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A method for optimizing maritime emergency resource allocation in inland waterways

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ABSTRACT

Maritime safety and emergency operation management are critical to preventing maritime accidents and mitigating risks. In this study, we propose a novel method to optimize maritime emergency resource allocation to improve emergency management efficiency. We combine the analytic hierarchy process (AHP) and coefficient of variation (CV) to develop an inverse comprehensive weight (CW) - data envelopment analysis (DEA) model. We apply this model to evaluate the efficiency of allocating emergency resources among ten Maritime Safety Administrations (MSAs) in the Jiangsu section of the Yangtze River in China. Our results indicate that five MSAs have low emergency management benefits, and we propose emergency resource allocation optimization options to improve their emergency management benefits. This study provides policymakers with valuable insights and guidelines for optimizing maritime emergency resource allocation in inland waterways.

1. Introduction

Recently, maritime traffic accidents have occurred frequently, causing considerable economic and environmental losses (Zhang et al., 2021b; Zhang et al., 2023). Therefore, the requirements for maritime emergency management have become increasingly strict (Wu et al., 2021; Wang, 2021). According to the statistical bulletin on transportation development issued by the Ministry of Transport of the People's Republic of China in 2020,[1] Maritime Search and Rescue Centers organized and coordinated 1793 SAR (Search And Rescue) operations, rescuing 66 Chinese and foreign ships in distress and 1515 Chinese and foreign casualties in the SAR responsibility area of China. This report shows that emergency management is crucial for ensuring maritime safety. The scientific allocation of maritime emergency resources is crucial for ensuring efficient rescue because of the suddenness of maritime traffic accidents and the timeliness of emergency rescue (Ma et al., 2022a,b; Amiri and Zwanzig, 2011).

The allocation of maritime emergency resources involves many problems such as resource types, water area features, restriction conditions and modes of transportation (Ma et al., 2022a,b). The critical literature review indicates that, due to the complex maritime transportation environment in inland waters, it is difficult for correlational research to take all the influencing factors and their weighs into account, which may reduce the applicability of the research, see more in Section 2.

To address the research gaps in maritime emergency resource allocation, we propose an approach that analyzes the efficiency ratio of inputs and outputs in emergency resource allocation schemes. This approach evaluates the emergency management benefits of Maritime Safety Administrations (MSAs) based on their SAR requirements and resource inputs, thus providing a measure of the utilization efficiency of emergency resources. Furthermore, we optimize the emergency resource allocation of MSAs based on their emergency management benefits, thereby improving their overall emergency management effectiveness (Xiong et al., 2020).

The aim of this study was to quantitatively analyze the optimization scheme of maritime emergency resource allocation in inland waterways. We considered the impact of objective data and subjective preferences of

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emergency decision-makers on emergency benefits evaluation. To begin with, a comprehensive weights-data envelopment analysis (CW-DEA) model is proposed based on the combination of objective data and expertise, so as to prevent free weights of traditional DEA model (Rashidi and Cullinane, 2019; Wei et al., 2000; Zhou et al., 2018). Subsequently, we used the CW-DEA model to investigate the relationship between emergency resource inputs and emergency rescue efficiency in maritime emergency management. Finally, an inverse CW-DEA model was introduced to optimize the resource allocation scheme of ten MSAs in the Jiangsu section of the Yangtze River. In this paper, we have made several significant contributions to the field of maritime emergency resource allocation optimization:

(1) We have improved the traditional Data Envelopment Analysis (DEA) model by introducing a comprehensive weighting method that combines the Analytic Hierarchy Process (AHP) and Coefficient of Variation (CV) to consider the decision makers' subjective preferences and objective differences in the indicator data. This method enables us to distinguish the significance of different indicators.
(2) We have evaluated the emergency management benefits of 10 Maritime Safety Administrations (MSAs) on the Jiangsu section of the Yangtze River trunk based on SAR requirements and resource inputs, and ranked all MSAs comprehensively by efficiency value. For the less efficient five MSAs, we have proposed corresponding optimization schemes for emergency resource allocation.
(3) The results of the inverse CW-DEA model have provided MSAs with insights into their emergency management status and have helped them improve their emergency resource allocation schemes. Our research work can provide decision-making support for the maritime management sector in inland rivers.

The rest of this paper is organized as follows. Section 2 presents a detailed literature review of emergency resource allocation research and the application of the DEA method. Section 3 describes the methodology. Section 4 presents the case study used to illustrate and validate the proposed model, Section 5 presents the discussion, and Section 6 presents the conclusion and findings.

2. Literature review

This section mainly introduces related studies on emergency resource allocation and the application of the DEA method.

2.1. Emergency resource allocation research

Many studies have investigated resource allocation in emergency response to ensure emergency rescue efficiency and reduce losses caused by accidents, as shown in Table 1. Azofra et al. (2007) used a gravitational model to propose an objective method for allocating maritime rescue resources. The model was used to define individual and zonal distribution models. Zhang et al. (2021a) developed a dynamic multi-objective location-routing model considering the effect of the dynamic motion of offshore oil film to support the practical emergency response in a large-scale oil spill accident. Zhang et al. (2017) established the dynamic demand of maritime emergency resources and proposed a robust optimization model to allocate the resources. Guo et al. (2019) proposed an integer nonlinear programming model to solve the problem of allocating a plurality of resources in a long-range maritime SAR. The model maximized both the probability of accomplishing the rescue operations and the benefits of allocating emergency resources. Ai and Zhang (2019) proposed a two-stage location optimization model, which integrates the problems of locating maritime emergency supply repertories, distributing emergency supplies, and cooperation between the government and enterprises.

The studies mentioned above were mainly aimed at the allocation optimization method of single emergency resources. Some studies have also comprehensively investigated different methods of allocating emergency resources, such as the emergency base location and rescue ship allocation. Ai et al. (2015) proposed an integrated model considering both location-allocation of the reserve bases of maritime emergency supplies and salvage vessel configuration. However, only a few studies have focused on the allocation of emergency human resources. Bersani et al. (2020) proposed an optimal resource allocation model that can determine the intervention route and time arrangement of fire engines and emergency personnel according to the specific dynamics of accidents to minimize losses during emergencies.

It can be seen from the foregoing analysis that two are some limitations in the existing research. (a) Few models in these studies are applicable for various emergency resources allocation. In general, basic allocation standards vary from resource to resource. Therefore, it is desirable to propose an optimal model capable of calculating demand of emergency resources reflecting various types of resources. (b) Few studies investigate inland waterway emergency management. The freight volume of inland waterway systems accounts for more than half of that of waterway transportation in China. However, most of the existing studies focus on vessel emergency rescue in open sea areas. Thus, to ensure the safety of inland waterway navigation, inland waterway emergency management deserves great attention.

2.2. Data envelopment analysis

DEA is a method for evaluating production efficiency by quantitatively calculating input-output quantities of decision-making units (DMUs) (Wang et al., 2020). DEA has been widely applied in many disciplines, especially in the field of transportation. Wu et al. (2015)

Table 1
Summary of emergency resource allocation research.

Literature	Emergency system			Types of emergency resources				Emergency management efficiency
	Land	Maritime	Inland waterway	Human resource	Transport vehicle	Reserve facility	Emergency supply	
Azofra et al. (2007)		✓			✓			
Zhang et al. (2021a)		✓			✓			
Zhang et al. (2017)		✓					✓	
Guo et al. (2019)		✓			✓			
Ai and Zhang (2019)		✓				✓		
Ai et al. (2015)		✓			✓	✓		
Bersani et al. (2020)	✓			✓	✓			
Lehikoinen et al. (2013)		✓			✓			
Zachary et al. (2022)		✓				✓		
Wang (2021)	✓						✓	
The proposed model		✓	✓	✓	✓	✓	✓	✓

considered the impact of the navigation environment on maritime safety level and used the spatial sequential frontier and grey relational analyses to improve the traditional DEA model. This method can be used to accurately evaluate the maritime safety level in a dynamic navigation environment where the navigation environment data are the input and output accident data. Zahedi-Seresht et al. (2021) analyzed uncertainty in the dataset and proposed a DEA model with alternatives by assuming that multiple alternatives have a given probability of occurrence.

The traditional DEA model does not limit indicator weights (Tsionas, 2021). In order to distinguish the differences in the importance of indicators, some studies have adopted various methods to improve the DEA model. Xue and Zhao (2021) combined the DEA model, Malmquist index, and Tobit regression analysis and presented a method that can be used to assess the operational efficiency of China's urban rail transit system. They also analyzed the impact of related factors. Omrani et al. (2020) introduced the preferences of decision-makers into the DEA model and optimized the traditional DEA model using the group best-worst method (BWM). The authors proposed a group BWM DEA-based road safety model and used the model to assess road safety efficiency in Iran's provinces. In this paper, the method including both the subjective preferences of decision makers and the information contribution of indexes, can be more in line with the actual situation in emergency decision-making. Although the above-mentioned DEA methods can be used to scientifically evaluate the efficiency of DMUs, the methods cannot solve the allocation problems and optimize DMUs with lower evaluation.

According to the DEA evaluation results, the inverse DEA model can be used for optimizing non-effective DMUs (Zhang and Cui, 2020), and the method has been applied widely in practice because of its effectiveness. Emrouznejad et al. (2019) used the inverse DEA model to solve the quota allocation problem of carbon dioxide emission from manufacturing industries in different regions of China. Wegener and Amin (2019) used the inverse DEA model to increase production and reduce greenhouse gas emissions in oil and gas. Amin et al. (2019) combined goal programming with the inverse DEA model to propose a merger target-setting method that considers the preferences of decision-makers, which can be used for making the input-output plans of the banking industry. Chen et al. (2021) used the inverse DEA model with unexpected output indicators to define China's road transport safety objectives and provided an optimal solution to achieve the objectives. The model can calculate the input, expected output, and unexpected output for adjustment schemes using the given efficiency. However, few existing studies have solved the allocation of maritime emergency resources using the inverse DEA model.

3. Methodology

Fig. 1 illustrates an overall framework for applying the inverse CW-DEA configuration optimization model. The framework includes building an emergency efficiency evaluation system, evaluating the efficiency of emergency decision units, and optimizing the allocation of emergency resources. The framework is implemented in the following stages:

- **Stage I: Evaluation system of emergency management efficiency.** According to the characteristics of the maritime emergency DMUs, an evaluation system is proposed including emergency resource input indicators and emergency management output indicators to measure the efficiency of emergency management.

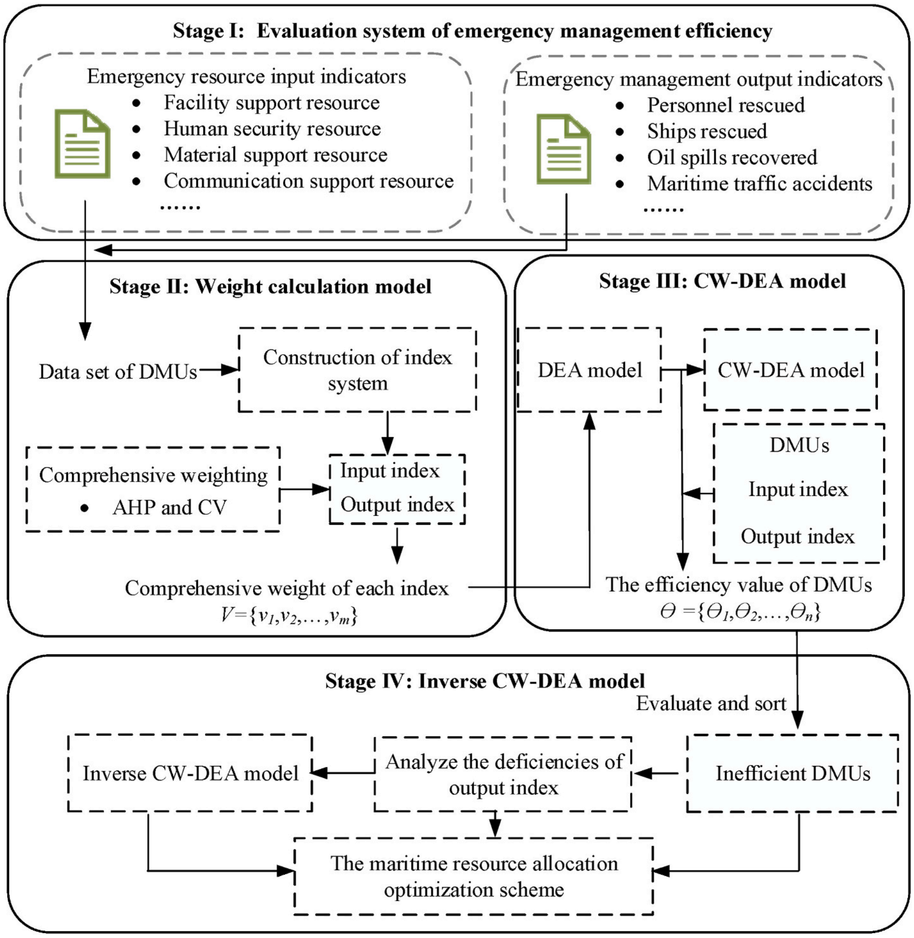

Fig. 1. The framework of an inverse CW-DEA.

- **Stage II: Weight calculation model.** The AHP and CV are used to calculate each indicator's subjective and objective weights, respectively. Then, a linear weighting method is used to assign a comprehensive weight to each indicator.
- **Stage III: CW-DEA model.** The calculated comprehensive weights are introduced into the DEA model to build the CW-DEA efficiency evaluation model. The indicator data of each emergency DMU are substituted into the built model to calculate the relative efficiency value of each DMU.
- **Stage IV: Inverse CW-DEA model.** The output deficiency of the CW-DEA non-effective DMUs is analyzed, and the increment of each output indicator in the CW-DEA non-effective DMU is determined. The inverse CW-DEA model is then developed to calculate the optimization scheme of the emergency DMUs with increased output. Finally, the optimal solution of each input indicator is obtained: the optimal solution is the scheme of optimizing emergency resource allocation under the effective condition of CW-DEA.

3.1. Stage I: Evaluation system of emergency management efficiency

In this stage, an evaluation system is proposed by considering emergency resource input indicators and emergency management output indicators to reasonably evaluate the emergency management efficiency of the DMUs.

The emergency resource input indicator reflects various representative emergency resources allocated by the DMUs. The main maritime emergency resources include facility support resources, human support resources and material support resources (Zhou, 2022). Facility support resources include refuge facilities, transportation facilities, medical facilities, special construction machinery, etc. Human support resources include full-time emergency management personnel, relevant emergency experts, full-time emergency teams and auxiliary emergency personnel, social emergency organizations, volunteer teams and international organizations. The material support resources involve the most extensive aspects, which can be divided into protection and rescue, transportation, food supply, daily necessities, medical and health care, power lighting, communication broadcasting, tools and equipment, and engineering materials(Wu et al., 2023).

The emergency management output indicators are mainly used to measure the emergency response effectiveness after the decision-making unit invests a certain amount of emergency resources. Zhang et al. (2014) regarded the accident number, death toll and rescued ship as an important factor in evaluating the efficiency of maritime traffic safety supervision of the MSA. In addition, considering the damage of maritime accidents to the natural environment, oil spillage can also be used as an important indicator to evaluate the effectiveness of the emergency management of the MSA (Zhong et al., 2020).

3.2. Stage II: Weight calculation model

In this section, we will introduce the weighting methods used in the model, including AHP, CV and CW. The subjective and objective comprehensive weighting method can effectively reflect the importance of each indicator, limit the free weight in the traditional DEA model, and lay the foundation for the construction of the CW-DEA model.

3.2.1. Calculating subjective weights using AHP

Due to the complexity of maritime emergency resource allocation problems, this paper uses expert experience and objective data to improve the applicability of DEA method. In this paper, the AHP is employed to calculate the subjective weight of each evaluation indicator based on the expertise. The AHP method is chosen due to its ability to integrate qualitative and quantitative analysis in dealing with complex decision-making factors, as well as its flexibility and conciseness in modeling subjective preferences. AHP is a widely used and mature subjective weighting method, as a hierarchical weighting decision analysis method (Tonoğlu et al., 2022). AHP is based on dividing evaluation objects and attributes into appropriate hierarchical structures according to membership relationship and then inviting renowned experts and researchers to compare and score the relative importance level of each indicator from the bottom to obtain the importance matrix. The specific application process of AHP is summarized as follows:

Step 1: The AHP model is established to evaluate the efficiency of emergency resource allocation.
Step 2: Judgement matrix A is constructed according to the opinions of the decision-makers. Table 2 shows that the scale method is typically used for constructing the matrix.
Step 3: The maximum eigenvalue ($\lambda_{\max}$) and corresponding eigenvectors of the judgement matrix are calculated.
Step 4: By normalizing the eigenvectors, the subjective weights of the elements in the matrix are obtained.
Step 5: Consistency check is performed on the judgment matrix to determine whether it has satisfactory consistency. The specific steps are as follows:
Step 5-1: Calculation of consistency indicators (CI): $\mathrm{CI} = \frac{\lambda_{\max} - n}{n-1}$, where n is the order of the judgment matrix, for example, that of the number of indicators of the criteria layer.
Step 5-2: Calculation of consistency ratios (CR): $\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}$, where RI is an average random consistency indicator, which may be obtained by the query in Table 3.
Step 5-3: When $\mathrm{CR} < 0.1$, the judgment matrix is consistent. Otherwise, the value in the judgment matrix needs to be adjusted again until it has a satisfactory consistency.

Finally, the subjective weights calculated by AHP will be substituted into the CW part to calculate the comprehensive weight of emergency resource allocation.

3.2.2. Calculation of objective weights using CV

CV is an objective weighting method typically used in statistics for measuring data differences (Islek and Yuksel, 2022). According to Equation (1), the coefficient of variation can be calculated, and the size of the indicator weights can be determined using the obtained coefficient of variation. When the coefficient of variation is significant, it is difficult for the evaluation subject to reach the average value of the indicator, and the indicator weight is more significant. On the other hand, when the coefficient of variation is small, the evaluation subject can easily reach the average value of the indicator, and the indicator weight is more minor. Therefore, we used the CV to clearly distinguish the difficulty of each emergency efficiency evaluation indicator for MSAs to reach the average level. When the coefficient of variation is 0, the emergency efficiency evaluation index has no value for MSAs and should be deleted.

The coefficient of variation V_i of any indicator i in the evaluation system of indicators is defined as the ratio of the standard deviation to the mean value, which can be calculated using:

Table 2
Scale method.

Scale	Meaning
1	Two factors are equally important.
3	One factor is slightly more important than the other.
5	One factor is obviously more important than the other.
7	One factor is more important than the other.
9	One factor is excessively more important than the other.
2, 4, 6, 8	The median value of the above two adjacent judgments.
Reciprocal	If the factor i is compared with the factor j, the result is a_{ij}, and if the factor j is compared with factor i, the result is $a_{ji} = 1/a_{ij}$

Table 3

Average random consistency indicator value.

Rank	1	2	3	4	5	6	7	8	9
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45

$$V_i = \frac{\sigma_i}{\bar{x}_i}, i = 1, 2, \cdots, n \tag{1}$$

where σ_i is the standard deviation of indicator i, and $\bar{x}_i$ is the average of indicator i.

The weight of each indicator is:

$$\omega_i = \frac{V_i}{\sum\limits_{i=1}^{n} V_i} \tag{2}$$

where $\omega_i \leq 1$, and $\sum_{i=1}^{n} \omega_i = 1$.

Similarly, the objective weights calculated by CV will be substituted into the CW part to calculate the comprehensive weight of emergency resource allocation.

3.2.3. *Combination weight calculation using the linear weighting method*

To fully reflect the evaluation indicator differences, we considered the preferences of decision-makers and the ability of empirical judgments. The typical "addition" integration method was selected to combine the AHP-calculated subjective and CV-calculated objective weights. The combined weights of each indicator can be determined using:

$$\begin{aligned} &\theta_j = \alpha\varphi_j + \beta\varphi_j (j = 1, 2, \cdots, m) \\ &\alpha = \frac{\varphi_j}{\varphi_j + \varphi_j} \end{aligned} \tag{3}$$

where α is the importance factor of the subjective weighting method; β is that of the objective weighting method; and $\alpha + \beta = 1$, α, $\beta \in [0,1]$.

3.3. *Stage III: CW-DEA model*

In this stage, we combine the comprehensive weight with the DEA model to establish the CW-DEA model, so as to quantitatively evaluate the emergency management benefits of the MSAs.

The DEA model is an effective method for evaluating homogeneous DMUs. The model is based on identifying units with relatively low efficiency by comparing the production efficiency of similar units. Firstly, the original input-output data is calculated and the input-output of the DMU is kept constant. Using mathematical programming method, a linear programming model for efficiency evaluation is constructed to determine the effective production frontier. Then, the input-output data of each DMU is marked on the production frontier of the DEA. Finally, analyze each DMU and calculate the distance between each DMU and the DEA production frontier to evaluate their relative effectiveness. Overall, the standard for determining whether a DMU is effective is actually to determine whether the DMU is located on the production front, where the production front refers to the effective part of the envelope of the input output data of the DMU. Therefore, the DEA model was used to quantitatively evaluate the emergency benefits of MSAs. Meanwhile, we also considered the subjective preferences of emergency decision-makers and the objective differences in emergency indicators. This study combined the comprehensive weighting method with the DEA model to construct the CW-DEA model and then identified relatively inefficient MSAs. The formula for the CW-DEA model is given as follows.

Supposing that there are n DMUs, each with m inputs and s outputs, respectively: $x_j = (x_{1j}, x_{2j}, \cdots, x_{ij}, \cdots, x_{mj})^T$, $y_j = (y_{1j}, y_{2j}, \cdots, y_{rj}, \cdots y_{sj})^T$. The weights of the input and output indicators are: $v_i = f(v_{1i}, v_{2i}), i = 1, 2, \cdots, m$, $u_r = f(u_{1r}, u_{2r})$, $r = 1, 2, \cdots, s$;where v_{1i} and u_{1r} are the inherent weights in the DEA model, v_{2i} and v_{2i} are the comprehensive weights of the indicators obtained using the comprehensive weighting method.

For any DMU_{j_0} in the evaluation system, the new comprehensive weights are substituted to get the efficiency value of the decision unit ($\bar{h}_{j_0}$):

$$\bar{h}_{j_0} = \frac{\sum\limits_{r=1}^{s} u_r \cdot y_{rj_0}}{\sum\limits_{i=1}^{m} v_i \cdot x_{ij_0}} = \frac{\sum\limits_{r=1}^{s} u_{1r} \cdot u_{2r} \cdot y_{rj_0}}{\sum\limits_{i=1}^{m} v_{1i} \cdot v_{1i} \cdot x_{ij_0}}. \tag{4}$$

To solve the problem of multiple DEA effectiveness in the calculation results of the traditional DEA model, we evaluated the efficiency value of DMU, replaced the DEA inputs and outputs with the remaining DMUs, and constructed a CW-DEA model. The model is expressed using Equation (5), as follows:

$$\begin{cases} \max \dfrac{\bar{u}^T y_{j_0}}{\bar{v}^T x_{j_0}} = E_{\overline{D}} \\ s.t. \dfrac{\bar{u}^T y_j}{\bar{v}^T x_j} \leq 1, j = 1, 2, \cdots, n; j \neq j_0 \\ \bar{v} \geq 0 \\ \bar{u} \geq 0 \end{cases} \tag{5}$$

In order to evaluate the benefits of inland river emergency management, we have formulated the following definitions according to the characteristics of inland river emergency resource allocation (Kao, 2022). When the CW-DEA model (Equation (5)) has an optimal solution, the proposed method defines the efficiency of an emergency decision-making unit DMU_{j_0} as follows:

- If $E_D \geq 1$ is satisfied and $s_i^+ = s_r^- = 0$, DMU_{j_0} is called strongly CW-DEA effective, where E_D is the relative efficiency values of DMU_{j_0}, s_i^+ is the relaxation variables, and s_r^- is the remaining variables.
- If $E_D \geq 1$ is satisfied, but s_i^+ *or* $s_r^- > 0$, DMU_{j_0} is called weakly CW-DEA effective.
- If $E_D < 1$ is satisfied, DMU_{j_0} is called CW-DEA non-effective.

3.4. *Stage IV: Inverse CW-DEA model*

In this stage, we will introduce the process of building the Inverse CW-DEA model. After obtaining the calculations of the DEA model, we obtained the relative efficiency scores for DMUs and identified the relatively inefficient DMUs. However, the general DEA model can only obtain the efficiency scores of DMUs and cannot further quantitatively optimize the resource allocation of DMUs. Therefore, the inverse DEA model is required.

The inverse DEA model is based on calculating the input and output levels required to achieve the given efficiency. If the overall production level of the evaluation object can maintain its current state for a certain period, for DMUs with DEA effectiveness, we can consider maintaining its DEA effectiveness state and further adjusting input or output; For non-DEA efficient DMUs, it is possible to consider adjusting inputs or outputs to achieve DEA efficient status. For the MSAs, the allocation of maritime emergency resources is a long-term decision-making process. In a short period of time, its emergency search and rescue capabilities, such as emergency plans and the professional level of staff, will not undergo significant changes. Therefore, it conforms to the premise that the production structure and level remain unchanged. Moreover, the

CW-DEA model constructed earlier has achieved an evaluation of the efficiency of emergency resource allocation on water, Therefore, it is possible to consider using the inverse DEA model to conduct more in-depth research on the optimization of water emergency resource allocation based on the evaluation results.

By combining the optimization idea of the Inverse DEA model, we have established the Inverse CW-DEA model to optimize the resource allocation scheme with low relative efficiency. The calculation is shown below.

Supposing that when the output indicator of DMU_{j_0} increases by an increment $\Delta y_{j_0} \geq 0$ to $\beta = (\beta_{1j_0}, \beta_{2j_0}, \cdots, \beta_{sj_0})$ from $y = (y_{1j_0}, y_{2j_0}, \cdots, y_{sj_0})$, the input variable $x = (x_{1j_0}, x_{2j_0}, \cdots, x_{mj_0})$ is required to be increased by an increment $\Delta x_{j_0} \geq 0$ to $\alpha = (\alpha_{1j_0}, \alpha_{2j_0}, \cdots, \alpha_{mj_0})$ to keep the efficiency value of DMU_{j_0} unchanged.

The virtual decision unit (DMU_{n+1}) is introduced to represent the DMU_{j_0} with changed input and output. The DEA efficiency value of DMU_{n+1} is the optimal solution.

$$\begin{cases} \min \theta \\ s.t. \sum_{\substack{j=1 \\ j \neq j_0}}^{n} \lambda_i x_{ij} + \lambda_{n+1} \alpha_{ij_0} \leq \theta \alpha_{ij_0} \\ \sum_{\substack{j=1 \\ j \neq j_0}}^{n} \lambda_j y_{ij} + \lambda_{n+1} \beta_{sj_0} \geq \beta_{sj_0} \\ i = 1, 2, \cdots, m; r = 1, 2, \cdots, s \end{cases} \tag{6}$$

When the optimal solution of Equation (6) is equal to the DEA efficiency value E_{j_0} of DMU_{j_0}, $\alpha = (\alpha_{1j_0}, \alpha_{2j_0}, \cdots, \alpha_{mj_0})$ is the solution of the inverse DEA model. An increment is added to the output indicator to ensure the increment of the input indicator while the DEA efficiency is constant. To solve the above multi-objective programming problem, we developed a model as expressed in Equation (7).

$$\begin{cases} V - \min(\alpha_1, \alpha_2, \cdots, \alpha_n) \\ s.t \sum_{\substack{j=1 \\ j \neq j_0}}^{n} \lambda_j x_j + V_{CW}\left(A_{CW} x_{j_0}\right) \lambda_{j_0} \leq \theta_{j_0} \alpha \\ \sum_{\substack{j=1 \\ j \neq j_0}}^{n} \lambda_j y_j + \left(B_{CW} y_{j_0}\right) \geq \beta \\ \lambda_j \geq 0 \end{cases} \tag{7}$$

where α and β are the changed values of the input and output indices respectively, and θ_{j_0} is the efficiency value calculated for the CW-DEA model. Provided that $\theta_{j_0} = 1$ is the optimal solution in the multi-objective programming (Equation (7)), the weak efficient solution (α, β) can be obtained, that is, a new weak CW-DEA efficient DMU.

4. Case study

4.1. Description of the study areas

We selected ten MSAs in the Jiangsu section of the Yangtze River trunk line as case studies. Yangtze River is a major river in China, and it has played a vital supporting role in China's inland navigation and transportation. The Changjiang MSA is the competent maritime authority in the Yangtze River Basin, including four management units, namely, Jiangsu MSA, Changjiang Communication Administration, Changjiang Pilotage Center, and Logistic Management Center of Changjiang MSA. We selected ten branches under the jurisdiction of Jiangsu MSA as DMUs, including Nanjing MSA, Zhenjiang MSA, Yangzhou MSA, Taizhou MSA, Changzhou MSA, Jiangyin MSA, Zhangjiagang MSA, Nantong MSA, Changshu MSA, and Taicang MSA. Fig. 2 shows the jurisdiction of each MSA in the Jiangsu section.

Overall, the maritime traffic safety situation in each jurisdiction and the demand for maritime emergency resources were different. Therefore, it is necessary to analyze the efficiency of emergency resource allocation of each MSA, optimize the allocation of various maritime emergency resources, improve the emergency SAR capacity, and reduce casualties and property losses.

4.2. Emergency management efficiency evaluation

In order to reasonably evaluate the emergency management efficiency of various MSAs, we need to select appropriate input and output indicators to build an evaluation system.

The input indicators were selected according to the emergency resources mainly used in emergency SAR. The emergency SAR of maritime traffic accidents is inseparable from the support of shore emergency rescue facilities. When a maritime traffic accident occurs, the personnel in the maritime emergency bases near the water area make the first emergency response. The maritime emergency base is a professional facility for maritime SAR. It has functions of docking ships, storing and repairing navigation marks, and some bases also have helicopter landing functions and storing oil spill emergency equipment. The number of maritime emergency bases determines the speed of emergency response and efficiency of emergency rescue. Therefore, the number of maritime emergency bases was selected as an emergency input indicator.

Most maritime emergency disposals require the operation of a professional emergency personnel. The efficiency of maritime emergency rescue is considerably improved if sufficient emergency personnel are engaged in rescue operation on time whenever a maritime emergency occurs. Human security resources include full-time emergency personnel on duty, emergency experts, social organizations, international organizations, as well as the army and armed police. We mainly focused on the resource allocation scheme that can be regulated by the MSAs. Therefore, we only selected the emergency duty personnel in the emergency management department as an emergency input indicator.

The definition of material support resources is relatively broad. Common material support resources include life jackets, lifebuoys, life rafts, immersion suits, thermal insulation suits, and other life-saving appliances or supplies. These materials are difficult to quantify as life-saving materials because they are easy to consume and are stored in scattered places. Considering the independence of the evaluation indicators, we did not regard the scattered life-saving materials as an evaluation indicator. As an important traffic support resource, sea patrol boats are imperative in daily cruise and maritime emergency SAR. Sea patrol boats near the water often arrive first at maritime accident scenes and participate in rescue because they are fast, convenient, and flexible. In addition, other official ships of the fishery administration, marine police and other departments often participate in maritime emergency SAR, which is helpful for finding dangerous situations and personnel rescue. Therefore, sea patrol boats and other official vessels were regarded as transportation. Finally, tugs, as necessary ships in ports, are usually used to assist large ships to enter and leave the port and dock. For the rescue of ships in distress, the tug is also an independent resource in emergency SAR. Therefore, tugs were selected as an evaluation indicator of emergency resources.

The output indicators must reflect the results of the MSAs' emergency management. The numbers of rescued people and rescued ships indicate an MSA's emergency rescue results in ensuring human life safety and reducing property loss, respectively. Although undesirable outputs, such as casualties or ship pollution, can also indicate the effectiveness of emergency management to a certain extent, the traditional DEA model cannot adequately address the problem of undesirable outputs. Therefore, we set the numbers of people and vessels that were

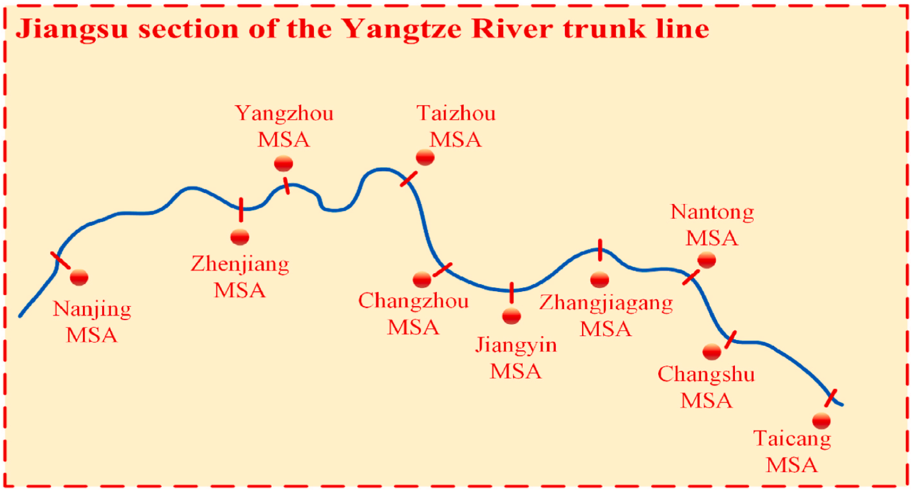

Fig. 2. Scope of the water study area.

rescued as the output indicators.

In summary, we comprehensively considered the characteristics of emergency resources and combined the characteristics with the CW-DEA evaluation model to construct the evaluation system of indicators of maritime emergency resource allocation. The input indicators in the system include emergency bases, sea patrol boats, other official vessels, tugs, and emergency personnel on duty. The output indicators include the number of people and vessels that were rescued. The system is illustrated in Fig. 3.

We used the data from the official website (Changjiang MSA, 2022) where the navigation environment information within the jurisdiction is regularly updated. According to the emergency resource allocation and maritime rescue record of each MSA in 2020, the input and output indicator data of each DMU are shown in Table 4.

4.3. Weight of indicators determinations

To reflect the difference on importance of each emergency efficiency evaluation indicators, this paper adopts a subjective and objective weighting method to limit the free weight of the traditional DEA model. The following introduces the calculation process of indicator weights with MSAs as an example.

Step 1: Subjective weight determination using AHP

In this step, we calculate the subjective weight by AHP, according to the experts' evaluation of the importance of each indicator. To ensure the efficiency and credibility of the AHP evaluation results, 20 experts from each member unit of the Jiangsu maritime SAR center were invited to compare the importance levels of the input–output indicators (Fu et al., 2018). Appendix B presents the experts' profiles. And then, we constructed the judgment matrix by using the scale method as shown in Table 2. The judgment matrices A and B of the input and output indicators were obtained.

$$A = \begin{bmatrix} 1 & 3 & 6 & 9 & 2 \\ 1/3 & 1 & 2 & 3 & 1/2 \\ 1/6 & 1/2 & 1 & 2 & 1/2 \\ 1/9 & 1/3 & 1/2 & 1 & 1/4 \\ 1/2 & 2 & 2 & 4 & 1 \end{bmatrix} \quad B = \begin{bmatrix} 1 & 5 \\ 1/5 & 1 \end{bmatrix}$$

The calculated maximum eigenvalues are $\lambda_{Amax} = 5.0432$ and $\lambda_{Bmax} = 2$. The consistency ratios are $CR_A = 0.0096$ and $CR_B = 0$, showing that the judgment matrices of the input and output indicators have satisfactory consistency. The corresponding weight vector is obtained, and the subjective weights of the input and output indicators are normalized, as shown in Table 5.

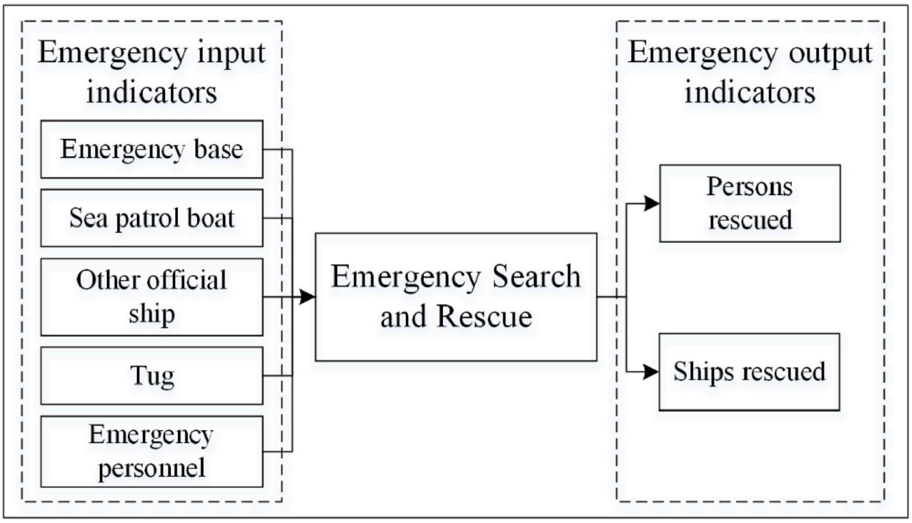

Fig. 3. The evaluation system of water emergency resource allocation efficiency.

Table 4
Raw data on inputs and outputs.

DMU	Input indicator					Output indicator	
	Emergency base	Sea patrol boat	Other official vessel	Tug	Emergency personnel	Person rescued	Vessel rescued
D_1	10	13	23	29	104	215	51
D_2	8	14	20	25	36	157	34
D_3	3	4	10	13	12	80	15
D_4	4	8	16	10	15	50	7
D_5	1	1	8	9	17	67	11
D_6	4	7	13	17	17	149	22
D_7	5	8	21	14	24	94	18
D_8	5	9	17	14	14	159	27
D_9	5	10	19	15	19	102	19
D_{10}	3	5	9	12	9	55	8

Step 2: Objective weight determination using CV

In this step, we use the CV to calculate the objective weight of each indicator. The coefficient of variation of each indicator can be calculated by substituting the data in Table 4 into Equation (1), and the coefficient of variation can be substituted into Equation (2) to calculate the objective weights of the input–output indicators, respectively. The calculation results are presented in Table 5.

Step 3: Weight combination using CW

In this step, we use the CW to calculate combination weights of each indicator. The combination weights of each indicator calculated in stages 1 and 2 were substituted into Equation (3) to obtain the combination weights of each indicator. The calculation results are presented in Table 5.

The importance levels of the input indicators are: Emergency bases > Emergency personnel > Sea patrol boats > Tugs > Other official vessels (see Table 5). The emergency base coverage input indicator often determines the response efficiency of the MSAs. The larger the coverage is, the faster the speed of the emergency response is. However, the construction costs of the emergency bases are much higher than those of other emergency resources; therefore, the importance level of the emergency bases is considerably higher than that of the other input indicators. The importance degrees of the output indicators are: Persons rescued > Vessels rescued (see Table 5). Among the output indicators, the importance level of persons rescued is slightly higher than that of the vessels rescued because human life safety is more important than property safety. Compared with the traditional DEA method, in the combination weighting method, each indicator is weighted, and both the subjective preference of decision makers and the impact of the difference in the evaluation indicators on the evaluation results are considered. Thus, the analysis of DMU defects is improved in the evaluation results obtained using the inverse CW-DEA method.

After obtaining the comprehensive weight of each indicator, this result will be substituted into the DEA model to build the CW-DEA model, and to evaluate the emergency management efficiency of each MSA.

4.4. Evaluation of maritime emergency resource allocation efficiency using CW-DEA model

In this stage, we establish a CW-DEA model to evaluate the emergency management benefits of the MSAs. Using MSA D_1 as an example, we counted the data of each evaluation indicator in Table 4 and calculated the corresponding weights in Table 5. The results were substituted into Equation (5) to establish a CW-DEA model for evaluating maritime emergency resource allocation efficiency as shown in Equation (8).

$$
\left\{
\begin{array}{l}
\min = \theta - 0.000001 * \left(\sum_{i=1}^{5} s_i^{+} + \sum_{r=1}^{2} s_r^{-} \right) \\
s.t. \\
0.3575 * (8 * \lambda_2 + 3*\lambda_3 + 4*\lambda_4 + 1*\lambda_5 + 4*\lambda_6 + 5*\lambda_7 + 5*\lambda_8 + 5*\lambda_9 + 3*\lambda_{10}) + s_1^{+} = 0.3575 * 10*\theta; \\
0.1493 * (14 * \lambda_2 + 4*\lambda_3 + 8*\lambda_4 + 1*\lambda_5 + 7*\lambda_6 + 8*\lambda_7 + 8*\lambda_8 + 10*\lambda_9 + 5*\lambda_{10}) + s_2^{+} = 0.1493 * 13*\theta; \\
0.0980 * (20 * \lambda_2 + 10*\lambda_3 + 16*\lambda_4 + 8*\lambda_5 + 13*\lambda_6 + 21*\lambda_7 + 17*\lambda_8 + 19*\lambda_9 + 9*\lambda_{10}) + s_3^{+} = 0.0980 * 23*\theta; \\
0.1075 * (25 * \lambda_2 + 13*\lambda_3 + 10*\lambda_4 + 9*\lambda_5 + 17*\lambda_6 + 14*\lambda_7 + 14*\lambda_8 + 15*\lambda_9 + 12*\lambda_{10}) + s_4^{+} = 0.1075 * 29*\theta; \\
0.2876 * (36 * \lambda_2 + 12*\lambda_3 + 15*\lambda_4 + 17*\lambda_5 + 17*\lambda_6 + 24*\lambda_7 + 14*\lambda_8 + 19*\lambda_9 + 9*\lambda_{10}) + s_5^{+} = 0.2876 * 104*\theta; \\
0.5941 * (157 * \lambda_2 + 80*\lambda_3 + 50*\lambda_4 + 67*\lambda_5 + 149*\lambda_6 + 94*\lambda_7 + 159*\lambda_8 + 102*\lambda_9 + 55*\lambda_{10}) - s_1^{-} = 0.5941 * 215; \\
0.4059 * (34 * \lambda_2 + 15*\lambda_3 + 7*\lambda_4 + 11*\lambda_5 + 22*\lambda_6 + 18*\lambda_7 + 27*\lambda_8 + 19*\lambda_9 + 8*\lambda_{10}) - s_2^{-} = 0.4059 * 51; \\
\lambda_i, s_i^{+}, s_r^{-} \geq 0, i = 1, 2, \cdots, 10; r = 1, 2
\end{array}
\right.
\tag{8}
$$

The efficiency value (θ_1) corresponding to D_1 obtained by the CW-DEA model is 1.315353. Similarly, the maritime emergency resource allocation efficiency values θ_i of ten DMUs under the jurisdiction of the Jiangsu MSAs were calculated, which are listed in Table 6.

As shown in Table 6, the CW-DEA model was used to determine the full ranking of the MSAs' evaluation efficiency. According to the evaluation scores, the order of 10 MSAs is $D_5 > D_8 > D_1 > D_6 > D_3 > D_2 > D_7 > D_9 > D_{10} > D_4$. D_5 MSA gets the highest evaluation because of its low input cost and high output. On the contrary, the efficiency value of D_4 MSA is only 0.44025, which shows that the input and output efficiency of the MSA in emergency management is very low. The number of

Table 5
Calculated weights of input and output indicators.

Type of weight	Input indicator					Output indicator	
	Emergency base	Sea patrol boat	Other official vessel	Tug	Emergency personnel	Person rescued	Vessel rescued
Subjective weight	0.4761	0.1511	0.0921	0.0511	0.2297	0.8333	0.1667
Objective weight	0.1887	0.1763	0.1204	0.1428	0.3715	0.4331	0.5669
Combination weight	0.3575	0.1493	0.0980	0.1075	0.2876	0.5941	0.4059

Table 6
The efficiency of maritime emergency resource allocation.

DMU	θ_i	Ranking
D_1	1.315353	3
D_2	0.9603288	6
D_3	1.000474	5
D_4	0.44025	10
D_5	3.231561	1
D_6	1.225443	4
D_7	0.6923652	7
D_8	1.490243	2
D_9	0.6809181	8
D_{10}	0.6037749	9

person rescued and the number of vessel rescued in the D_4 MSA are the lowest among all the MSAs, which may be an important reason for its low efficiency. Similarly, five MSAs scored below 1 are evaluated as CW-DEA non-effective. Therefore, it is necessary to optimize its configuration and improve emergency management of these MSAs.

$$\begin{cases} \mathrm{V}-\min(\alpha_1,\alpha_2,\cdots,\alpha_6) \\ s.t. \\ 10*\lambda_1+3*\lambda_3+4*\lambda_4+1*\lambda_5+4*\lambda_6+5*\lambda_7+5*\lambda_8+5*\lambda_9+3*\lambda_{10}+0.9603288*0.3575*\lambda_2\le\alpha_1; \\ 13*\lambda_1+4*\lambda_3+8*\lambda_4+1*\lambda_5+7*\lambda_6+8*\lambda_7+8*\lambda_8+10*\lambda_9+5*\lambda_{10}+0.9603288*0.1493*\lambda_2\le\alpha_2; \\ 23*\lambda_1+10*\lambda_3+16*\lambda_4+8*\lambda_5+13*\lambda_6+21*\lambda_7+17*\lambda_8+19*\lambda_9+9*\lambda_{10}+0.9603288*0.0980*\lambda_2\le\alpha_3; \\ 29*\lambda_1+13*\lambda_3+10*\lambda_4+9*\lambda_5+17*\lambda_6+14*\lambda_7+14*\lambda_8+15*\lambda_9+12*\lambda_{10}+0.9603288*0.1075*\lambda_2\le\alpha_4; \\ 104*\lambda_1+12*\lambda_3+15*\lambda_4+17*\lambda_5+17*\lambda_6+24*\lambda_7+14*\lambda_8+19*\lambda_9+9*\lambda_{10}+0.9603288*0.2876*\lambda_2\le\alpha_5; \\ 215*\lambda_1+80*\lambda_3+50*\lambda_4+67*\lambda_5+149*\lambda_6+94*\lambda_7+159*\lambda_8+102*\lambda_9+55*\lambda_{10}+0.5941*31*\lambda_2\ge 188; \\ 51*\lambda_1+15*\lambda_3+7*\lambda_4+11*\lambda_5+22*\lambda_6+18*\lambda_7+27*\lambda_8+19*\lambda_9+8*\lambda_{10}+0.4059*0*\lambda_2\ge 34; \\ \lambda_i,\ge 0, i=1,2,\cdots,10 \end{cases} \tag{9}$$

4.5. *Optimization of maritime emergency resource allocation using inverse CW-DEA model*

In this stage, we establish the inverse CW-DEA model to optimize the emergency resource allocation scheme of the MSAs. According to the calculation results of CW-DEA model, the allocation efficiency values of maritime emergency resources of D_2, D_4, D_7, D_9, and D_{10} are $\theta_2=0.96033$, $\theta_4=0.44025$, $\theta_7=0.\ 69237$, $\theta_9=0.\ 69092$, and $\theta_{10}=0.6037749$. These values are less than 1, indicating that the allocation of maritime emergency resources of D_2, D_4, D_7, D_9, and D_{10} are relatively ineffective. The corresponding output shortfalls of the five maritime administrations are presented in Table 7.

Table 7
Statistics of insufficient output of CW-DEA non-effective DMUs.

DMU	Insufficient output	
	Person rescued	Vessel rescued
D_2	30.97118	0
D_4	0	0.6065113
D_7	2.724803	0
D_9	6.019984	0
D_{10}	0	0.3403983

We suppose that the output increments are $\Delta y_2=(31{,}0)$, $\Delta y_4=(0{,}1)$, $\Delta y_7=(3{,}0)$, $\Delta y_9=(7{,}0)$, and $\Delta y_{10}=(0{,}1)$, respectively. In this case, the inverse CW-DEA model was used to adjust and optimize the input number of resources to make the corresponding DMU achieve weak CW-DEA efficiency when the output increases. Using D_2 as an example, we substituted the original input and output data and the output increment in Table 4 into Equation (7). Then, the optimization problem of invalid DMUs was obtained by Equation (9). The optimal solution of the resource input of the MSA is $x_2=(8, 12, 21, 22, 61)$.

Similarly, when the output of other MSAs increased, the optimal solution of various emergency resource investments was calculated. Table 8 presents the emergency resource allocation optimization scheme of each MSA.

As shown in Table 8, the efficiency of MSAs with efficiency value lower than 1 in Table 6 has been improved to 1 after optimization. Compared with the original data in Table 4, the resource allocation schemes of D_2, D_4, D_7, D_9, and D_{10} have changed significantly. After the inverse CW-DEA optimization, the emergency resource allocation efficiency of several DMUs improved while the emergency input relatively reduced, corresponding to the concept of the DEA model. Thus, the maximum output was obtained using less input (Liu et al., 2021), showing the efficiency of the inverse CW-DEA model. Among the input indicators, the number of emergency bases has the smallest change, which may be due to the high construction cost of the emergency base and the difficulty in building or dismantling it. And the number of emergency personnel changes is the largest, probably because staff mobilization is easier. In the output indicators, the number of persons

Table 8
Optimization scheme of maritime emergency resource allocation.

DMU	Input indicator					Output indicator		CW-DEA efficiency
	Emergency base	Sea patrol boat	Other official vessel	Tug	Emergency personnel	Person rescued	Vessel rescued	
D_2	8	12	21	22	61	188	34	1
D_4	3	4	6	5	6	50	8	1
D_7	4	7	12	10	11	97	18	1
D_9	4	7	13	11	11	109	19	1
D_{10}	3	4	7	6	6	55	9	1

rescued changes more than the number of vessels rescued, which is also consistent with the actual situation of maritime SAR. To sum up, the inverse CW-DEA model was used to create a detailed optimization scheme for MSAs with lower efficiency, which can improve its emergency management efficiency.

5. Discussion

5.1. Allocation policies of maritime emergency resources

Emergencies are addressed using emergency management policies and guidelines. However, a scientific system of laws, regulations, and policies can better clarify the functions, authorities, and obligations of governments, departments, organizations, and individuals at all levels in emergency management, coordinate the relationship between all parties, and standardize the behavior of emergency preparation, early warning, disposal, and recovery. Maritime traffic emergency management is a highly theoretical and practical subject. It includes complex contents and changeable situations, involving various interests and requiring the participation of all parties. All aspects of emergency management should be regulated by law, and this is a common practice in China's maritime administration.

However, most of the current emergency management policies and guidelines in China focus on emergency rescue after accidents, ignoring pre-emergency preparation. Prominent problems still exist in maritime emergency SAR, such as inadequate policies and regulations as well as insufficient support capacity. Moreover, the guidelines and standards of inland river emergency management mostly appear effective in principle, whereas quantitative calculation standards are lacking for important emergency resource management, such as emergency personnel allocation, emergency base construction, and emergency material reserve. According to the Action Plan For New Infrastructure Construction in the Field of Transportation (2021–2025), in the future, China's inland waterway transportation system will rely on high-grade channels such as the Yangtze River trunk line, Xijiang shipping trunk line, Beijing Hangzhou canal, Wujiang River, Fujiang River, and Hangzhou Shenzhen line to construct intelligent waterways, thereby improving the operation guarantee, collaborative supervision, and comprehensive service capacities of inland waterways. Therefore, it is necessary to improve China's inland river emergency management system, which is crucial for constructing intelligent waterways.

The proposed inverse CW-DEA model can be used to specifically evaluate the organization of each emergency management according to the emergency resource inputs and generated emergency benefits. This method can be used to quantitatively calculate the optimization scheme of maritime emergency resource allocation, serves as a reference for formulating guidelines and standards related to such allocation, and compensates for the deficiencies of China's inland river emergency management system. Taking the ten MSAs of the Jiangsu section of the Yangtze River trunk line as an example, each MSA can establish a dynamic emergency adjustment mechanism to conduct scientific deployment according to the optimization scheme, strengthen the search of official boats and the functions of law enforcement and rescue, and promote the integrated construction of inland river search and rescue. This method provides a scientific emergency resource allocation strategy for MSAs and is suitable for formulating legal guidelines related to emergency resource allocation.

5.2. Emergency efficiency evaluation system

The DEA model is a linear programming model expressed as a ratio of output to input. We established an emergency efficiency evaluation system using the DEA model, including the input and output indicators. The selection process of the input indicators is described in Section 5.1. It is difficult to count the absolute quantity of small life-saving materials because of the materials' wear and tear and scattered storage locations. Similarly, considering the independence of evaluation indicators, we did not use the scattered life-saving resources as the main evaluation indicators. However, the role of small life-saving resources in saving lives cannot be ignored. For example, wearing a life jacket can increase the probability of being rescued when persons fall into the water, and wearing fireproof clothing can protect people in distress from being injured by fire or explosions. Therefore, when life-saving efficiency is considered as the main evaluation object, the small life-saving resources should be set as the main input indicator. The complementary and substitution characteristics of maritime emergency resources can also be considered in the DEA model, as some emergency resources such as life jacket and life buoy with similar functions often have complementary or alternative relationships.

Section 5.1 describes the selection process of the output indicators. The rescued ships and personnel were selected as the output indicators to measure the emergency efficiency because they can intuitively reflect the emergency output of the MSAs. However, in practice, the emergency output of the MSA is affected by other factors. For example, an MSA with many accidents also has relatively many ships and personnel in need of rescue, which may lead to a relatively high emergency efficiency of the MSA. If undesirable outputs such as accident rate or number of casualties can be added to the evaluation system, the emergency efficiency of the MSA can be more truly reflected. For MSA with a large average tonnage of ships in its jurisdiction, it is difficult to fully indicate its emergency benefits only by the number of rescued ships. Including the impact of port throughput on the emergency benefits in the evaluation system may be a good direction for improvement.

Additionally, the maritime emergency process involves various sources of uncertainty, including the accuracy and completeness of collected indicator data, the potential impact of neighboring MSAs' emergency actions and resource investments, and the complexity of emergency coordination situations where multiple MSAs may be involved in search and rescue operations. These uncertainties may lead to errors in emergency benefit assessment. Therefore, it is necessary to address the emergency coordination problem by ensuring the accuracy of statistical indicator data and dividing emergency benefits according to the resource input of multiple MSAs participating in the rescue. Furthermore, adjacent MSAs or those with mostly overlapping rescue scopes can be considered as a DMU to mitigate uncertainty. To deal with diverse types of data, both qualitative and quantitative, some data processing methods have been introduced to enhance the applicability of the DEA model (Wanke et al., 2018). With the improved DEA model, more diverse indicator data can be considered to measure the emergency efficiency of the MSA, including the time taken to arrive at an accident scene, percentage of pollutants not captured by booms, and proportion of rescued people not requiring hospital treatments.

6. Conclusions and future works

To improve the maritime emergency management system of inland rivers and emergency management efficiency of MSAs, we introduced a method for optimizing maritime emergency resource allocation. The inverse CW-DEA model was proposed to quantitatively calculate the optimization scheme of maritime emergency resource allocation according to the input and output of maritime emergency resources. We evaluated the relative benefits of emergency management of ten MSAs and optimized the resource allocation of five MSAs with low benefits in the Yangtze River. The case study indicates that the proposed method may help to optimize the allocation scheme of various emergency resources. The main conclusions are summarized as follows:

- The case study demonstrates that the comprehensive weighting method can better distinguish the importance of indicators (see section 4.3), which were ignored in traditional DEA model. In addition, the inverse CW-DEA model can accurately evaluate the emergency management benefits of the MSAs (see section 4.4) and optimize the emergency resource allocation scheme of the MSAs with low efficiency in the Yangtze River (see section 4.5).
- The proposed method theoretically supports the MSAs to optimize the maritime emergency resource allocation, and it can considerably improve the maritime traffic safety management level of the MSAs. The obtained resource allocation optimization scheme includes specifically adjusting the quantity of emergency resources, providing a more comprehensive direction for improving the channel collaboration supervision ability.
- The inverse CW-DEA model can be used to solve the optimization problem of maritime emergency resource allocation in inland waterways.

The proposed inverse CW-DEA model has demonstrated its effectiveness in solving the maritime emergency resource allocation problem. However, there are still several limitations and areas for improvement that require further investigation. First, the current emergency efficiency evaluation system of the model may not fully consider various unknown parameters (such as accident rates and traffic flow characteristics) that could affect the emergency search and rescue efficiency, potentially impacting the accuracy of the MSA's emergency benefit assessment. Therefore, a more comprehensive emergency efficiency evaluation system that accounts for various factors should be further explored. Moreover, the current model's applicability is restricted due to the traditional DEA model's assumption that all DMUs have positive input and output values. However, in the context of maritime emergency management, there are both desirable and undesirable outputs, such as the number of accidents or casualties. These undesirable outputs need to be minimized while maximizing desirable outputs. Future research can consider the impact of undesirable output on emergency management efficiency and explore the slack-based model with undesirable outputs to evaluate the emergency management efficiency of MSAs. Additionally, improving the effectiveness of ineffective DMUs could be explored through reducing inputs, increasing desirable outputs, or reducing undesirable outputs. Furthermore, there is a need to consider the increasing number of maritime emergency factors, such as traffic situations, waterway complexity, and accident types, which could impact the model's accuracy. Incorporating new fuzzy data processing methods and expanding the range of indicators used in the DEA model can also enhance the model's accuracy.

In conclusion, while the proposed inverse CW-DEA model has been effective in maritime emergency resource allocation, further studies are required to improve the model's accuracy and applicability by considering the three aspects: (1) Improve the DEA model, such as accounting for an undesired output in the DEA model. (2) Improve the weighting methods, such as using the Analytic Network Processor method or the Decision-making Trial and Evaluation Laboratory method. (3) Improve the evaluation indicators system, for example, consider the impact of accident rate or traffic flow on emergency rescue efficiency.

CRediT authorship contribution statement

Quandang Ma: Visualization, Investigation, Writing – original draft, preparation, Data curation, Methodology, Writing-Reviewing. **Yang Zhou:** Visualization, Investigation, Data curation, Methodology, Writing – review & editing. **Mingyang Zhang:** Conceptualization, Writing – original draft, preparation, Writing – review & editing. **Qi Peng:** Methodology, Writing-Reviewing. **Shanshan Fu:** Writing – review & editing. **Nengchao Lyu:** Validation, Writing – review & editing, Supervision, Funding acquisition, Project administration.

Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled, '*A Method for Optimizing Maritime Emergency Resource Allocation in Inland Waterways- A Case Study in the Yangtze River*'.

Data availability

Data will be made available on request.

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Appendix A. Nomenclature

Abbreviation	Definition	Variable	Definition
DEA	Data Envelopment Analysis	ε	Non-Archimedean infinitesimal
CW-DEA	Comprehensive weights-data envelopment analysis	s_i^+	Relaxation variable
AHP	Analytic hierarchy process	s_r^-	Remaining variable
CV	Coefficient of variation	λ_{max}	Maximum eigenvalue of the judgement matrix
MSA	Maritime Safety Administration	D_i	Identifier of DMUs
DMU	Decision Making Unit	E_D, θ_i	Efficiency evaluation value of DMU
CI	Consistency indicator	φ_{x_i}, φ_{y_r}	Subjective weights of input and output indicators
CR	Consistency ratio	ω_{x_i}, ω_{y_r}	Objective weights of input and output indicators
VHF	Very High Frequency	v_{2i}, u_{2r}	Combination weights of input and output indicators
SAR	Search and Rescue		

Appendix B. The profiles of the experts

Expert list	Detail information
Experts 1, 2	The associate professors engaged in maritime safety management since more than five years.
Experts 3-8	Emergency duty personnel, are responsible for the water search and rescue emergency duty work in the jurisdiction.
Experts 9-12	The senior tug captains with more than ten years' experience in the Nanjing water.
Experts 13-15	The senior pilots with more than fifteen years' experience in Yangtze River.
Experts 16-18	Navigation management officers, are responsible for the investigation of maritime accidents in the jurisdiction
Experts 19-20	The senior captains with more than fifteen years' experience in Nanjing water.

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