzhou, and other provincial capital cities were basically distributed in the first and second levels, undertaking the main radiation and transit functions, and were further polarizing in terms of importance. Hub cities such as Luoyang, Shangqiu, and Weinan, which are located in major traffic arteries, continued to consolidate their links with provincial capitals and railroad feeder cities and became strong local traffic hubs, making the overall anti-interference performance difference narrower (Table 3).

3.3. Impact of Network Structural Resilience in the Context of the 7·20 Rainstorm Disaster in Zhengzhou

In July 2021, in Zhengzhou City, Henan Province, after extraordinary heavy rainfall, the east–west Longhai Railway Zhengzhou section and the north–south Beijing–Guangzhou Railway traffic was blocked. The railroad corridors in Henan Province are interwoven, and Zhengzhou is an extremely important transmission hub in China's railroad passenger network, where many railroad trunk lines such as the Longhai Railway and Beijing–Guangzhou Railway intersect. After the sudden rainstorm in Zhengzhou briefly appeared, the Zhengzhou site failed, that is, passengers could not enter and exit Zhengzhou station, and the railroad line by way of Zhengzhou began to stop, with railroad access to the wave of railroad passenger cars passing through Zhengzhou being stopped. Putting the above background together, in the context of the urban network carved by the railroad network, what would be the impact of the failure of the Zhengzhou node, or the failure of all trains involving the Zhengzhou node, on the resilience of the urban network in the Yellow River Basin? How well does the Yellow River Basin urban network function after coping with external shocks?

3.3.1. Network Resilience Impact

Consider two cases of node failure and line failure in the urban network (as in Figure 6). In the node failure case, node C stops working normally, but the same line A–B and D–E can still pass normally. In the line failure case, nodes A, B, C, D, and E all fail. Therefore, this paper defines that when the Zhengzhou node fails, the Zhengzhou transmission and transit functions are canceled, but the remaining city connections of the trips containing the Zhengzhou node can still work normally, and such a situation is the node failure state. When the trips involving all the lines in Zhengzhou cannot operate normally, such a situation is the line failure state.

The impact of node failure and line failure on the urban network in the Yellow River Basin was simulated through a complex network to explore the urban network resilience characteristics under the failure of the Zhengzhou node and the line involving Zhengzhou. The changes in the network resilience characteristics values for the three cases of the original network, node failure, and line failure were obtained by calculation (Table 4).

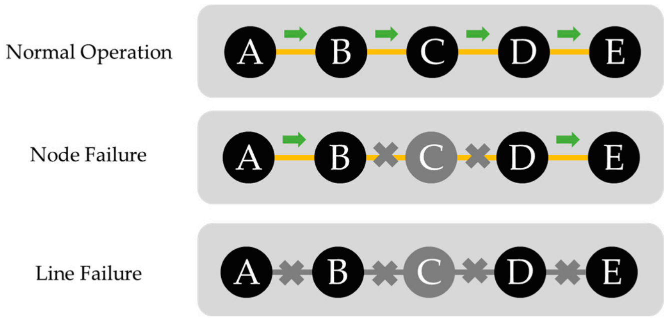

Figure 6. Schematic diagram of node failure and line failure.

Table 4. Node failure and line failure urban network characteristic value change.

	Average Degree	Average Path Length	Network Efficiency	Maximum Connected Subgraph Relative Size	Agglomeration Coefficient	Percentage of Isolated Nodes
Normal operation	41.90	1.48	0.76	1.00	0.75	0.00
Node failure	40.68	1.49	0.76	0.98	0.75	0.01
Line failure	27.21	1.73	0.66	0.97	0.69	0.03

The changes in the average clustering coefficient, the relative size of the maximum connected subgraph, and the proportion of isolated nodes in the node failure and line failure states were within 10%. The network efficiency decreased by 0.004 and the average path length change increased by 0.01 for node failure, indicating that the Zhengzhou node failure case had little impact on urban network resilience. When the line failed, the average degree decreased to 27.2, indicating a strong transmission and access capacity. The average path increased by 0.23, and the network efficiency, as well as the clustering coefficient, could still be maintained above 60%, indicating that the urban network in the Yellow River Basin could still maintain a good network operation efficiency when suffering from the state of paralysis of important nodes and important railroad lines, and the network had a strong resilience.

Comparing the urban network structures in different states, it was found that whether in the node failure state or in the line failure state, the urban network in the Yellow River Basin was able to adapt to the destructive changes in the network through its own structure when it was hit by natural disasters. The network efficiency, average path length, and clustering coefficients remained high even in the case that all lines involving Zhengzhou failed, and the urban network in the Yellow River Basin had strong destructive resistance and robustness.

3.3.2. Network Node Impact

The impact of extraordinary heavy rainfall on the overall network resilience in Zhengzhou was not significant, but it had a large impact and difference for some cities. The impact of sudden natural disaster time on urban nodes was explored in terms of changes in urban network degree centrality, neighborhood centrality, and betweenness centrality during node failure and line failure.

In terms of proximity centrality, overall node failure was similar to line failure on spatial distribution, but the impact on urban nodes was significantly deepened with an overall change of 58%, including Kaifeng with a change of more than 85%, indicating that Kaifeng was significantly dependent on Zhengzhou for east–west regional transmission. Comparing node failure and line failure (Figure 7(Aa,Ba)), the high-level change nodes were mainly distributed along the Longhai Railway and Beijing–Guangzhou Railway, and Zhengzhou was the intersection hub of two important railroad trunk lines; node failure and line failure had a large impact on the two railroads. While the provincial capital cities of Xi'an, Taiyuan, and Lanzhou were large in scale in the network and had a strong self-regulation function, the impact was relatively weak. The cities with lower impact showed obvious sporadic distribution characteristics, mainly including Haidong Tibetan Autonomous Prefecture, Haibei Tibetan Autonomous Prefecture, Xining, Hanzhong, Ankang, Linyi, Zaozhuang, and Rizhao City.

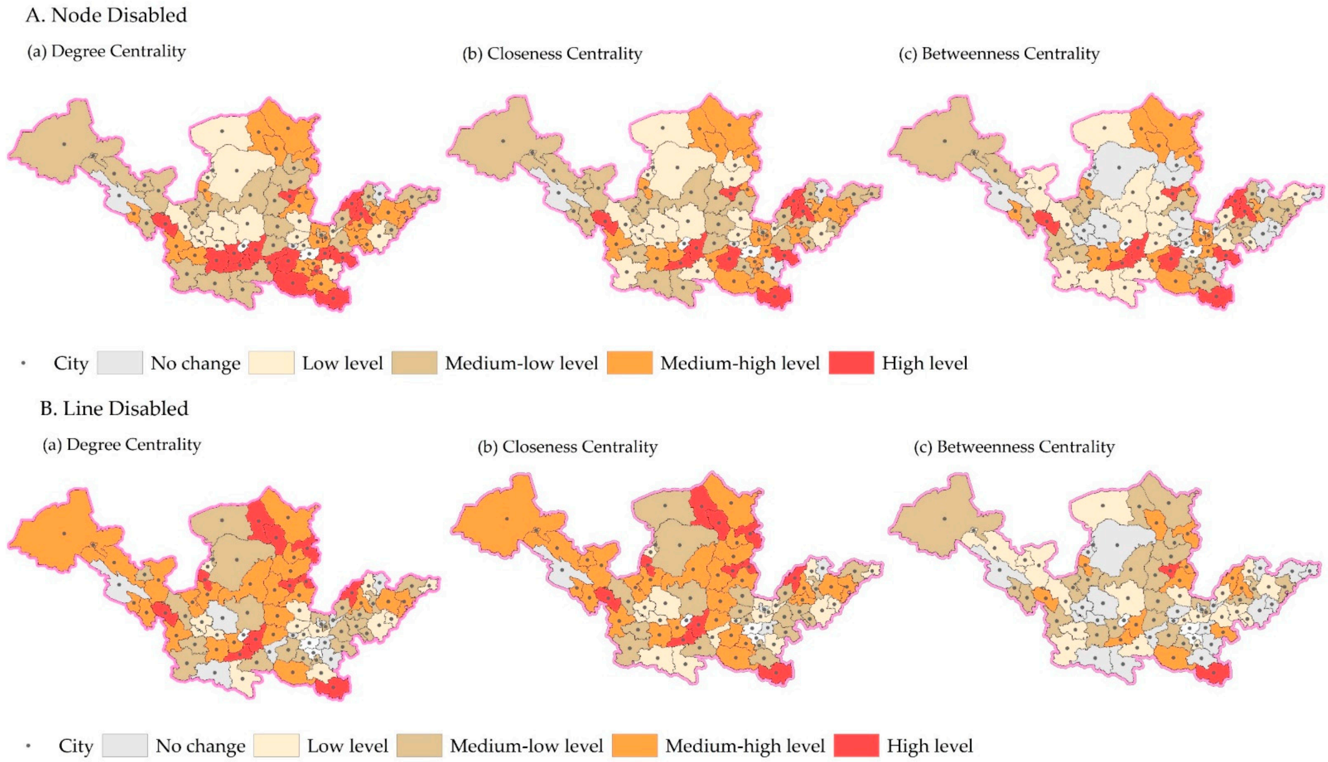

Figure 7. Spatial pattern distribution of node failure and line failure urban impact.

In terms of betweenness centrality, the mean values of betweenness centrality were 0.0064 and 0.0094 for the node failure and line failure states (Figure 7(Ab,Bb)), respectively. When the nodes failed, the medium and high levels were mainly distributed along the Longhai Railway, and the impact on the provincial capital cities was more significant, reflecting the weakening effect on the transit function of the railroad corridor under the failure of the core railroad hub, and the medium-low levels and low levels were farther away from Zhengzhou. When the line failed, all the railroad lines related to Zhengzhou failed, and the medium and high levels were distributed along the Beijing–Guangzhou Railway and Longhai Railway in an axial belt with Zhengzhou as the core.

In terms of degree centrality, the mean values were 0.52 and 0.35 for the node failure and line failure states (Figure 7(Ac,Bc)), respectively, and the line failure significantly expanded the influence range and further deepened the influence degree compared with the node failure. In terms of the degree of impact, urban nodes were mainly dominated by a decrease in degree centrality, indicating that under the state of node failure and line failure, the city generally reduced its self-core degree to compensate for the lack of a core degree in the failed area in order to achieve network rebalancing.

4. Discussion

4.1. Network Resilience

Strengthening or weakening key node connections in a network can increase the network's ability to proactively respond to external disturbances and shocks [18]. Cities need resilience, and urban networks, as in the case of the relational expressions of the many cities in the Yellow River Basin, need even more resilience. The Yellow River Basin is an important basin geographic unit in China, and a complex network of connections has been formed within it, and how to cope with the uncertainties in the network remains an urgent problem [33].

For the structural resilience characteristics of the city network, this paper found that the hierarchical and heterogeneous nature of the city network in the Yellow River Basin was prominent, indicating that the cities in the Yellow River Basin, such as Xi'an, Zhengzhou, Lanzhou, Jinan, and other cities at the top level of the city network, could use their control and competitive advantages to stimulate other cities in the region, enhance inter-city functional complementarity and multi-directional collaboration, respond quickly to a regional unexpected shock response, and drive the overall city network such that the efficiency of the network as a whole could be improved. For transmissibility and agglomeration, efficient transmissibility efficiency and rich path selection can ensure the normal operation of the network to a greater extent when sudden node failures or disturbances occur in the region. This was also confirmed by Peng et al. in their study of urban network resilience in the middle reaches of the Yangtze River urban agglomeration [34].

For the assessment of the structural resilience of urban networks, the network disintegrated rapidly after the 60% threshold in the case of deliberate attacks, and in the face of large-scale node attacks, on the one hand, the nodes at the middle and upper levels should functionally fail to have a huge impact on the network as a whole, and the phenomenon of weak centrality of vulnerability nodes themselves and weak connections with neighboring regions also emerges, which is consistent with the findings of Xie et al. [35]. From the perspective of interference resistance performance, the transfer function resistance performance increased sequentially from the first to the fifth level with the number of cities, reflecting that more than half of the cities were in the sub-middle level and did not have a prominent position in the network as well as undertaking functions.

Combined with cases of natural disasters and other emergencies, the study of urban network resilience has a positive effect on analyzing the negative effects of urban networks and improving urban safety, and it especially has theoretical guidance to improve the adaptability and recovery ability of regional urban networks when they are hit.

4.2. Policy Suggestions

The assessment of urban network resilience and structural resilience characteristics analysis in the Yellow River Basin has a positive effect on improving urban and regional spatial security and has theoretical guidance to increase the structural resilience of urban networks in the Yellow River Basin, can reduce the vulnerability of the urban network, and can strengthen the anti-disturbance performance of regional urban nodes. According to the characteristics and spatial development of the urban network in the Yellow River Basin, the following suggestions are drawn:

(1) Promote the construction of resilient cities to guarantee the reliability of core cities. When core cities such as comprehensive hubs are deliberately attacked, they have a greater impact on the overall resilience of the urban network, so we can try to add the concept of resilient cities to urban planning, enhance the resilience rebound of cities, and improve the reliability of urban nodes as well as the overall network resilience.

(2) Build a comprehensive network to enrich inter-regional inter-provincial connectivity. We should form an interconnected inter-provincial integrated connectivity network through land transmit connections and the layout of feeder airports, build a common management information platform, guarantee network route substitution, share the core city network carrying pressure, reduce network vulnerability, and enhance network structural resilience.

(3) Strengthen risk prevention and guarantee the anti-disturbance performance of urban nodes. We should improve the safety supervision system, strengthen the linkage development of provinces and regions both upstream and downstream, strengthen the construction of an emergency response system, form a risk prevention system containing multi-sectoral collaboration, develop emergency plans, reduce the physical damage sit-

uation of the urban network in the high-speed rail network by natural disasters or line failures, and improve the anti-interference performance of the urban network in the Yellow River Basin.

4.3. Limitations and Prospects

Due to the limitations of the data, it is not yet possible to fully assess and reveal the structural resilience characteristics of the Yellow River Basin network. In the future, we will try to construct multi-city networks with multi-stream data to achieve more empirical support. Meanwhile, this paper selected prefecture-level cities as the research unit, and in the future, we can consider county administrative units to achieve a more refined analysis so as to comprehensively understand the multi-scale divergence of regional network structural resilience.

5. Conclusions

This paper constructed the Yellow River Basin urban network based on railroad passenger flow data, explored the changing characteristics of network structure resilience when the Yellow River Basin urban network responds to disasters or attacks, and further analyzed the resilience characteristics of the Yellow River Basin urban network through complex network measurement indicators, combining vulnerability and anti-disruption performance perspectives and changes in urban network resilience after node failure and line failure, with the following main conclusions:

(1) The urban network in the Yellow River Basin was clearly hierarchical, with a significant spatial distribution of “low in the north and high in the south” and the overall characteristics of “robustness” in small areas and “fragility” in large areas. The network connection forms were diversified and open. The network transmission efficiency was high, and the edge cities depended on the core cities with prominent characteristics, and the risk load of regional core cities rose.

(2) The network structure was “robust” as it maintained high operational efficiency and connectivity under random attacks. Under a deliberate attack, the city network operated efficiently with a small increase in connectivity before the 60% threshold, and after the threshold, the overall network started to split into many sub-networks, and the network fragmentation gradually increased until the network collapses.

(3) Zhengzhou node failure and line failure states in the Yellow River Basin urban network were resilient, and in suffering important nodes and lines going down it could still maintain good network operation efficiency. The core nodes in the impact of natural disasters could adapt to the destructive nature of the network through the urban network structure self-regulation.

Author Contributions: Conceptualization, Y.X.; Data curation, Y.X. and H.T.; Investigation, Y.X. and X.T.; Methodology, Y.X.; Writing—original draft, Y.X.; Writing—review and editing, H.T. and X.T. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Project for Philosophy and Social Science Foundation of Hunan Province (No. 20YBQ024) and the Key Laboratory of Key Technologies of Digital Urban–Rural Spatial Planning of Hunan Province (No. 2018TP1042).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available because research is ongoing.

Conflicts of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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