

Article

Ecological Quality Status Evaluation of Port Sea Areas Based on EW-GRA-TOPSIS Model

Kun Lang ^{1,*} , Lijun Gu ¹, Zhiying Chen ¹, Chunhui Niu ¹, Lin Li ² and Jinyuan Ma ¹

¹ School of Maritime Economics and Management, Dalian Maritime University, Dalian 116026, China; gulijun1999@dlmu.edu.cn (L.G.); czy98@dlmu.edu.cn (Z.C.); nch@dlmu.edu.cn (C.N.); 18098841456@163.com (J.M.)

² School of Foreign Studies, Minzu University of China, Beijing 100086, China; lilin_sfs@muc.edu.cn

* Correspondence: kun.lang@dlmu.edu.cn

Abstract: It is of great significance to research a method to evaluate the ecological quality status of port sea areas objectively for the ecological environmental protection and sustainable development of sea areas. In this paper, a novel ecological quality status evaluation model is proposed based on the entropy weight method (EW), the gray relational analysis method (GRA), and the TOPSIS method. Firstly, a comprehensive evaluation indicator system is constructed from three aspects, namely seawater quality, sediments, and marine organisms. Secondly, the weight values of different indicators are obtained via the EW method, which can be obtained more objectively than via the subjective weighting method. Afterwards, the ecological quality status of port sea areas can be evaluated using the proposed method, which combines the advantages of the TOPSIS method and the GRA method. Finally, the effectiveness of the proposed EW-GRA-TOPSIS model is illustrated by a case study based on a port sea area of Tianjin. The results show that 66.7% of the monitoring stations in the port sea area are at a good level, 25% of them are at a fair level, only 8.3% are at a poor level, and none are at an excellent or bad level. Additionally, the evaluation results obtained using the proposed model are more consistent with the actual survey results than the compared typical TOPSIS method. It can objectively reflect the ecological quality status of monitoring stations, and consequently, it could be helpful for the marine department to make decisions on the sustainable development of port sea areas. In a further study, the influence of decision makers' preferences on the evaluation results could be considered, and a more reasonable method to determine the evaluation grade standard should be researched to improve the proposed model.

Keywords: ecological quality; entropy weight; gray relational analysis; TOPSIS method



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1. Introduction

With the rapid development of the economy and the accelerated exploitation of resources, the ecological environment of offshore waters and coastal zones has become one of the primary environmental problems of coastal countries in the world [1]. As human activities in offshore waters and coastal zones have become increasingly frequent, the problem of port sea area ecological environmental damage caused by human activities has become more and more prominent. Port sea area ecological environment pollution will lead to a decline in water environment quality in the sea area, the frequent occurrence of red tides, a decline in sea resources, and the loss of biodiversity [2], which will restrict the sustainable development of the environment. At the same time, port sea area environmental pollution can also cause adverse effects on the marine atmosphere, sediments, and marine organisms, threaten the ecological security of offshore waters and coastal zones seriously, and restrict the sustainable development of the marine economy [3,4].

Due to the complexity and fragility of the port sea ecosystem, once the system is damaged, the restoration cost is extremely high [5]. Offshore waters and coastal zones

are facing severe challenges and great pressure from the ecological environment. Therefore, how to monitor and evaluate the ecological quality of port sea areas and guarantee the sustainability of marine economic development effectively have become significant problems [4,6,7].

The establishment of a comprehensive evaluation indicator system is the premise of evaluating the ecological quality of the port sea areas. Recently, the establishment of the ecological quality status evaluation indicator system based on a single kind of factor has been widely researched.

For instance, Yang et al. constructed an evaluation system based on the seawater quality indicator for the comprehensive evaluation of marine dumping removal water quality by using a support vector machine and other technologies [8]. Qi et al. adopted the water quality indicator (WQI) as a kind of evaluation indicator to express the condition and variation trend of water environmental quality in Yihe River objectively and built a water quality evaluation model based on multiple linear regression [9]. Diaz-Casallas et al. considered water quality as a kind of key indicator to evaluate the ecological status of rivers, and this research aimed to determine the status of surface water in the watershed [10]. These studies evaluated the marine ecological quality based on seawater quality indicators.

Qiao et al. conducted sampling and analysis of marine sediment indicators, and the principal component analysis (PCA) method was used to evaluate the ecological quality of coastal waters [11]. Neyestani et al. proposed the enrichment factor method to evaluate ecological risk based on surface sediments in the northern Persian Gulf [12]. Xu et al. evaluated the pollution levels in the Jiaozhou Bay area based on major sediment concentrations in 29 surface sediment samples [13]. Liu et al. proposed an improved potential ecological risk indicator method (MRI) to study the pollution degree, chemical composition, and ecological risk of heavy metals in the marine sediments of Daya Bay [14]. All the above studies focused on evaluating the marine ecological quality based on the kind of marine sediment indicators.

Alavian et al. considered marine benthic macrophysics as a very important organism element to construct an ecological evaluation indicator system to assess the ecological status of the Persian Gulf [15]. Ji et al. selected a variety of suitable biomarkers and constructed a marine environmental quality assessment model of the Philippines based on the multi-integrated biomarker indicator method to achieve a systematic and comprehensive assessment of marine conditions [16]. These studies are aimed at evaluating marine ecological quality based on the kind of marine organism indicators.

To sum up, the above research just selects a single kind of factor as the evaluation indicator, which can reflect the impact of main indicators on the ecological quality status and obtain reasonable evaluation results. However, it is difficult to consider the comprehensive influence of various indicator factors, which leads to missing some valuable information. As a result, it is difficult for the evaluation result to fully reflect the overall ecological quality status of port sea areas. Therefore, the above three kinds of factors are selected as evaluation indicators to establish an integrated indicator system in this paper, which can reflect the ecological quality status of port sea areas in a more comprehensive way.

What's more, it is crucial to develop a suitable method to evaluate the ecological quality status of port sea areas. Recently, many mature evaluation methods have been widely used in the field of environmental quality evaluation of sea areas and have achieved good research results [17]. For example, Tu et al. analyzed the ecological environment characteristics of offshore waters, built an indicator system with 29 indicators, and proposed a pressure–state–response framework to evaluate the ecological quality of Tianjin offshore waters [18]. Xiao et al. combined the AHP method with objective entropy theory to evaluate the overall water quality of coastal waters [19]. Sun et al. constructed the marine ecological carrying capacity assessment model based on the AHP and TOPSIS methods, which were helpful to improve the ability of the marine sector to achieve sustainable development [20]. Wang et al. researched the statistical relationship between marine water quality indicators and marine ecological parameters and assessed the seawater quality based on the fuzzy

comprehensive evaluation (FCE) method [21]. Wang et al. constructed an ecological vulnerability evaluation model based on the FCE method; the presented model truly reflected the ecological quality of Danjiang River Basin [22]. Tian et al. established the remote sensing ecological index (RSEI) as an evaluation indicator of Poyang Lake ecological environment quality based on the PCA method and built an ecological assessment model based on the Google Earth engine; the results of the study showed that there were obvious regional differences in the ecological environment quality in the basin [23].

According to the above research results, there are methods for evaluating the ecological quality of offshore waters, including the PSR framework model based on AHP, the vulnerability evaluation model based on the FCE method, the marine ecological assessment model based on the AHP and TOPSIS methods, and so on. Among them, the AHP method is used widely, which is a simple and useful method to determine the weights according to the experts' experience and domain knowledge. In this method, the decision makers' preferences can be fully considered as well. At the same time, the TOPSIS method is a common and effective evaluation method, in which the original data information can be fully utilized to describe the comprehensive influence degree of different indicators. In summary, the existing research methods can evaluate the ecological quality of offshore waters, reflecting the current ecological status of offshore waters well. However, as most evaluation models rely on the subjective weight calculation method, such as AHP and fuzzy comprehensive evaluation method, to obtain different indicators weights, its subjectivity is strong, which results in the evaluation model's difficulty in reflecting the status of ecological quality accurately and objectively. In addition, it is not suitable to solve the decision-making problem involving too many factors based on the AHP method. Considering that the factors affecting the ecological quality are complicated and various, it is not appropriate to evaluate the ecological quality status of port sea areas based on the AHP method.

Therefore, in order to overcome the shortcomings of the existing methods, it is necessary to establish a comprehensive indicator system that can take full consideration of various kinds of influence factors and propose a scientific evaluation method to evaluate the ecological quality status of port sea areas, which can obtain the results objectively and accurately.

In this paper, the ecological quality status evaluation of port sea areas is taken as the research object, and a comprehensive indicator system and a scientific evaluation model are researched.

The contribution of this paper is as follows. Firstly, in order to comprehensively consider the influence of various evaluation indicators on the ecological quality status, a comprehensive evaluation indicator system is established based on indicators for three aspects. Secondly, in order to evaluate the ecological quality status of port sea areas more objectively and realistically, a new evaluation model is constructed, which combines the advantages of the entropy weight method, gray relational analysis method, and TOPSIS method. The entropy weight method is used to determine the weight of indicators objectively to avoid interference from human factors. The TOPSIS method and the gray relational analysis method are combined to form a new evaluation method that has a good performance with low complexity, high computational efficiency, and high objectivity. Finally, the evaluation results can be obtained based on the relative proximity calculated via the proposed evaluation method and the evaluation grade standards proposed in this research.

The rest of this paper is arranged as follows. In Section 2, an evaluation indicator system of port sea area ecological quality is established, with 20 indicators in three aspects. In Section 3, the ecological quality status evaluation model is constructed based on the entropy weight method, the TOPSIS model, and the gray relational analysis. In Section 4, the results of the case study are given. In Section 5, discussions are carried out. In Section 6, the conclusions are drawn.

2. Establishment of an Evaluation Indicator System

As is known, there are many factors affecting the ecological environment of the port area. In this section, a comprehensive indicator system is developed according to the principles of scientificity, representativeness, and operability, and consulting the Clean Water Action Plan [2] and the comprehensive evaluation method of coastal areas [24] proposed by the U.S. Environmental Protection Agency and relevant research achievements all over the world [7,11]. It is established by taking full account of the ecological environment characteristics of port sea areas and making full use of the survey data in order to provide a comprehensive and accurate evaluation basis. In the indicator system, the most representative factors are the seawater quality, the sediments, and the marine organisms, which can be selected as the first-level indicator factors.

The seawater quality indicator can be used to measure whether the water in the port area can meet the requirements of the survival of human beings and marine organisms and the development of society and the economy. Relevant research achievements show that excessive inorganic nitrogen and active phosphate can lead to seawater eutrophication; as a result, ecological disasters such as red tides are more likely to occur [25–29]. According to the seawater quality standards proposed by China [30], the factors, such as salinity, suspended solids, dissolved oxygen, chemical oxygen demand (COD), active phosphate, inorganic nitrogen, and petroleum, have an important influence on seawater quality. They can be regarded as the key indicators to evaluate water eutrophication. Thus, they can be selected as the second-level indicator factors of the system. Among them, the dissolved oxygen is a benefit indicator. Within a reasonable range, the higher the dissolved oxygen indicator value is, the better the ecological quality of seawater is. The other second-level indicators are cost indicators, and the higher the indicator value is, the worse the seawater quality is.

In addition, the enrichment of cuprum, zinc, and other sediments in the port sea area can lead to high toxicity and persistent pollution of the sea. The sediments are formed by marine sedimentation with high physical and chemical stabilities. They can reflect the average status of the marine environment. Relevant research achievements show that it could be a threat to the survival of organisms and cause serious damage to the marine ecosystem if the content of cuprum, plumbum, and other sediments is too high [31–35]. According to the marine sediment quality standards proposed by China [36], the influencing factors, such as cuprum, plumbum, zinc, chromium, total mercury, sulfide, and organic carbon, can be selected as the second-level indicator factors of the system. These indicators are cost indicators. The higher the indicator values, the worse the marine ecological quality.

What's more, the marine organism quality index is crucial in the evaluation of the ecological environment of the port sea area. It can be used to measure the stability of the port sea area ecosystem, the structural balance of marine organisms, and the level of biological diversity. It can also reflect the environmental pollution status of the port sea area [15,16]. The marine organisms mainly include the phytoplankton, the zooplankton, and the benthos in the port sea area. The status of the marine environment quality can be reflected by the phytoplankton, zooplankton, and benthos. These organisms are highly sensitive to chemical pollutants and have the ability to absorb heavy metals. The importation of exotic marine organisms could lead to changes in the species in the port sea area. Therefore, the indicators used to measure the organism quality of the phytoplankton, the zooplankton, and the benthos, such as phytoplankton diversity index, phytoplankton abundance, zooplankton diversity index, zooplankton abundance, benthos diversity index, and benthos abundance [37–39], can be selected as the second-level indicator factors of the system. The above indicators are benefit indicators. The higher the indicator values, the better the marine ecological quality.

The evaluation indicator system of the ecological quality status of the port sea area is given in Table 1.

Table 1. Evaluation indicator system of ecological quality status.

First-Level Evaluation Indicators	Second-Level Evaluation Indicators
Seawater quality	Salinity
	Suspended solids
	Dissolved oxygen
	Chemical oxygen demand
	Inorganic nitrogen
	Active phosphate
	Petroleum
Sediments	Cuprum
	Plumbum
	Zinc
	Chromium
	Total mercury
	Sulfide
	Organic carbon
Marine organisms	Phytoplankton diversity index
	Phytoplankton abundance
	Zooplankton diversity index
	Zooplankton abundance
	Benthos diversity index
	Benthos abundance

3. Modeling

In this section, a novel ecological quality status evaluation model of port sea areas is proposed based on the evaluation indicator system developed in Section 2.

The TOPSIS method is a relatively mature evaluation model. The comprehensive ranking of evaluation indicators can be obtained conveniently by calculating the relative proximity between evaluation indicators and the ideal solution via this method [40,41]. It is suitable for the condition with a large evaluation indicator set. However, everything has two sides. The ideal solution calculated using the TOPSIS method may vary with the number of evaluation objects. Meanwhile, there is a large amount of computation when calculating the Euclidean distance between evaluation objects and the ideal solutions. It is difficult to reflect the changing trend of the evaluation indicator value sequence. Therefore, it is difficult to ensure the accuracy of decision results by using the raw data of evaluation objects directly.

In order to overcome the above shortcomings that the ideal solution of the TOPSIS method is easily affected by the number of evaluation objects and the fluctuation in data, the gray relational analysis method [42] is introduced into the TOPSIS method in this research. As is known, the gray relational degree can reflect the strength of the relationship between indicators. The larger the value of the gray relational degree, the stronger the consistency between the tendency of the evaluation indicator value and the tendency of the optimal solution. The gray relational degree can reflect the variation tendency of various indicators in the system very well. In addition, it has the advantages of fewer raw data required and simple principles. It is easy to mine the inherent rules of data as well.

Therefore, a novel ecological quality status evaluation method is developed, which combines the advantages of the TOPSIS method and the gray relational analysis method in this paper. Considering that the size of the evaluation indicator set is relatively large, the TOPSIS method is suitable to be used as the basic evaluation model, which can improve the objectivity of the evaluation results, reduce the computational complexity, and improve the computational efficiency of the model. Taking advantage of the gray relational analysis method, it is introduced to calculate the relational coefficient between the evaluation indicators and the ideal solution. In addition, in order to overcome the shortcomings of traditional subjective weighting methods, the entropy weight method [43] is used to determine the indicator weights to avoid the interference of human factors.

As a consequence, the EW-GRA-TOPSIS model is developed to evaluate the ecological quality status of the port sea area based on the EW method, the GRA method, and the TOPSIS method. Firstly, the EW method is used to determine the weight value of each evaluation indicator objectively. Secondly, the TOPSIS method and the GRA method are combined to form a new evaluation method that can be used to calculate the relative proximity. Then, the ecological quality status of each station in the port sea area can be sorted by the obtained relative proximity. Finally, the level of the ecological quality status of each station can be determined according to the evaluation grade standard.

3.1. Determination of Indicator Weights

It is necessary to allocate appropriate weights to various indicators, which can have a significant impact on the evaluation results. In this research, the EW method is used to allocate the weights to indicators. It is a kind of objective weighting method, which can be used to calculate the weights based on the objective data describing the values of indicators and the variability of indicators. The weights can be more objective than those obtained using traditional subjective weighting methods, which depend on the subjective judgment of the evaluator. In the proposed model, the weights of ecological quality evaluation indicators can be determined as follows.

(1) Data processing

First of all, the decision matrix should be constructed. It can be expressed as A , which is composed of values of m evaluation indicators for n objects.

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1m} \\ a_{21} & a_{22} & \cdots & a_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nm} \end{bmatrix}$$

(2) Standardization of evaluation indicators

The value of the kind of benefit indicators can be standardized according to Formula (1).

$$r_{ij} = \frac{a_{ij} - a_{ij}^{\min}}{a_{ij}^{\max} - a_{ij}^{\min}} (i = 1, 2, \dots, n, j = 1, 2, \dots, m) \quad (1)$$

The value of the kind of cost indicators can be standardized according to Formula (2).

$$r_{ij} = \frac{a_{ij}^{\max} - a_{ij}}{a_{ij}^{\max} - a_{ij}^{\min}} (i = 1, 2, \dots, n, j = 1, 2, \dots, m) \quad (2)$$

where r_{ij} and a_{ij} stand for the standardized value and the initial value of the j -th indicator of the i -th object, respectively. $a_{ij}^{\min}$ and $a_{ij}^{\max}$ stand for the minimum value and the maximum value of the j -th indicator, respectively.

(3) Calculation of feature weights of indicators

The indicator feature weights can be calculated according to Formula (3).

$$p_{ij} = \frac{r_{ij}}{\sum_{i=1}^n r_{ij}} (i = 1, 2, \dots, n, j = 1, 2, \dots, m) \quad (3)$$

where p_{ij} represents the feature weight value of the j -th indicator of the i -th object.

(4) Calculation of entropy values of indicators

The entropy of the evaluation indicator can be calculated as follows.

$$E_j = \frac{1}{\ln n} \left(\sum_{i=1}^n p_{ij} \ln p_{ij} \right) (i = 1, 2, \dots, n, j = 1, 2, \dots, m) \quad (4)$$

where E_j represents the entropy value of the j -th indicator.

(5) Calculation of variation coefficients

The variation coefficient of the evaluation indicator can be obtained according to Formula (5).

$$D_j = 1 - E_j (j = 1, 2, \dots, m) \quad (5)$$

where D_j stands for the variation coefficient of the j -th indicator.

(6) Calculation of indicator weights

The indicator weights can be determined according to Formula (6).

$$w_j = \frac{D_j}{\sum_{j=1}^m D_j} \quad (6)$$

where w_j stands for the weight of the j -th indicator.

3.2. Comprehensive Evaluation of Ecological Quality Status of Port Sea Areas

Based on the obtained weights of the indicators above, the weighted normalization matrix can be constructed at first. Afterwards, the TOPSIS method is used to determine the initial positive ideal solution of indicators. Then, the initial positive ideal solution can be improved using the gray relational analysis method. Thus, the relative proximity of the evaluation objects to the ideal solutions can be calculated, which can be used to determine the ranking results of evaluation objects. Finally, the ecological quality status level of evaluation objects can be determined according to the evaluation standards. The detailed steps are as follows.

(1) Data processing

The original decision matrix A should be normalized according to Formula (7).

$$z_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^n a_{ij}^2}} \quad (7)$$

where z_{ij} stands for the normalized value of the j -th indicator of the i -th object, and the normalized matrix Z can be written as:

$$Z = \begin{bmatrix} z_{11} & z_{12} & \cdots & z_{1m} \\ z_{21} & z_{22} & \cdots & z_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ z_{n1} & z_{n2} & \cdots & z_{nm} \end{bmatrix}$$

(2) Calculation of weighted normalization decision matrix

Considering the different effects on the evaluation result caused by various indicators, the normalization decision matrix Z should be weighted by indicator weights. As a result, the weighted normalization decision matrix V can be obtained according to Formula (8).

$$V = (v_{ij})_{n \times m} = (w_j z_{ij})_{n \times m} \quad (8)$$

where v_{ij} stands for the weighted normalized value of the j -th indicator of the i -th object.

(3) Determination of the initial positive ideal solution of evaluation indicators

The initial positive ideal solution of evaluation indicators can be determined according to Formula (9).

$$A^+ = (f_1^+, f_2^+, \dots, f_j^+) \quad (9)$$

where f_j^+ stands for the initial positive ideal solution of the j -th indicator, and $f_j^+ = \max\{v_{ij}\}, i = 1, 2, \dots, n, j = 1, 2, \dots, m$.

(4) Calculation of the gray relational coefficient

The gray relational coefficient between the evaluation indicator and the initial positive ideal solution can be calculated according to Formula (10).

$$S_{ij} = \frac{\min_{1 \leq i \leq n} \min_{1 \leq j \leq m} |f_j^+ - v_{ij}| + \rho \cdot \max_{1 \leq i \leq n} \max_{1 \leq j \leq m} |f_j^+ - v_{ij}|}{|f_j^+ - v_{ij}| + \rho \cdot \max_{1 \leq i \leq n} \max_{1 \leq j \leq m} |f_j^+ - v_{ij}|} \quad (10)$$

where the value range of the parameter ρ is $[0, 1]$. In general, $\rho = 0.5$ is defined.

Hence, the gray relational coefficient matrix $S = (S_{ij})_{n \times m}$ can be obtained.

The improved positive ideal solution S^+ and the improved negative ideal solution S^- of evaluation indicators can be formatted as Formulas (11) and (12), respectively.

$$S^+ = (S_1^+, S_2^+, \dots, S_j^+) \quad (11)$$

$$S^- = (S_1^-, S_2^-, \dots, S_j^-) \quad (12)$$

where $S_j^+ = \max\{S_{ij}\}, S_j^- = \min\{S_{ij}\}, i = 1, 2, \dots, n, j = 1, 2, \dots, m$.

(5) Calculation of the distance between the evaluation object and the improved ideal solutions

The Euclidean distance between the evaluation object and the improved positive ideal solution can be obtained according to Formula (13).

$$d_i^+ = \sqrt{\sum_{j=1}^m (S_{ij} - S_j^+)^2} \quad (i = 1, 2, \dots, n) \quad (13)$$

where d_i^+ stands for the distance between the i -th evaluation object and the improved positive ideal solution.

The Euclidean distance between the evaluation object and the improved negative ideal solution can be obtained according to Formula (14).

$$d_i^- = \sqrt{\sum_{j=1}^m (S_{ij} - S_j^-)^2} \quad (i = 1, 2, \dots, n) \quad (14)$$

where d_i^- stands for the distance between the i -th evaluation object and the improved negative ideal solution.

(6) Calculation of the relative proximity

The relative proximity of the evaluation objects to the ideal solutions can be obtained according to Formula (15).

$$C_i = d_i^- / (d_i^- + d_i^+) \quad (i = 1, 2, \dots, n) \quad (15)$$

The evaluation objects can be sorted according to values of the relative proximity C_i . The larger C_i is, the closer the evaluation object is to the ideal goal, and the better the ecological quality status of the evaluation object is.

(7) Determination of the ecological quality status level of evaluation objects

First, the ecological quality status of port sea areas can be divided into five levels according to the existing relevant industry standards [30,36]. In order to reduce the membership degree error caused by unequal grade intervals and the coincidence of adjacent intervals, the range of evaluation indicator values is divided into five equal segments in this paper. Thus, the interval values of different evaluation indicators at each grade can be determined.

Then, the relative proximity interval of each evaluation grade can be calculated according to the interval boundary value of each grade of indicators.

Finally, the ecological quality status level of evaluation objects can be determined according to the grade interval that the relative proximity of each evaluation object falls into.

As a result, the EW-GRA-TOPSIS model is constructed in this section. The time complexity of the model is $O(n)$ and the space complexity is $O(l)$. It is obvious that the proposed model is efficient with low complexity and it contributes to the evaluation of the ecological quality status of port sea areas objectively.

4. Case Study

In order to illustrate the effectiveness of the presented EW-GRA-TOPSIS model, it is used to evaluate the ecological quality status of a port sea area of Tianjin (around $38^{\circ}56' \sim 38^{\circ}59' \text{ N}$, $117^{\circ}42' \text{ E} \sim 117^{\circ}58' \text{ E}$) in China.

In this research, the source data are the historical data in May 2015, which are provided by a certain research institute in China.

In the case study, twelve monitoring stations are randomly selected as the evaluation objects in this port sea area. The locations of these stations are shown in Figure 1. According to the ecological quality status evaluation indicator system proposed in Section 2, the monitoring data of the twenty evaluation indicators of the twelve stations are extracted from all the environmental monitoring data.



Figure 1. Locations of the selected stations in the port sea area of Tianjin.

In order to display all the monitoring stations in the Figure 1, the image of Tianjin port sea area has been scaled down properly. In fact, S2, S6, S8 are monitoring stations under a bridge of the port sea area.

The process of the ecological quality status comprehensive evaluation of this port sea area is as follows.

(1) Determination of indicator weights and ideal solutions of indicators

Firstly, the values of indicators should be normalized to eliminate the effect of different dimensions of indicators on the evaluation results according to Formulas (1) and (2).

Secondly, the weights of evaluation indicators can be obtained according to Formulas (3)–(6).

Thirdly, the improved positive ideal solution and the improved negative ideal solution of indicator values can be calculated according to Formulas (7)–(12). The results are displayed in Table 2.

Table 2. Weights and improved ideal solutions of indicators based on the proposed model.

Indicator	Weight	Positive Ideal Solution	Negative Ideal Solution
Salinity	0.0558	1.0000	0.9747
Suspended solids	0.0379	1.0000	0.7338
Dissolved oxygen	0.0803	1.0000	0.7731
Chemical oxygen demand	0.0690	1.0000	0.5431
Petroleum	0.0441	1.0000	0.4366
Cuprum	0.0190	1.0000	0.8838
Plumbum	0.0386	1.0000	0.7606
Zinc	0.0400	1.0000	0.8101
Chromium	0.0385	1.0000	0.7707
Total mercury	0.0374	1.0000	0.6268
Active phosphate	0.0657	1.0000	0.6838
Inorganic nitrogen	0.0422	1.0000	0.8941
Organic carbon	0.0616	1.0000	0.6352
Sulfide	0.0478	1.0000	0.3514
Phytoplankton diversity index	0.0420	1.0000	0.7931
Phytoplankton abundance	0.0723	1.0000	0.5493
Zooplankton diversity index	0.0240	1.0000	0.8351
Zooplankton abundance	0.0370	1.0000	0.6284
Benthos diversity index	0.0611	1.0000	0.5975
Benthos abundance	0.0848	1.0000	0.3333

(2) Ranking of monitoring stations

Firstly, the Euclidean distance d_i^+ between the ecological quality status of the monitoring station and the improved positive ideal solution can be obtained according to Formula (13), and the Euclidean distance d_i^- between the ecological quality status of the monitoring station and the improved negative ideal solution can be obtained according to Formula (14).

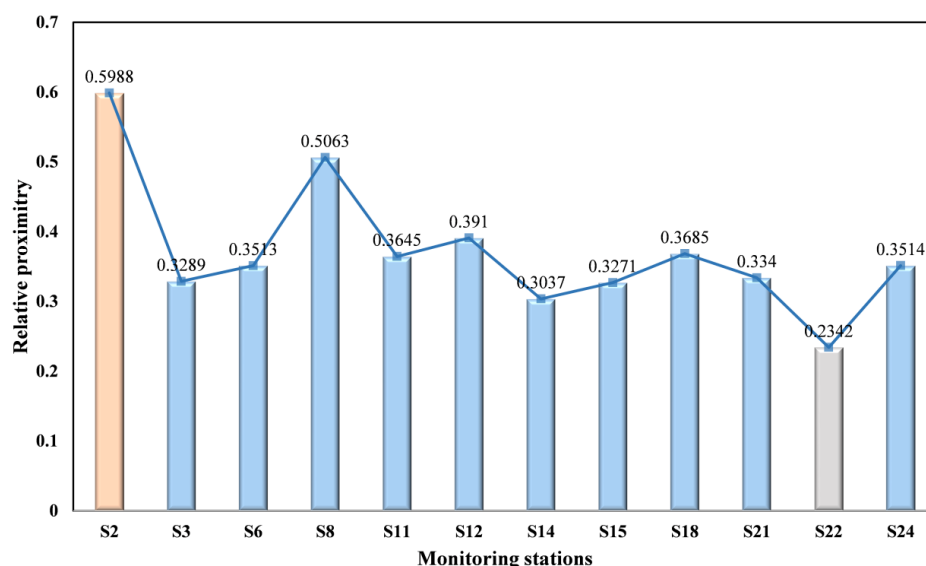
Secondly, the relative proximity of the ecological quality status of the monitoring station to the ideal solution can be obtained according to Formula (15).

Thirdly, the monitoring stations can be sorted based on the relative proximity.

The results are displayed in Table 3. The trend of the relative proximity of the selected stations is shown in Figure 2.

Table 3. Ranking results of monitoring stations based on relative proximity.

Station	d_i^+	d_i^-	Relative Proximity C_i	Ranking
S2	0.8789	1.3121	0.5988	1
S3	1.3169	0.6454	0.3289	9
S6	1.1981	0.6489	0.3513	7
S8	1.0161	1.0423	0.5063	2
S11	1.1763	0.6749	0.3645	5
S12	1.0811	0.6942	0.3910	3
S14	1.2238	0.5338	0.3037	11
S15	1.2167	0.5914	0.3271	10
S18	1.1292	0.6589	0.3685	4
S21	1.2473	0.6257	0.3340	8
S22	1.3956	0.4269	0.2342	12
S24	1.2888	0.6983	0.3514	6

**Figure 2.** The relative proximity of monitoring stations in the port sea area of Tianjin based on the proposed model.

As shown in Table 3 and Figure 2, it can be seen that station S2 is ranked first, followed by S8, S12, S18, S11, S24, S6, S21, S3, S15, S14, and S22.

(3) Determination of the ecological quality status level of monitoring stations

Firstly, the evaluation standards should be given to quantify the ecological quality status of monitoring stations.

Referring to relative industry standards, such as the European Union's Water Framework Directive, the National coastal condition report III proposed by the U.S. Environmental Protection Agency [24], the Seawater Quality Standard proposed by the State Environment Protection Administration of China [30], and the Marine Sediments Quality Standard proposed by the State Oceanic Administration of China [36], this research divides the evaluation level into five grades. The evaluation grades are excellent, good, fair, poor, and bad.

The interval values of different grades of evaluation indicators are displayed in Table 4.

Table 4. Evaluation grade standards for evaluation indicators.

Indicator	Grade				
	Excellent	Good	Fair	Poor	Bad
Salinity (mg/L)	[20, 25]	[25, 27]	[27, 30]	[30, 35]	[8, 20], [35, ~]
Suspended solids (mg/L)	[10, 20]	[20, 30]	[30, 40]	[40, 50]	[50, ~]
Dissolved oxygen (mg/L)	(5, 6]	(4, 5]	(3, 4]	(2, 3]	(0, 2]
COD (mg/L)	[1, 2]	[2, 3]	[3, 4]	[4, 5]	[5, ~]
Petroleum (mg/L)	[0.05, 0.10]	[0.10, 0.20]	[0.20, 0.30]	[0.30, 0.50]	[0.50, ~]
Cuprum (µg/L)	[30, 50]	[50, 100]	[100, 150]	[150, 200]	[200, ~]
Plumbum (µg/L)	[60, 100]	[100, 150]	[150, 200]	[200, 250]	[250, ~]
Zinc (µg/L)	[100, 150]	[150, 250]	[250, 200]	[200, 250]	[250, ~]
Chromium (µg/L)	[0.50, 1.0]	[1.0, 2.0]	[2.0, 3.0]	[3.0, 4.0]	[4.0, ~]
Total mercury (µg/L)	[0.2, 0.5]	[0.5, 0.75]	[0.75, 1.0]	[1.0, 1.5]	[1.5, ~]
Active phosphate (µg/L)	[0.015, 0.020]	[0.020, 0.025]	[0.025, 0.030]	[0.030, 0.035]	[0.35, ~]
Inorganic nitrogen (µg/L)	[150, 200]	[200, 250]	[250, 300]	[300, 400]	[500, ~]
Organic carbon (%)	[1, 2]	(2, 3]	(3, 4]	(4, 5]	[5, ~]
Sulfide (%)	[100, 200]	[200, 300]	[300, 400]	[400, 500]	[500, ~]
Phytoplankton diversity index	(3, 4]	(2, 3]	(1, 2]	(0.6, 1]	(0, 0.6]
Phytoplankton abundance	(2.0, 2.5]	(1.5, 2.0]	(1.0, 1.5]	(0.1, 1.0]	(0, 0.1]
Zooplankton diversity index	(3, 4]	(2, 3]	(1, 2]	(0.6, 1]	(0, 0.6]
Zooplankton abundance	(2.0, 2.5]	(1.5, 2.0]	(1.0, 1.5]	(0.1, 1.0]	(0, 0.1]
Benthos diversity index	(3, 4]	(2, 3]	(1, 2]	(0.6, 1]	(0, 0.6]
Benthos abundance	(2.0, 2.5]	(1.5, 2.0]	(1.0, 1.5]	(0.1, 1.0]	(0, 0.1]

According to the boundary value of each grade of indicators in Table 4, the value of the relative proximity of the evaluation grade can be calculated. As a result, the interval values of different grades of the ecological quality status can be determined based on the relative proximity, as demonstrated in Table 5.

Table 5. Evaluation grade standards for the ecological quality status.

Grade	Interval Value
Excellent	(0.6, 1]
Good	(0.33, 0.6]
Fair	(0.25, 0.33]
Poor	(0.10, 0.25]
Bad	(0.0, 0.10]

Secondly, the ecological quality status level of the selected monitoring stations can be determined according to the above evaluation standards. The evaluation results are displayed in Table 6.

Table 6. Results of the ecological quality status evaluation of monitoring stations based on the proposed model.

Station	Relative Proximity	Grade
S2	0.5988	Good
S3	0.3289	Fair
S6	0.3513	Good
S8	0.5063	Good
S11	0.3645	Good
S12	0.3910	Good
S14	0.3037	Fair
S15	0.3271	Fair
S18	0.3685	Good
S21	0.3340	Good
S22	0.2342	Poor
S24	0.3514	Good

It can be seen from Table 6 that none of these stations are in the excellent grade or the bad grade. There are eight stations in the good grade, namely S2, S6, S8, S11, S12, S18, S21, and S24. There are three stations in the fair grade, namely S3, S14, and S15. Station

S22 is in the poor grade. The above evaluation results are obtained based on the proposed EW-GRA-TOPSIS model, and the calculation results based on the proposed model are shown in Tables S1–S12 of the Supplementary Materials.

In addition, in order to further verify the effectiveness of the proposed model, the typical TOPSIS method can be used as a control model in the contrast experiment. The evaluation results based on the TOPSIS method are displayed in Table 7. The trend of the relative proximity of the selected monitoring stations is shown in Figure 3.

Table 7. The evaluation results of monitoring stations based on the TOPSIS model.

Station	Relative Proximity	Grade
S2	0.5073	Good
S3	0.4955	Good
S6	0.3539	Good
S8	0.4016	Good
S11	0.3874	Good
S12	0.5076	Good
S14	0.5191	Good
S15	0.6123	Excellent
S18	0.4464	Good
S21	0.5730	Good
S22	0.6006	Excellent
S24	0.3514	Good

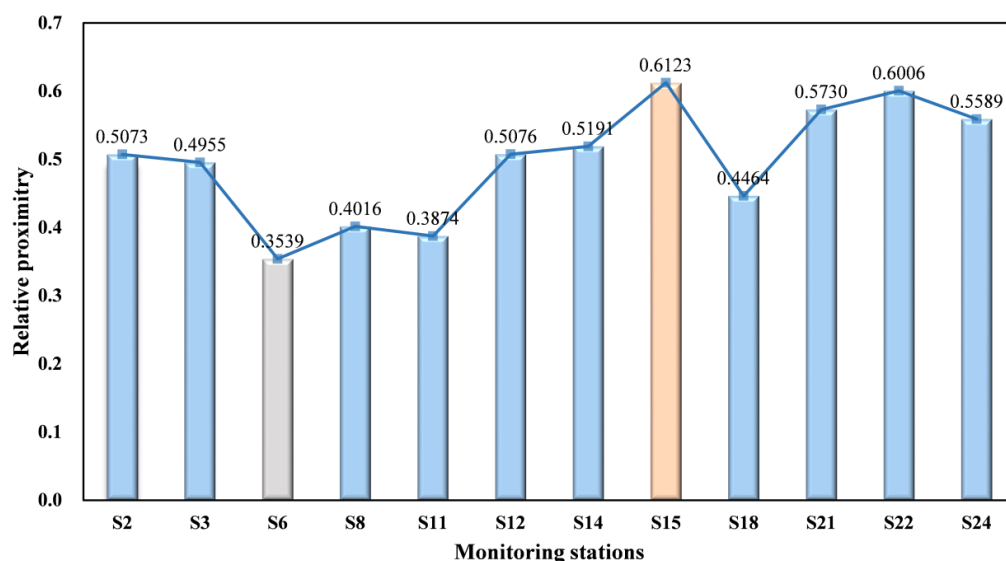


Figure 3. The relative proximity of monitoring stations based on the TOPSIS model.

As shown in Table 7, the levels of these stations are intensively distributed in the excellent grade and the good grade. There are ten stations in the good grade, namely S2, S3, S6, S8, S11, S12, S14, S18, S21, and S24. There are two stations in the excellent grade, namely S15 and S22.

As shown in Figure 3, it can be seen that station S15 is ranked first, followed by S22, S21, S24, S14, S12, S2, S3, S18, S8, S11, and S6. The calculation results based on the TOPSIS method are shown in the Tables S13–S17 of the Supplementary Materials.

The evaluation results based on the proposed model and the TOPSIS model are compared as follows. The comparison results of the evaluation grade are shown in Figure 4. The comparison results of the relative proximity trend are shown in Figure 5.

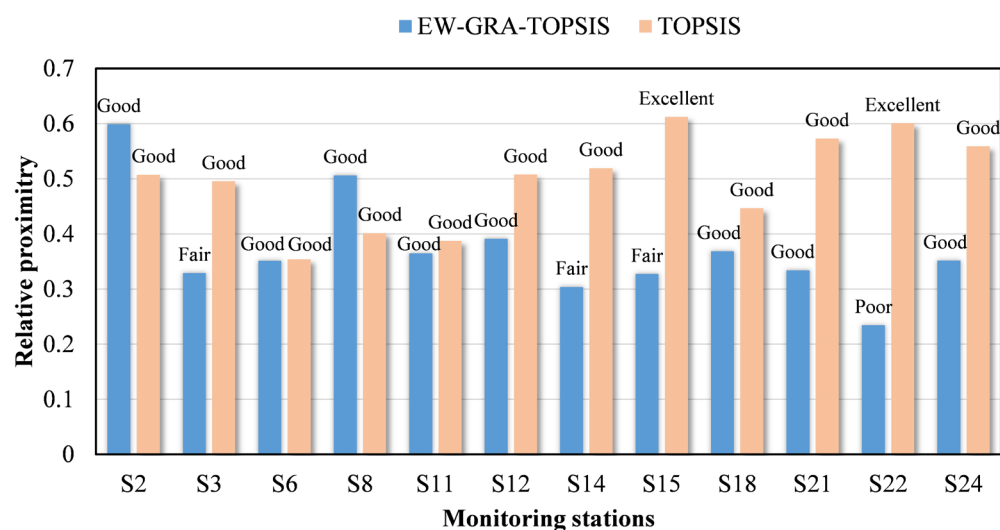


Figure 4. Comparison results of the evaluation grade.

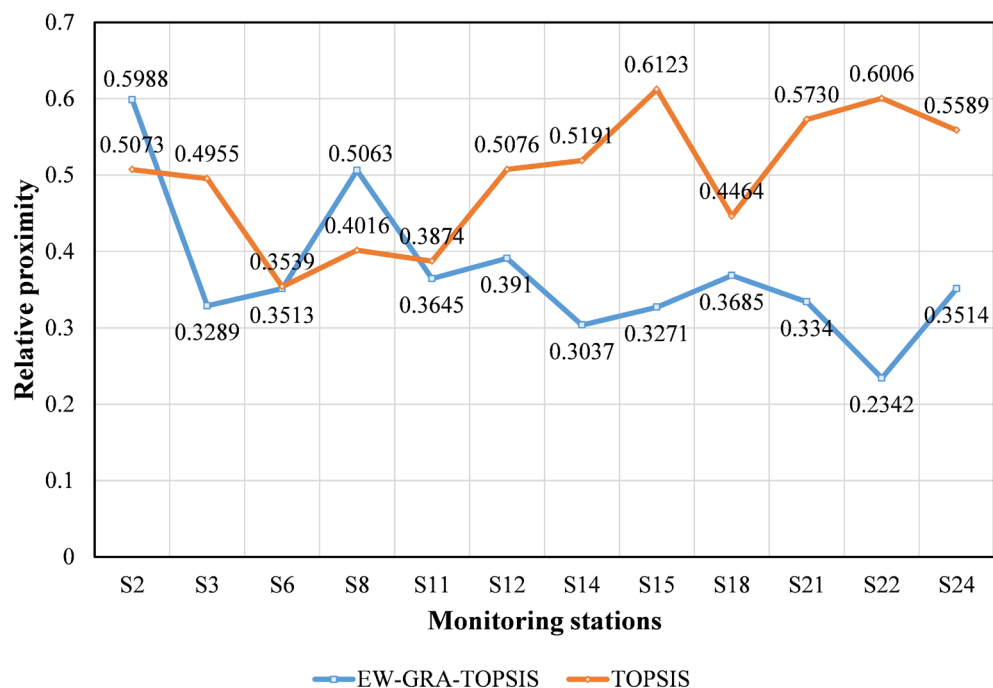


Figure 5. Comparison results of the relative proximity.

As shown in Figure 4, the evaluation results of selected monitoring stations based on the proposed model and the typical TOPSIS model can be described as the orange bar and the blue bar, respectively. It can be seen from Figure 4 that 33.3% of the stations have different evaluation grade results based on these two different evaluation models. In particular, the monitoring stations with significant differences in the relative proximity are S22, S15, S21, S14, and S24. For example, the deviation value of the relative proximity of S22 based on different models is 0.37, and the evaluation grade of S22 is at a poor level based on the proposed model, while it is at an excellent level based on the TOPSIS method. Although the evaluation results of S24 based on different evaluation models are consistent, namely at a good level, the deviation value of the relative proximity of S24 based on different models is as large as 0.29.

Taking station S22 as an example, the ecological quality status level is evaluated at an excellent grade based on the TOPSIS model. However, the actual survey data show that

several indicator values of this station are below the standards of the first-level standard requirements. For example, the content of suspended solids of S22 is 23.2 mg/L, which cannot meet the first-level standard requirement, i.e., [10, 20). At the same time, there are several indicator values of S22 below the fourth-level standard requirements, which indicates that the ecological quality level of station S22 is closer to the poor grade. The survey results are consistent with the evaluation result obtained based on the proposed model. On the contrary, the evaluation result obtained based on the TOPSIS model cannot match this fact. It can be seen that the proposed model can reflect the actual ecological quality status of this port sea area more accurately than the typical TOPSIS model.

In Figure 5, the relative proximity trend of the selected monitoring stations based on the proposed model and the typical TOPSIS model can be described as the blue curve and the orange curve, respectively. It can be seen from Figure 5 that the calculation results of the relative proximity based on the TOPSIS model range from 0.35 to 0.6, and the calculation results of the relative proximity based on the EW-GRA-TOPSIS model range from 0.23 to 0.6. Compared to the proposed model, the evaluation method based on the TOPSIS model cannot easily reflect the changing trend of the value sequence of evaluation indicators, and the reason is that the Euclidean distances between the evaluation object and the ideal solutions differ slightly due to the correlation between indicators. This is the limitation of the TOPSIS method. The comparison results indicate that the proposed model can improve the deficiencies of the TOPSIS method effectively and reflect the differences in the ecological quality status of monitoring stations more clearly. The evaluation results based on the proposed model are closer to the survey results. Therefore, the effectiveness of the proposed EW-GRA-TOPSIS model can be verified.

In summary, a comparison between the proposed model and the TOPSIS model shows that the evaluation results based on the proposed model are more consistent with the actual results, and the proposed model has a higher accuracy for evaluation. Therefore, the practicability and effectiveness of the proposed model is verified according to the case study and the contrast experiment.

5. Discussion

The proposed EW-GRA-TOPSIS method is applied to evaluate the ecological quality status of a certain port sea area in Tianjin. Firstly, a comprehensive evaluation indicator system including 20 indicators from three aspects is developed referring to relevant standards and existing research achievements. Secondly, based on the proposed evaluation indicator system, the weights of evaluation indicators are obtained using the EW method. Thirdly, the relative proximity is calculated based on the improved GRA-TOPSIS method. Based on the obtained relative proximity, ranking results of the selected monitoring stations are carried out. Finally, the ecological quality status level of monitoring stations is determined based on the proposed evaluation standards with five grades, which is developed according to relevant industry standards.

The results of the case study show that 66.7% of the selected stations in the port sea area are at a good level, 25% of them are at a fair level, only 8.3% are at a poor level, and none are at an excellent or bad level.

The order of the ecological quality status of the 12 stations in the port sea area of Tianjin is S2, S8, S12, S18, S11, S24, S6, S21, S3, S15, S14, and S22. The relative proximity of station S2 is the largest, indicating that the ecological quality status of station S22 is the best and its ecological structure is the most stable among all of the selected stations.

Further, 66.7% of the stations are at a good level, namely S2, S6, S8, S11, S12, S18, S21, and S24. The result indicates that the ecological quality status of these stations has obvious advantages. The seawater quality, sediment quality, and marine organism quality of these stations can basically meet the requirements of the second-level standard. Additionally, the ecological structure is stable. It is necessary to protect these areas by preventing pollution.

Further, 25% of the stations are at a fair level, namely S3, S14, and S15. The result shows that the seawater quality, sediment quality, and marine organism quality of these

stations can meet the requirements of the third-level standard. Additionally, the overall ecological environment is basically stable. It is necessary to monitor these areas regularly to prevent serious pollution.

Further, 8.3% of the stations are at a poor level, namely S22. The overall ecological quality status of the station is relatively poor, indicating that the seawater quality, sediment quality, and marine organism index of the station may reach the fourth-level standard. There is existing potential light pollution. It is urgent and necessary to take measures to control and protect the ecological environment of this area.

Actually, the survey results of station S22 show that values of several indicators (i.e., inorganic nitrogen, active phosphate, petroleum, and mercury) are below the fourth-level standard requirements to various degrees. The zooplankton diversity index and the benthos diversity index are somewhat below the average level. The remaining indicator values can meet the requirements of the ecological environment standards. In consequence, the general ecological quality status of the station S22 is relatively poor, which is consistent with the calculation results obtained using the proposed model. It indicates that the evaluation result of S22 based on the proposed EW-GRA-TOPSIS model is reasonable. Similarly, it is verified that the survey data of other stations are also consistent with the results acquired using the presented model.

What's more, the comparison results of different evaluation models show that the proposed model can effectively make up for the shortcomings of the TOPSIS method, in that it is difficult to reflect the changing trend of indicator values accurately. The obtained evaluation results based on the proposed model are more consistent with the survey results, indicating that the proposed model can improve the accuracy of evaluation compared with the TOPSIS method.

Above all, the proposed EW-GRA-TOPSIS model performs well in the ecological quality status evaluation of port sea areas, and it has good practicability and effectiveness.

In addition, the limitations of this research and suggestions for further research are as follows.

Firstly, although the ecological quality status evaluation indicator system with 20 indicators established in this paper is more comprehensive than the evaluation indicator system including a single kind of indicator, it can be perfected by selecting some more influencing factors according to the actual situation in future research.

Secondly, in the process of determining the evaluation grades, the interval length of each grade is assumed to be equal in this paper, which is an ideal situation of grade classification. However, it is possible that the intervals of different grades are not strictly equidistant. Therefore, the simplified method to determine the evaluation grade intervals can affect the evaluation results to a certain extent. In the future, a more scientific and reasonable method to determine the evaluation grade should be further researched.

Thirdly, the entropy weight method is adopted to calculate the weight of evaluation indicators in this paper, and the actual data are fully utilized to determine the weight value, while the subjective preferences of decision makers on the importance of different evaluation indicators are not fully considered, which could cause the indicator weights to deviate from the actual situation. Therefore, the comprehensive weighting method can be adopted to improve the evaluation model in further research.

6. Conclusions

A novel method is proposed to evaluate the ecological quality status of port sea areas objectively in this paper. The conclusions of this research are as follows.

At first, a comprehensive evaluation indicator system is established, which is suitable for the ecological quality status evaluation. According to relevant industry standards, including the seawater quality standards and the marine sediment quality standard, as well as relevant research achievements, twenty indicators are selected from three aspects, namely seawater quality, sediment, and organisms, to construct the evaluation indicator

system. It provides a foundation for the objective and accurate evaluation of the ecological quality status of port sea areas.

Then, a novel evaluation model is developed, which combines the advantages of the entropy weight method, gray relational analysis method, and TOPSIS. Eventually, the effectiveness of the proposed model is illustrated by a case study based on a port sea area in Tianjin. The results show that the presented EW-GRA-TOPSIS model has a good performance in evaluating the ecological quality status of port sea areas with low complexity and high objectivity. The evaluation results based on the proposed model are very consistent with the actual ecological quality status. It can provide a theoretical basis for decision making about the ecological environmental protection and sustainable development of offshore sea areas, and it has promising application prospects.

However, there are limitations that should be further improved in future research as follows.

Firstly, a more comprehensive evaluation system, including some more factors, should be researched to improve the evaluation effectiveness in the future, and a more objective and reasonable evaluation grade determination method should be further studied.

Secondly, other effective multi-attribute decision-making methods can be considered to be used to improve the proposed model in future research.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su15118809/s1>, Table S1: The standardization results of evaluation indicators; Table S2: The calculation results of indicator feature weights; Table S3: The calculation results of indicator entropy; Table S4: The calculation results of coefficient of variation; Table S5: The calculation results of indicator weights; Table S6: The data preprocessing results; Table S7: The calculation results of the weighted normalized decision matrix; Table S8: The calculation results of the initial positive ideal solutions of the evaluation indicators; Table S9: The calculation results of gray correlation coefficient; Table S10: The calculation results of the improved indicators positive and negative ideal solutions; Table S11: The distance between the evaluation indicators and the ideal solutions; Table S12: The calculation results of relative proximity based on the proposed model; Table S13: The forward processing results of evaluation indicators; Table S14: The standardization results of evaluation indicators; Table S15: The calculation results of the weighted normalized decision matrix; Table S16: The distance between the evaluation indicators and the ideal solutions; Table S17: The calculation results of relative proximity based on the TOPSIS method.

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