VULNERABILITY ASSESSMENT OF OIL SPILL DISPOSAL IN RIVER TRUNK LINE BASED ON INTERDEPENDENT NETWORK

Jinlu Sheng,* Yiyang Wan,* and Xiangchun Xing*

Abstract

Since its application in the field of transportation, interdependent network theory has contributed a lot to the promotion and optimisation of aviation system, urban transport system, multimodal transport system, and so on. However, little work has been done to the safety and resource allocation about river oil spill emergency while this approach has been proven to be remarkably effective on multi-level management. In light of this, the article intends to analyse the vulnerability of oil spill rescue system within the fluctuating backwater zone and natural navigation area in the upper Yangtze River, thus laying the foundation for the construction of an automatic assessment system, so as to provide suggestions for the distribution and planning of local oil spill emergency rescue forces. Based on the system structure entropy, a multilayer interdependent river oil spill disposal network is constructed to illustrate and analyse the characteristics of the study area. The result shows that an interdependent network is more sensitive and effective to identify the weakness of the rescue system than the ordinary complex network, which tends to be more realistic and reliable.

Key Words

Oil spill, structure entropy, interdependent network, automatic assessment

1. Introduction

Due to the prosperity of shipping market, the increasing scale of water transportation and trade leads to frequent marine accidents, which are much more severe in the Yangtze River. Especially in the backwater zone, where there are lots of reefs and shoals, the risk of shipping will be greatly increased, so will cause the difficulty to rescue. It is inadvisable to blindly ask the maritime department to strengthen supervision and accident prevention. Obviously, accidents are inevitable, but a reasonable distribution of rescue force can effectively control their consequences. Among all kinds of water emergencies, oil spill is one of the most urgent and laborious accidents owing to its rapid diffusion, difficult recovery as well as huge potential ecological and public threat. In addition, the mainstream of the Yangtze River is fast and narrow, which puts forwards more stringent requirements for the distribution of rescue forces. Therefore, it is critical to distinguish the river oil spill from land-based, coastal, and offshore emergencies [1], [2]. Especially, a reformed automatic assessment system has been needed for dynamic risk identification and decision support. Though many methods about emergency allocation and oil spill modelling have been proposed [3]–[5], few studies have addressed emergency resources allocation river oil spill or chemical spill with interdependent network while this theory has been proven effective with many similar issues, such as load redistribution in aerial network [6]. Most of them are concentrated on the characteristics of the accidents and emergency materials themselves, *i.e.*, to search for the relevance among those complex rescue subjects and objects without considering the random or functional failure that may occur under extreme conditions. On this basis, complex network and its derived interdependent network theory have been widely used in resource allocation and robustness analysis in many other fields, including but not limited to power grid optimisation, epidemic spread, key infrastructure planning and maintenance, *etc.* As for interdependent ones, they are more sensitive to the knock-on effects of failures. Therefore, using this theory, emergency simulations will be more realistic and conducive to the traceability of cascading failures that may occur in oil spill rescue systems under extreme conditions. And that is why interdependent networks can be much more capable of the system synergy efficiency and vulnerability analysis ignored by the traditional river emergency material allocation models.

In the initial studies about interdependent network, some scholars realised that critical infrastructures were always highly interconnected in many complicated ways, and the prolonged power crisis at that time pushed people to identify and evaluate these interdependencies through the complex network [7], [8]. Though there are other models

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to judge whether the network crashes [9]–[11], the most essential and common method to analyse the network's robustness and failure mode is to clarify the cascading failures in it, and it is more usual to detect a large-scale fault propagation caused by a single node in power grids, communication or collaboration systems, and so forth [12]–[14]. When it comes to thriving transportation, various traffic flows are becoming more and more interdependent with each other, such as flights in the air transport network (ATN), vehicles in the urban transport network, as well as freightage in multimodal transportation, which brings complicated interaction between overloads and interdependency loss and makes them distinct from those without flow [15]. For instance, from the perspective of load propagation mechanism, the characteristics and auxiliary support of passenger propagation in the interdependent public transport network can be carried out [16]. Furthermore, in order to find the differences between complex network and interdependent network, it is much more significant to utilise multilayer network to analyse heterogeneous networks. However, while studying European ATN rescheduling, it was found that multilayer interdependent network composed of specific airline subnet had lower anti-interference ability than the equivalent single-layer network, which meant the application of this ATN was too simplified to estimate its elasticity correctly at that time [6]. Furthermore, in the actual operating process, certainly, the robustness may be better than the theoretical one, because each node of network has its own properties and the links among them are likely to be weakly interdependent [17]. Nonetheless, we still need to consider the worst situation under emergency or attack, so that the cascading failure analysis is usually carried out under the assumption that the network is interdependent. Of course, some obvious properties can be obtained by analysing statistical characteristics of network itself [18]. However, the analyses are not always totally based on interdependent networks, but become part of the overall model and form complementarity. In view of this, the interdependency of multimodal networks filled the gap for modeling crossing disruptions [19], and the multilayer interdependent network was constructed to analyse the vulnerability of ATN by combining with the structure entropy theory of cyber–physical system [20].

This article aims to analyse the vulnerability of fluctuating backwater zone and natural navigation area in the upper Yangtze River (from Yangjiaobao to Jieshipan), in order to provide a methodological reference for the automatic assessment system construction, which can identify dynamic risks and advise on the distribution and re-planning of local oil spill emergency rescue forces. Thereby, this can also serve as a reference for the subsequent construction of inland river network model. As a result, a multilayer interdependent river oil spill rescue network is constructed to illustrate the characteristics of study area based on system structure entropy and network efficiency. Finally, the obtained results are analysed to identify the emergency resource allocation strategies to meet the estimated demand.

2. Study Area

The study area is the fluctuating backwater zone and natural navigation area in the upper Yangtze River, referring to the area between Yangjiaobao (582.3 km of the upper Yangtze River Channel) in Changshou District and Jieshipan (825 km of the upper Yangtze River Channel) in Yongchuan District under the jurisdiction of Chongqing Maritime Safety Administration (hereinafter referred to as study area). Its special geography conditions, such as fast current, narrow channel bend, and large water level change, have brought great difficulties to emergency rescue. In addition, the navigation environment within the area changes with the water level of Three Gorges Reservoir, and the internal scales of channel are uneven. There are also many navigation obstacles, such as the riverbank topography, reef, and debt dam, which will cause uncertain influences with the change of water level. Even the navigation reference objects in the river channel would change greatly. For example, in flood season, the original reef and bond dam in the channel are submerged into the water. However, when they are affected by the high-water level, the original complex flow characteristics will weaken or disappear, so their accurate positions become difficult to identify and judge. By comparison, in the dry season, underwater reefs and dams gradually emerge from the water surface, the river channel narrows, and the crossing line for ferry and crossover need to be adjusted and changed continuously with the decrease of water level, which brings great difficulties to emergency rescue. At present, in the study area, the distribution of emergency rescue forces led by the maritime department is imbalanced, and the emergency rescue facilities are imperfect, contributing to a certain gap with the actual needs. Therefore, reasonably determining the distribution of rescue forces in the research area plays a great role in elevating Chongqing Maritime Administration's performance of maintaining water traffic safety, preventing ship pollution, implementing human life rescue, and serving the development of Chengdu-Chongqing double city economic circle and the Yangtze River economic belt.

3. Construction of Oil Spill Emergency Rescue Network

The multilayer interdependent network is selected as the main structure of this rescue network, because the multilayer and single-layer inter-dependency networks have differences in the number and distribution of points and edges, and their construction and calculation results are also different. Especially for a network with single targets which have multiple attributes and functions, the relative independence of those attributes or functions will be weakened in the ordinary two-dimensional single-layer network. In addition, the coupling characteristics of some components and the local or overall network will be ignored in that way. As a result, simplified single-layer networks often lead to overestimation of the real network systems' resilience [6]. Therefore, multilayer independent networks are usually more practical than the equivalent single-layer

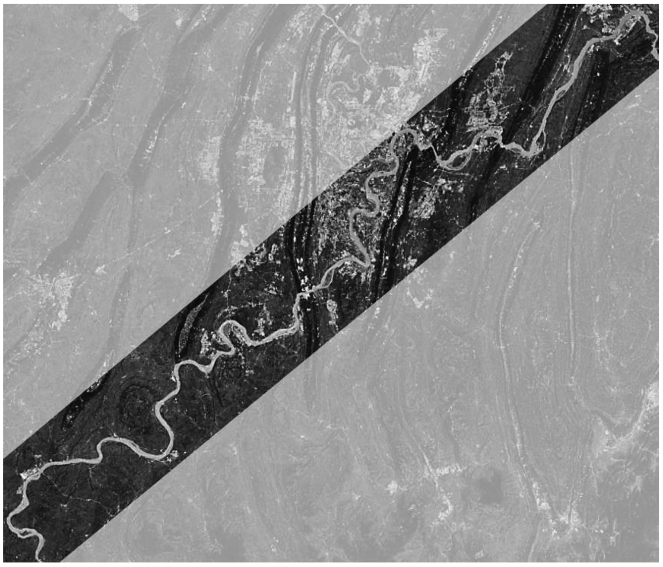

Figure 1. The fluctuating backwater zone and natural navigation area in the upper Yangtze River.

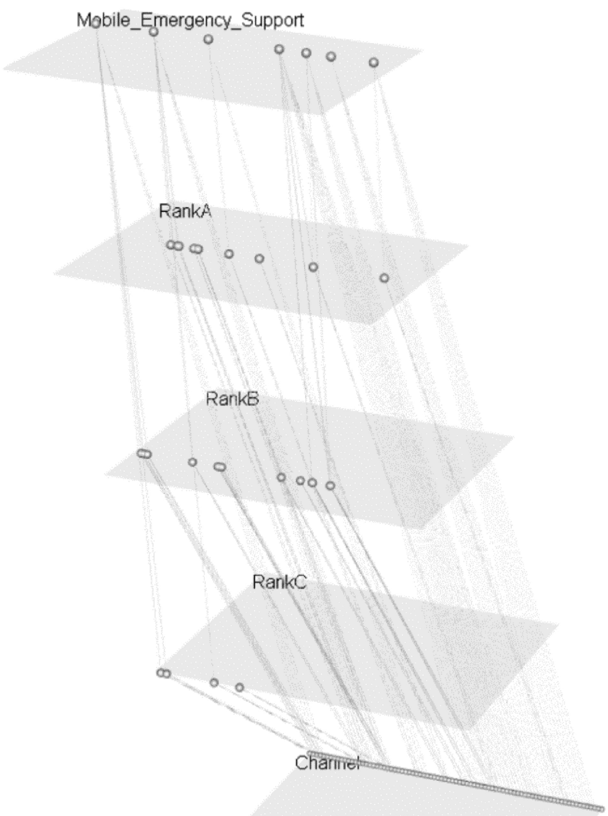

Figure 2. The multilayer interdependent network created by MuxViz [21].

dependent networks while they have lower anti-interference ability.

In order to illustrate the heterogeneous dependency of the rescue system, a multilayer interdependent network with five layers is established, which can also make the calculating programme easier to classify and visualise more intuitive. It consists of mobile rescue subnet (*Mobile_Emergency_Support*, which comprises of the law enforcement ships and rescue boats' standby stations and patrol range), fixed resource subnet (*RankA*, *RankB*, and *RankC*, which are the classifications of wharves based on their ability to handle oil spills), and channel subnet (*Channel*, made up of the channel mileage nodes).

This study classifies oil spill disposal capability of each wharf, rather than prioritising allocation based on the transport capacity of all ships and the mobilisation capacity of wharfs. Here are the reasons:

1. If using these two capacities to decide the allocation priority, since the number of social ships far exceeds the rescue ships, the proportion of the actual rescue transportation volume will be diluted, and the obtained result will be the transportation volume weight of the wharfs and the social ships. Therefore, in the process of calculating the oil spill disposal capacity, this study uses the transportation capacity of patrol ships and rescue ships to participate in the cascading failure process. Social ships are not taken into account because they appear randomly and are not easy to despatch in time.
2. In this network, the classification of rescue nodes is based on the ability of potential rescue forces (*RankA, B, &C*). It only carries out risk assessment and classification on its own attributes to facilitate multilayer network construction, but not represents the allocation priority. After the calculation and analysis, the priority allocation of each node is evaluated by wharfs' throughput, ships' oil spill expectation and actual rescue capabilities. During the period, it will be judged whether the situation will evolve further and affect other nodes according to the cascading failure model. Therefore, the priority of redistribution should be judged through the data results of structural entropy or efficiency after the whole calculation and analysis.
3. Priority does not represent the amount of allocation. Of course, a medium-sized wharf has a smaller mobilisation capacity and allocation capacity than these of a high-throughput port. However, if the calculation shows that its risk level is very high, it is likely to produce a reaction chain after an accident and influence the operation of subsequent channel nodes. Therefore, it needs to improve its own risk resistance ability as soon as possible. However, this change may only need to increase limited reserves for medium-sized terminals, which is far less than that of a large port to effectively improve the stability of themselves and the local subnet. In other words, one high-priority terminal in this network is very important for system security and needs to be redistributed first, but it does not mean that a large proportion of the allocation will be consumed.

Then, due to the different basic attributes and functions, this model needs to be divided into at least three layers. However, for the fixed resource node subnet in this study, there is neither spatial overlap nor the interaction of multiple attributes of a single node between the others, and no more nodes and edges connection are required. Therefore, for this subnet, single or multilayer will not make a difference in the calculation results. In light of this, this study classifies the post event risk status of each node, and extend the network from a basic three-layer network to a five-layer network for the convenience of information processing and analysis.

3.1 Establishment Basis of the Channel Nodes & Mobile Emergency Support Nodes

The network structure of river is quite different from the ones of land or air transportation. Specifically, the nodes on land are used to depict facilities, such as crossroads, public stations, transport hubs, *etc.* They are usually widespread on different directions while the terminals and vehicles are confined to only one line along the trunk line. As for the edges' construction, nodes of other networks are often directly connected for the trajectories which are usually constituted by straight lines. However, when it comes to Yangtze River trunk line, the channel segments become irregular curves. Furthermore, the sailing reference map's section standard is primarily intended to make mapping and reading easier. In light of this, some sections may be 6 or 7 km when the radians of their curves are obviously huge, while the others may be divided for only 4 km. This is really detrimental to quantitative analysis. Also, there is no need to consider the effects of oil quality or types, which will affect the drift of the spilled oil insignificantly.

For the effect of wind on the oil slick is relatively weak when the flow velocity is high, in this article, Luoqi is chosen as the worst scenario where the maximum flow velocity is 3 m/s during the flooding season. In that occasion, the oil spill front is approximately 10 km away from the leakage point at 100 min [22]. Also, according to *153040 Operating Mechanism for Speedy Reaction to Danger* released by Changjiang Maritime Safety Administration, the rescue squad should arrive at the accident site within 30 min in the reservoir area. Therefore, a distance step of 3 km is set, *i.e.*, the oil drift distance at 30 min. And nodes of *Mobile_Emergency_Support* represent the ships' resident location. As a consequence, an equivalent straight-line network is constructed to estimate the relative positions of wharves and ships, and the nodes' intervals are calculated according to the oil diffusion speed.

3.2 Classification Basis of the Fixed Resource Nodes

The fixed resource nodes are the wharves with oil absorbent felts as well as oil absorption and storage equipment. And the reason why oil boom products are not included as a consideration in judging the oil spill rescue capability is that all wharves in the study area have enough boom reserves according to the survey, and the efficiency of boom is hard to quantify in such an extreme scenario. In addition, it should be supposed to work out at the end of the leakage trajectory, the boom will restrain the leakage after ships' arrival or downstream wharves' control, but oil absorption equipment is still needed to further address the problem. Also, at the initial stage of an emergency, the resource of equipment stocks on the ground is difficult to be dispatched in time, meaning that stocks and on-land transport capacity are not considered in this network either.

To distinguish the significance of the nodes and provide a basis for the division of the network, the total quality of each wharf's equivalent oil absorption Q is used to achieve the qualification, which is calculated by the formula below:

$$Q = Gq + Vd \tag{1}$$

In (1), G is the total quality of oil absorbent felts, q is the oil absorbency multiple, V is the total capacity of oil storage equipment, and d is the density of spilled oil. In this article, all the oil absorbent felts of the wharves are assumed to be PP-1 felts (the absorption abilities of different kinds of oil are listed below), and the accidents are supposed to be light diesel spill. As a reference, the density of national standard diesel for China is between 0.83~0.855 g/ml, and 0.85 g/ml is selected as the unified density in the network.

Moreover, because different oil throughput among the wharves varies, each channel segment has its own oil flow, resulting in diversification of oil spill risk expectations. According to local maritime department's experience, oil products would not be transferred among the wharves within the study area, which means that most of the oil products shipped from the wharves would be transported downstream and further outside the study area *via* simple freight routes. Similar to the products shipped in, they can also be considered to get conveyed far away from downstream. Hence the risk expectation calculation can be simplified as (2).

$$R_i = \frac{\left(\sum_{j\geq i}^{n} H_{\text{in}}^{j} + \sum_{j\geq i}^{n} H_{\text{out}}^{j}\right) S}{\sum_{j=1}^{n} H_j} \tag{2}$$

R_i is the risk disposal expectation of each channel segment, H is the wharf's throughput, and S is the theoretical oil spill of single accident. After an upstream oil spill, this figure shows the quantity of oil that should be disposed of by the downstream. In terms of the reference data provided from the Ministry of Transport of the People's Republic of China, as shown in Table 2, the amount of oil spillage caused by a single incident is estimated to be 85% of the single hold capacity of the product oil tanker with a cargo capacity of 2400 tons, that is, the oil spill S is meant to be 265.8 t [23].

Therefore, as shown in (3), C_i, the oil spill emergency response capability can be assessed by the D-value between Q_i, the total equivalent oil absorption of wharves round each segment within 6 km, and the risk disposal expectation. With this evaluation index, the fixed resource subnets can be ranked, and the channel segment with high risk as well as low emergency response capability would be highlighted. Of course, when it comes to a channel segment's actual integrating task-response capability, the final result (as shown in Fig. 3) has taken into account the impact of the accessibility and capacity of law enforcement ships. Additionally, considering the timeliness of rescue work, tugboats and materials which cannot be allocated

Table 1
Absorbency of Felts

Type of Oil	PP-1 Felt		PP-2 Felt	
	Absorbency	Penetration Time	Absorbency	Penetration Time
2#Main Shaft Oil	17	2”	9.7	<1”
Light Diesel	16.4	3”	9.5	<1”
7#Mechanical Oil	16.8	10.2”	10	<1”
20#Mechanical Oil	18	50.3”	11.1	5”
11#Diesel Engine Oil	11.51	N/A	12.1	51.3”

Table 2
Cargo Statistics of Product Tanker

Dead-weight Tonnage/t	Gross Tonnage/t	Cargo Hold Storage/t (Loading Rate = 85%)
1000∼3000	640∼1920	85∼319
3000∼5000	1920∼3200	255∼531
5000∼10000	3200∼6300	425∼1063

timely are not included.

$$C_i = Q_i - R_i \tag{3}$$

3.3 Connection between Layers and Nodes

For the channel segments that are able to navigate in both directions, as well as the ships and wharves interact with each other, all the edges donate bidirectional connection in the whole system. On the one hand, according to the engine powers, patrols, and accessibilities within 15∼30 min for the ships, the *Mobile_Emergency_Support* nodes are connected to all the other nodes within their effective rescue ranges. In this way, the worst situation can be considered by using these ships' efficient rescue range instead of their standby locations in the network, so that all the random occasions caused by sudden conditions in the dynamic change of the nodes can be covered. Therefore, if the key index can be contained in the limited value range, the nodes' functions can still meet the rescue requirement. Otherwise, there must be a relatively high-risk possibility that will lead to accident-chains or even extreme conditions. On the other hand, a wharf's emergency equipment can only radiate a very limited area without the assistance of conveyance, so the nodes of fixed resource subnet (including layers: *RankA*, *RankB*, and *RankC*) link to *Channel* nodes within 3 km around them. What's more, the *Channel* nodes are connected in sequence according to their channel mileage.

Finally, after the calculation and classification mentioned above, the interdependent network is constructed and virtualised as multilayer network (Fig. 2) and its equivalent single-layer network (Fig. 3). As shown in Fig. 3, without any disturbance, some segments (the red nodes) already had accident risk. 1∼82 are *Channel* nodes, and the smaller their label is, the closer they are to the downstream; 83∼94 are *Mobile_Emergency_Support* nodes; other nodes represent fixed resources. Obviously, a few groups are formed by their close and complex connections. To be exact, the emergency resources at dense nodes are more plentiful and well-connected, while nodes connected with fewer resources are relatively sparse or even isolated and more problematic to resist the oil spill risk.

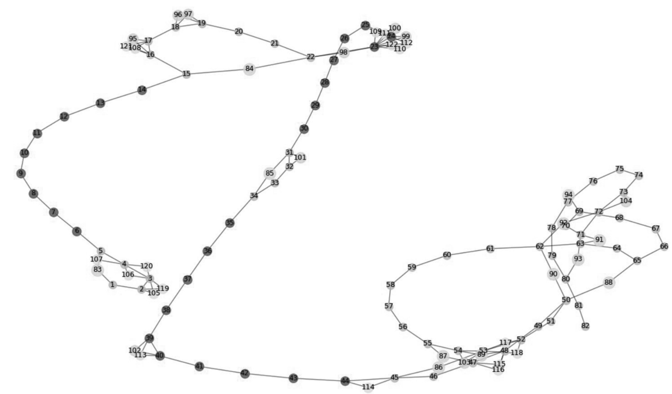

Figure 3. The equivalent single-layer network. (a) 1∼82 are *Channel* nodes: blue nodes are safe segments, and red nodes are dangerous segments; (b) 83∼94 in gold are *Mobile_Emergency_Support* nodes; (c) Green nodes are *RankA* nodes with adequate equivalent oil absorption; (d) Buff nodes are *RankB* and *RankC* nodes whose capabilities are close to or lower than expected.

4. Vulnerability Analysis of Network

The multilayer interdependent network represents the collection of relationships between various participants in key rescue operations in the study area: the abstract channel subnet serves as a unified ruler for measuring distance and spreading oil spills; the mobile force subnet, which is constructed by mobile rescue nodes and their connection relationships, indicates the mobilisation ability and influence range of rescue force; the fixed resource subnet is an essential reference for oil spill disposal capacity and effect scope. Then, to analyse the vulnerability of this network, the structure entropy and efficiency of the network are chosen to depict the chaos degree and work efficiency of the system instead of other parameters. By comparison, the resilience discusses the self-recovery ability of the network, which is more suitable for analysing the time expectation recover systems' basic functions in a period after a crash, rather than the ability to respond promptly in the assuming scenarios mentioned before.

4.1 Cascading Failure Rules

For typical complex networks without addressing interdependencies, though the failure of one node would damage the network's connectivity, it will not lead to the failure of other nodes, implying that the resistance of interdependent networks against perturbations is weaker than that of regular networks. In light of the practical significance of hazard disposal and vulnerability analysis, even though not all interdependencies will inevitably cause continuous failure of corresponding nodes in real life [17]—the interdependence between different nodes can be strong or weak, and the cascading failure process can be random—the worst scenario should be considered in extreme circumstances.

Therefore, combined with the operation mechanism among subnets in the study area, the cascading failure rules are formulated as follows.

1. The channel subnet serves merely as a frame of reference for measuring time and distance. Even if there is disruption, it is caused by the accident itself and makes that point a rescue target for other nodes upstream and downstream. However, according to accident statistics in recent 20 years, the possibility of multiple accidents occurring at the same time in the study area is extremely low, including events other than oil spills. As a result, failure and cascade process of channel nodes are not taken into account.
2. For ships, there may be not only one wharf connecting with them, so that only one or two corresponding nodes' failure won't totally crash the function of them but will reduce their weight in the system. Only when all the resources which reach in 30 min become invalid, the ships will subsequently fail.
3. When it comes to wharves, similarly, they will not fail as long as at least one ship could pass them during the effective rescue period.

On this foundation, since oil spills are more likely to occur downstream, and ships with longer reach ranges that cover sufficient resources as well as wharves with greater oil absorption and storage capacity play a major role in the network, the deliberate attack mode is used to simulate and calculate the failure effects of nodes from high to low degree or oil spill disposal capacity.

4.2 Structure Entropy of the Rescue Network

The entropy of a network is a measure of its structural complexity. Traditional degree distribution structure entropy reflects network structure characteristics based on the network's connection distribution, which is using edges as the research object and reflecting network heterogeneity based on the probability distribution of the nodes' number with a specified number of edges. As shown in (4) and (5), k is the degree of nodes, n is the number of nodes, $P(k)$ is the distribution of degree, and H is entropy.

$$P\left(k\right) = \frac{n(k)}{n} \tag{4}$$

$$H\left(k\right) = -P(k)lnP(k) \tag{5}$$

The smaller the structural entropy is, the greater the parts of the network differ, resulting in increased heterogeneity. On the contrary, it means that the more balanced the network structure is, a weaker heterogeneity it will lead to. However, the properties of a genuine network system are not totally controlled by its topological form, so it is difficult to explain and interpret the structural characteristics of a network using nodes or edges only [24]. When it comes to transportation and resource allocation, the network flow should be combined to illustrate the betweenness that represents the maximum flow through node u. In (6), $m(i, j)$ is the maximum flow from node i to node j, and $m_u(i, j)$ is the flow through node u in $m(i, j)$.

$$b_u = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N} m_u(i,j)}{\sum_{i=1}^{N}\sum_{j=1}^{N} m(i,j)}, i \neq j \neq u \tag{6}$$

As a result, to fit the operation characteristics of the oil spill rescue network, the equivalent absorption capacity is taken as the consideration object to illustrate the network vulnerability, referring to the operation mode based on flow betweenness. As shown in (7) and (8), Q_k donates the oil absorption capacity of node k while Q denotes the whole study area.

$$b_k = \frac{Q_k}{Q} \tag{7}$$

$$H_e\left(k\right) = -b_k \ln b_k \tag{8}$$

Both entropy results, $H(k)$ and $H_e(k)$ will be utilised to analyse the vulnerability of the system. Furthermore, in order to make the analysis more comprehensive, the investigation of network efficiency disturbance is added as (9) as well as (10), where d_{ij} is the equivalent distance between the node i and node j.

$$E_d = \frac{1}{n(n-1)} \sum_{i,j \in D, i \neq j}^{N} d_{\mathrm{ij}} \tag{9}$$

$$E_e = \frac{1}{n(n-1)} \sum_{k=1}^{N} Q_k \tag{10}$$

Obviously, any of the parameters above can only represent one single aspect of the network's features and cannot complete the evaluation of network performance independently. In view of this, these four indicators will jointly complete the vulnerability evaluation of the study area.

5. Results and Discussion

According to analysis above, whether structural entropy increases or decreases, a drastic change will affect the

Table 3
Entropy Changes Caused by Ship's Failure

Node ID	Normal H_k	Inter-H_k	Normal H_e	Inter-H_e
83	0.868111673	0.124434019	–	13.85500861
84	1.956601667	1.010973647	–	24.10510066
85	0.188694652	0.078437027	–	6.373873544
86	1.956601667	4.499580556	–	6.716073935
87	3.102299486	6.439628751	–	1.605235386
88	3.102299486	5.525652384	–	3.197451331
89	0.868111673	3.234663186	–	3.197451331
90	3.102299486	5.525652384	–	3.197451331
91	1.524165184	1.524165184	–	0
92	3.102299486	3.102299486	–	0
93	0.868111673	0.868111673	–	0
94	0.868111673	0.606641804	–	6.054144543
Limited Value	0.868111673	0.802744206	–	1.20392654

structural composition of the entire system, affecting the system's stability and revealing vulnerability; the specific impact of a sudden increase or decrease should be analysed in conjunction with other indicators. As a result, in order to determine whether the structural entropy is appropriate for assessing system vulnerability, we should observe if its mutation corresponds to a significant change in network efficiency and conduct a thorough analysis of its various change trends, as well as the actual attributes of nodes in reality.

The numeric differences between all indicators are enlarged 100 times on the chart to make the analysis results more intuitive. Simultaneously, the calculation without cascade failure is also taken into account, which shows that the results of interdependent network are more accurate. Furthermore, it is impossible to make the entropy or efficiency disturbance become zero, so analysing the absolute value of the data by quartile robust statistical method is enough to find a reasonable limit for a relatively small data set. For example, the limited value of entropy changes caused by ship's failure is displayed in Table 3, all the limited values are summarised in Table 4.

Table 4
Limited Values

	Ship	Wharf
Normal H_k	0.868111673	1.87740645
Inter-H_k	0.802744206	0.639558346
Normal H_e	–	3.540670723
Inter-H_e	1.20392654	3.495568738
Normal E_e	4.79338843	10.07059229
Inter-E_d	11.27124537	10.19834711
Normal E_e	–	11.96550672
Inter-E_e	1.679660735	10.40033578

Figures 4 and 5 show the impact on the system structure entropy and efficiency interference degree, respectively, after the failure of one single *Mobile_Emergency_Support* node. Obviously, the failure of one ship would have no influence on the oil spill rescue material reserve, even if the cascade failure is taken into account. As a result, the structural entropy and efficiency disturbance based on equivalent oil absorption (H_e and E_e) do not change when only one *M_E_S* node fails. However, the efficiency disturbance based on distance (E_d) and the structural entropy based on degree distribution (H_k) have relatively small fluctuations, and their disturbances are not transmitted downward. In contrast to the four elements under the interdependent network system, E_e is negatively correlated with the E_d, that is, when the H_e increases, the E_d increases, resulting in reduced efficiency and increased vulnerability. Although E_d and E_e are also suspected to have negative correlation characteristics visually, in fact, considering the specific values as well as reality, it is found to be an accidental phenomenon, which means that there is no direct connection and law between these two parameters in the study area. It can be seen that nearly half of the rescue fleet in study area have access to many associated wharves but intersect very little with each other. Among them, the rescue ships No.83 and No.84, in particular, have extensive emergency resources within their reachable range where there is a high risk of oil spill, while no other standby mobile rescue forces are nearby, resulting in a network with extremely low fault

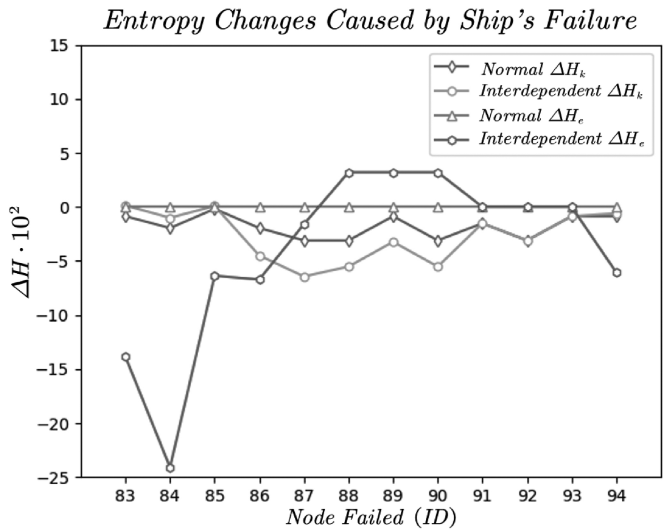

Figure 4. Entropy changes caused by ship's failure.

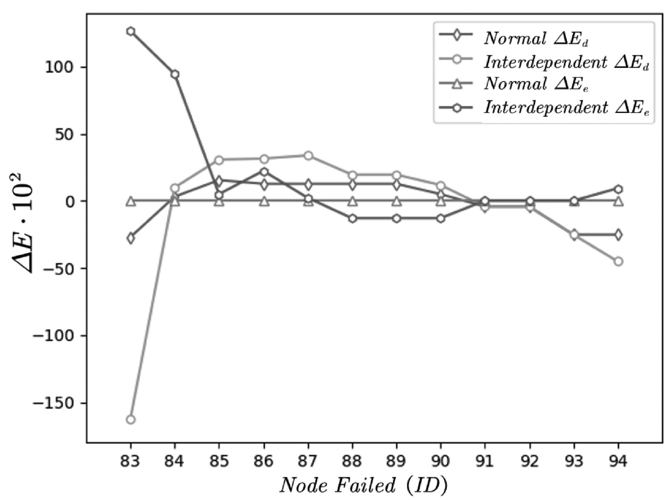

Figure 5. Efficiency disturbance changes caused by ship's failure.

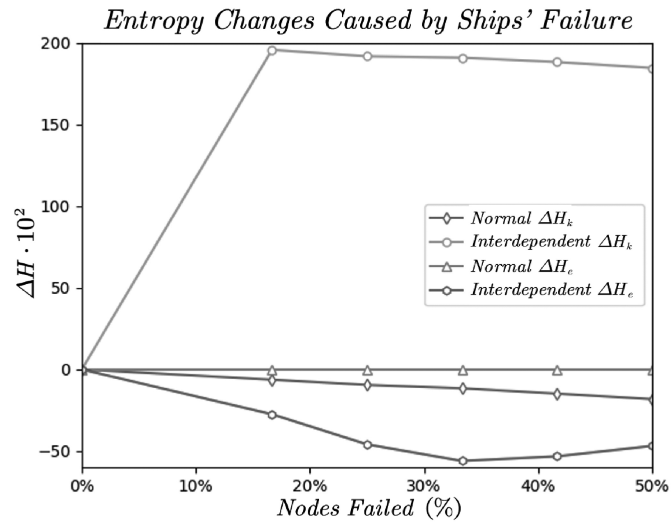

Figure 6. Entropy changes caused by ships' failure.

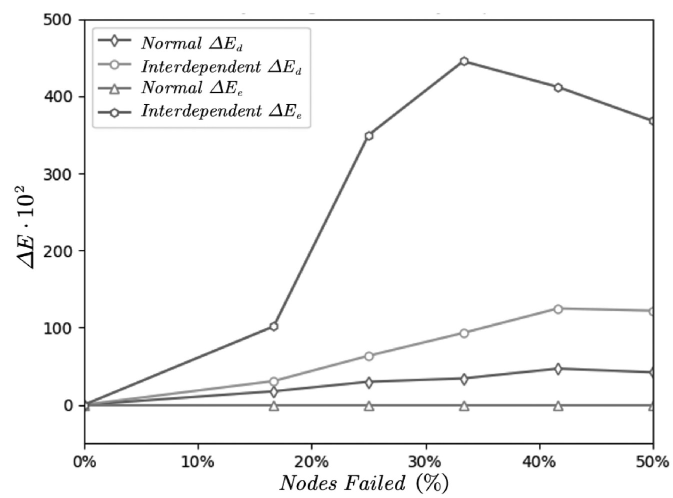

Figure 7. Efficiency disturbance changes caused by ships' failure.

tolerance and high vulnerability. In addition, though the failure of most mobile nodes would result in an increase in E_d, No.83 (law enforcement ship, HAIXUN12281) has an abnormally low value, which indicates that this node has a large number of connection objects whose dispersion is sparse, making its vulnerability more significant than No.84 (HAIXUN31257).

Figures 6 and 7 depict the impact on the system after multiple nodes failing under deliberate attacks (from the highest capacity and degree to the lower ones). Without considering cascading failures, the changes in four variables are insignificant. When compared to Fig. 4, it can be found that after concurrently removing two nodes with the highest degree distribution in the interdependent network (accounting for 16.67% of the subnet), its H_k soared far exceeding the impact of one single node in the system. Furthermore, it maintains a very high level of entropy increase in the subsequent failure growth, resulting in a sharp decline in heterogeneity and increase in chaos. At the same time, without a significant modification, H_e is extremely approximate to the numerical sum of single point's failures. What is more, E_e has a similar growth trajectory as H_k compared with Fig. 5. It surges after losing three nodes, keeping a high level, and the mobilisation efficiency of relief supplies reduces dramatically. Consequently, it can be deduced that there is only one rescue ship within the radiation range of most wharves.

Figures 8 and 9 illustrate how the failure of a single fixed resource node affects the system structure entropy and efficiency disturbance value. Respectively, only two nodes' E_e and H_e (No.107 and No.108) are not coordinated (the red line and the green line). Also, their performances in interdependent network are not considerably different from that in the regular network. Apart from specific wharves, H_e will decline significantly, while E_e will remain relatively the same all along. This indicates that in the study area, it is difficult for one single wharf to cause cascade failure, and most wharves' rescue reserves are lower than the average value, which also reveals the imbalanced distribution. As

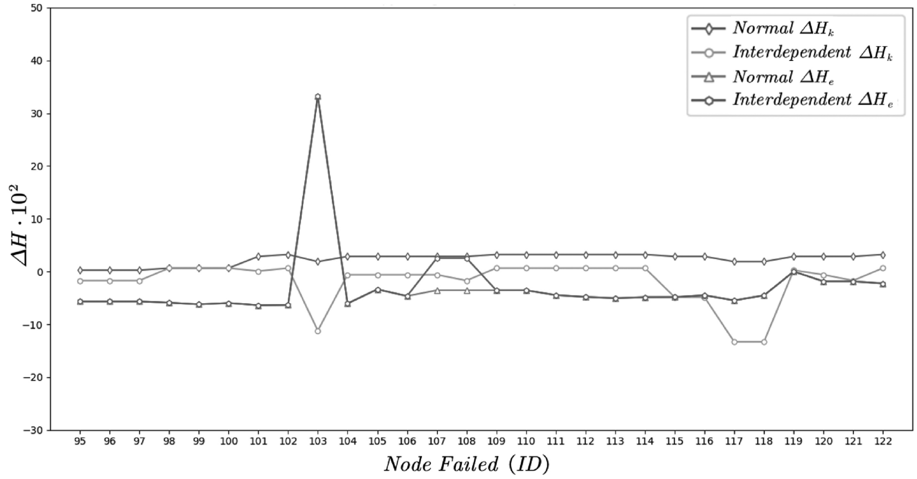

Figure 8. Entropy changes caused by wharf's failure.

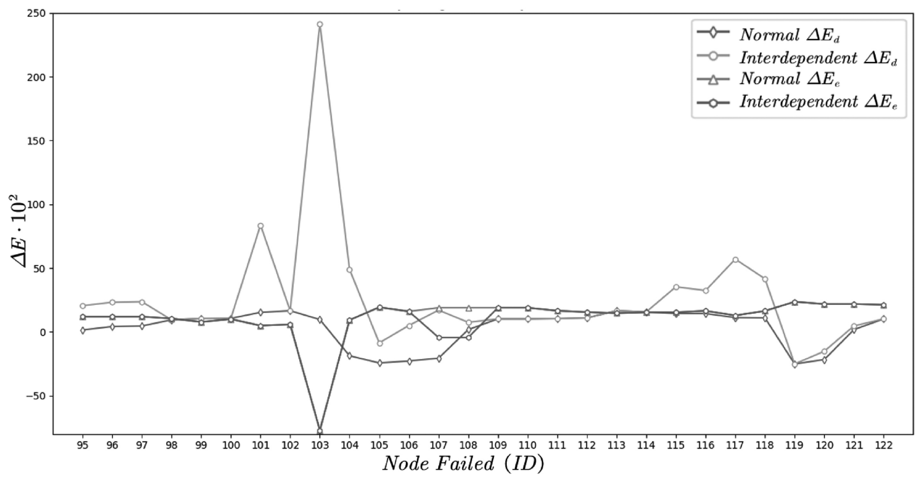

Figure 9. Efficiency disturbance changes caused by wharf's failure.

for No.103 (Lanjiatuo comprehensive operation area), its H_e surges after failed while E_e drops significantly, signaling that this wharf is experiencing two big issues at the same time:

1. The structure of this node has more links to other resource nodes, and most of them are not so adequate. So, without Node 103's resource or only with limited help from a few nodes around it, none could cover the accident itself.
2. When Node 103 shuts down, the stability of the network will be much lower than other situations, which may cause a series of delays and accidents.

So, we can also have two conclusions:

1. It has vastly more emergency rescue resources than other nodes.
2. Its rescue radiation range is so broad that there is no node as high quality as it with identical function and structure in the system, which enhances the system's homogeneity but considerably limits the total oil spill disposal capacity of study area.

In other words, once it fails, the rescue function in the local area would tend to collapse. Therefore, No.103 is both a vital hub in the rescue network and a weak link in the study area. In contrast, the H_k of the ordinary network is still quite stable, and only a few nodes E_d alter moderately. Although H_k and E_d only have individual mutation points in interdependent network, the comparable pattern only emphasises the importance and susceptibility of No.103, showing that the resource allocation of the subnet is polarised.

Figures 10–13, respectively, correspond to the changes of four parameters with the continuous failure of nodes in different networks. Obviously, in the ordinary network, the changes of H_k and E_d are relatively steady without significant fluctuation. And only the failure of *RankA* and *RankB* has caused significant changes in the interdependent network: E_d soars while H_k decreases significantly, indicating that the loss of backbone wharves (especially *RankA*'s high reserve wharves) in the interdependent network will continue to have a notable negative impact on the overall system's operation efficiency. No matter in which network, the failure of *RankA* nodes will maintain H_e at a high level after a sudden increase, while *RankB* nodes will make it decline steadily (Fig. 11). Similarly, after *RankA*'s E_e plummets, it remains at a low level while *RankB* increases steadily (Fig. 13), which is consistent

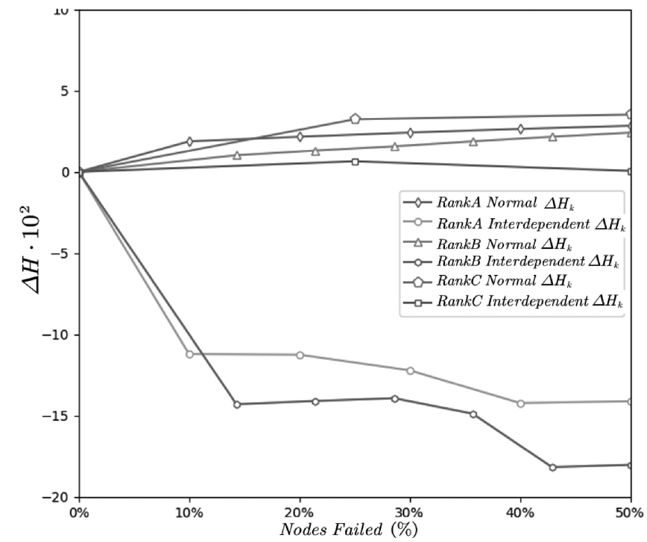

Figure 10. Entropy changes caused by wharves' failure considering degree distribution.

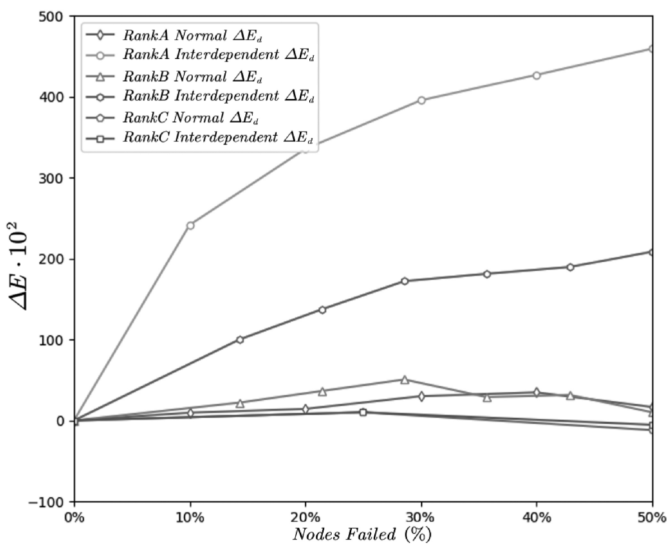

Figure 11. Efficiency disturbance changes caused by wharves' failure considering degree distribution.

with the situation of No.103 analysed above. Due to the polarisation trend of the resource volume of nodes in *RankA* and *RankB*, the changes of E_e parameters caused by the failure of the two nodes are exactly opposite. But it is obvious that the impact of *RankA* nodes' failures is more severe and significant.

To summarise, the vulnerability of rescue ships and *RankA* wharves in the study area is much greater than other objectives, as evidenced by the small number of ships within the effective accessibility range and the relative scarcity of spare material reserves. Furthermore, the polarisation of rescue reserve between different wharves is severe, as well as some regions' anti-risk ability is limited.

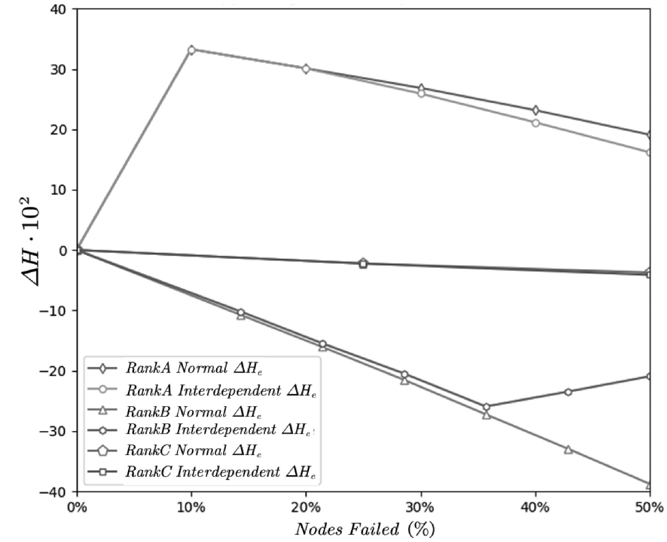

Figure 12. Entropy changes caused by wharves' failure considering oil absorption capacity.

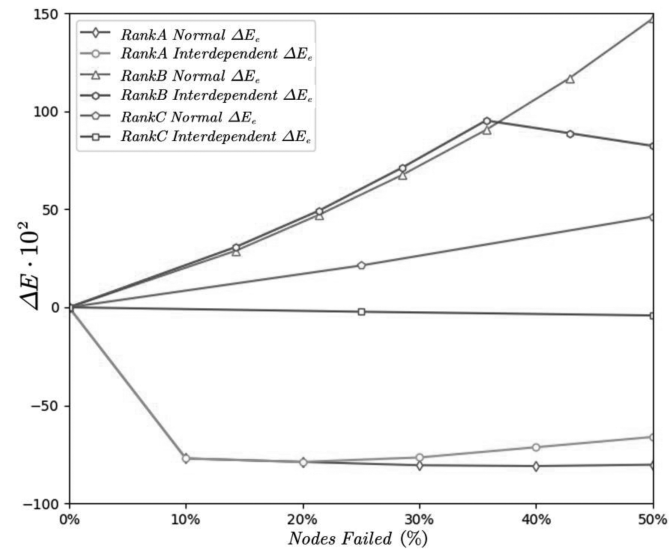

Figure 13. Efficiency changes caused by wharves' failure considering oil absorption capacity.

6. Conclusions

Because of the high unpredictability and devastating effects of oil spill accidents, emergency resource allocation for oil spill disposal should include not only the timely completion of rescue and post-disaster cleanup but also fault tolerance in extreme circumstances. In light of this, this article analyses the vulnerability of the inland river trunk oil spill treatment system combined with structural entropy and efficiency disturbance parameters, so as to evaluate the network structure and resource reserves based on interdependent network theory. In this way, the efficiency and risk of emergency rescue systems coping with sudden oil spill accidents and damaged capability could be obtained, which can also supply a methodical reference to construct a dynamic vulnerability assessment system.

Taking fluctuating backwater zone and natural navigation area in the upper Yangtze River (582.3 km to 825 km of the upper Yangtze River Channel) as an example, this article firstly constructs an oil spill emergency rescue network for the study area based on the maximum oil spill diffusion rate on the river, the Chongqing Maritime Safety Administration's (MSA) emergency response regulations, the throughput of product oil at the dangerous goods wharves, the recorded oil absorption and storage materials, as well as the participating law enforcement ships and rescue boats. Next, using this method, the changes in structural entropy and efficiency disturbance index in the system following the failure of different nodes and subnetworks are estimated, which is integrated with the cascade failure model of interdependent networks. Then, the vulnerability and notable characteristics of the rescue system are discovered by a comprehensive analysis of the changing trend of each parameter and the actual condition of the mutation point. Finally, it is discovered that an interdependent network is more sensitive, effective, and practical for identifying the vulnerability of the oil spill rescue network, which may aid decision makers in properly analysing and allocating.

The analysis results are primarily intended to show the model's construction idea and analysis process. Although they are not completely correct due to confidentiality requirements that only part of the data can be used, the analysis process still has certain reference value. In terms of this, there are still certain limitations:

1. This network is built based on the accessibility of ships and their resident locations, so all nodes in the analysis process are static ranges, whereas the position of law enforcement ships during the patrol period is constantly changing. In view of this, the position and strategy for receiving alarms and beginning to rush for help will be different. This study results can cover the worst situation but not accurately control the rescue strategy of each ship at any certain location, which could be possibly improved with automatic calculation methods like machine learning.
2. This study only got the information of patrol ships, rescue ships, tugs, engineering ships, navigation aids ships and a few social rescue ships from the MSA. The ships which are directly under the control of the MSA are not all registered. Therefore, compared with the actual situation, there are bound to be mistakes and defects. What is more, due to the unpredictability of social forces and sluggishness of tugs, neither of them is included in this model.

That is because the rescue speed of a tug is too slow to meet the *153040 Operating Mechanism for Speedy Reaction to Danger* (about 18 km/h, only covering one and a half channel nodes in 15 min). If they are counted, the nodes that can be connected to them are too limited. The scenario discussed in this study is the response and rescue in the process of first-time emergency rescue. Therefore, the subsequent mobile rescue forces for stable situation are not included. In addition, the number of tugs that are recorded and accepted by the transfer suggestions of the MSA will only stand by at certain main channel nodes in the flood season. Otherwise, they will move freely in the non-flood season and often leave the research area, making it difficult to be counted as mobile rescue force nodes.

However, if the chemical nature or accident characteristics of study objects are changed, the tugs may also be considered in certain situations.

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References

[1] D. Kvočka, D. Žagar, and P. Banovec, A review of river oil spill modeling, *Water*, *13*(12), 2021, 1620.

[2] H. Xiong, L. Chen, and Z. Sun, The impacts of piers on oil spill transport in a typical reach of the middle Yangtze River, *Water Supply*, *21*(6),2021, 3114–3125.

[3] Y.Q. Wen, R.X. Song, F. Zhang, C. Zhou, W. Yi, and Z. Sui, Site selection model and algorithm for oil spill emergency rescue point on the Yangtze River trunk line, *Proc. 5th International Conf. on Transportation Information and Safety*, Liverpool, 2019, 759–764.

[4] J. Liu, L. Guo, J.P. Jiang, D. Jiang, and P. Wang, Emergency material allocation with time-varying supply-demand based on dynamic optimization method for river chemical spills, *Environmental Science and Pollution Research*, *25*(18), 2018, 17343–17353.

[5] J. Liu, D.X. Jiang, L. Guo, J. Nan, W. Cao, and P. Wang, Emergency material location-allocation planning using a risk-based integration methodology for river chemical spills, *Environmental Science and Pollution Research*, *27*(15), 2020, 17949–17962.

[6] A. Cardillo, M. Zanin, J. Gomez-Gardenes, M. Romance, A.J. García del Amo, and S. Boccaletti, Modeling the multi-layer nature of the European Air Transport Network: Resilience and passengers re-scheduling under random failures, *European Physical Journal-Special Topics*, *215*(1), 2013, 23–33.

[7] M. Ouyang, Review on modeling and simulation of interdependent critical infrastructure systems, *Reliability Engineering & System Safety*, *121*, 2014, 43–60.

[8] S.M. Rinaldi, J.P. Peerenboom, and T.K. Kelly, Identifying, understanding, and analyzing critical infrastructure interdependencies, *IEEE Control Systems Magazine*, *21*(6), 2001, 11–25.

[9] J.X. Gao, S.V. Buldyrev, H.E. Stanley, and S. Havlin, Networks formed from interdependent networks, *Nature Physics*, *8*(1), 2012, 40–48.

[10] C.D. Brummitt, R.M. D'Souza, and E.A. Leicht, Suppressing cascades of load in interdependent networks, *Proceedings of the National Academy of Sciences of the United States of America*, *109*(12), 2012, E680-E689.

[11] G.J. Baxter, S.N. Dorogovtsev, A.V. Goltsev, and J.F.F. Mendes, Avalanche collapse of interdependent networks, *Physical Review Letters*, *109*(24), 2012, 248701.

[12] Z.H. Chen, J.J. Wu, Y.X. Xia, and X. Zhang, Robustness of interdependent power grids and communication networks: a complex network perspective, *IEEE Transactions on Circuits and Systems II: Express Briefs*, *65*(1), 2018, 115–119.

[13] E. Pournaras, M. Ballandies, D. Acharya, D. Acharya, M. Thapa, and B.-E. Brandt, Prototyping self-managed interdependent networks—Self-healing synergies against cascading failures, *Proc. IEEE/ACM 13th International Symposium on Software Engineering for Adaptive and Self-Managing Systems*, Gothenburg, 2018, 119–129.

[14] X.P. Ji, B. Wang, D.C. Liu, and T. Zhao, Review on interdependent networks theory and its applications in the structural vulnerability analysis of electrical cyber-physical system, *Proceeding CSEE*, *36*(17), 2016, 4521–4533.

[15] P. Zhang, B. Cheng, Z. Zhao, D. Li, G. Lu, Y. Wang, and J. Xiao, The robustness of interdependent transportation networks under targeted attack, *Europhysics Letters*, *103*(6), 2013, 68005.
[16] Q. Luo, J. Song, T. Zheng, T. Zheng, and L. Yang, Passenger evacuation at a malfunctioning urban rail station based on interdependent networks, *International Journal of Modern Physics C*, *30*(11), 2019, 1950098.
[17] H. Wei-Tao, Y.Peng, M. Hai-Long, Z. Peng, and T. Le, Robustness of interdependent networks with heterogeneous weak inter-layer links, *Acta Physica Sinica*, 68(18), 2019, 222–229.
[18] X. Wang, W. Pan, and W. Zhao, Analysis of network characteristics and robustness of aeronautical interdependent network in North China, *Science Technology and Engineering*, *18*(13), 2018, 180–185.
[19] Z. He, K. Navneet, W. Van Dam, and P. Van Mieghem, Robustness assessment of multimodal freight transport networks, *Reliability Engineering & System Safety*, *207*, 2021, 107315.
[20] M. Zhao, X. Wang, W. Pan, and X. Zhang, The vulnerability analysis of the multi-layer air transport system, *Proc. 5th International Conf. on Transportation Information and Safety*, Liverpool, 2019, 956–962.
[21] M. De Domenico, M.A. Porter, and A. Arenas, MuxViz: A tool for multilayer analysis and visualization of networks, *Journal of Complex Networks*, *3*(2), 2015, 159–176.
[22] P. Jiang, S. Tong, Y. Wang, and G. Xu, Modelling the oil spill transport in inland waterways based on experimental study, *Environmental Pollution*, *284*, 2021, 117473.
[23] *Technical guidelines on environmental risk assessment of oil spills at waters*, Standard JT/T 1143–2017, 2017.
[24] M. Cai, H.-F. Du, and M.W. Feldman, A new network structure entropy based on maximum flow, *Acta Physica Sinica*, *63*(6), 2014, 60504.

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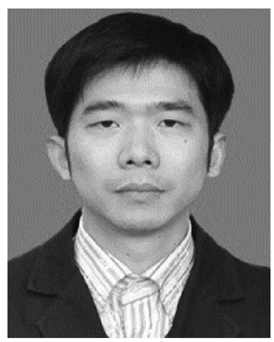

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