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Article

Quantitative Evaluation Method for Construction Disturbance and Ecological Restoration of Waterway Engineering and Its Application

Xia Shen [1,2], Haipeng Wang [1], Peng Wang [3,*], Rui Xie [1], Yongping Wang [1] and Changhui Ji [1]

1 State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Nanjing Hydraulic Research Institute, Nanjing 210024, China
2 Key Laboratory of Ocean Space Resource Management Technology, MNR, Hangzhou 310012, China
3 Key Laboratory of Integrated Regulation and Resource Development on Shallow Lake of Ministry of Education, Hohai University, Nanjing 210098, China
* Correspondence: hhwp@hhu.edu.cn

Abstract: With the increasing emphasis on the ecology and environment of rivers, the construction of ecological waterway projects has become a development trend in China. In recent years, more and more attention has been paid to the qualitative and quantitative evaluation of the ecological effects of ecological waterway construction. Based on pressure-state-response (PSR) and driver-pressure-state-impact-response (DPSIR) logical frameworks, this paper established a state-pressure-impact-response (SPIR) conceptual model. The model took the river ecology and environment state as the main line, and described the disturbance pressure of the engineering construction on the river state, the impacts of the project on the river comprehensive function, and the positive responses taken in the full lifetime cycle of the project. The analytic hierarchy process (AHP) and fuzzy evaluation model were used to study the changes of the river ecosystem status after suffering from the construction pressure and taking positive responses. Taking the 12.5 m deep water waterway project in the Taicang-Nantong section of the lower reaches of the Yangtze River as an example, the disturbance on the ecology and environment at different stages of the project construction and the effort of relieving the negative impacts of the project on the ecology and environment were evaluated by the health level of the ecosystem. The paper can provide a scientific method for the evaluation of ecological projects in river ecosystems.

Keywords: conceptual model; analytic hierarchy process; fuzzy evaluation model; ecological effect

Citation: Shen, X.; Wang, H.; Wang, P.; Xie, R.; Wang, Y.; Ji, C. Quantitative Evaluation Method for Construction Disturbance and Ecological Restoration of Waterway Engineering and Its Application. *Water* **2023**, *15*, 460. https://doi.org/10.3390/w15030460

Academic Editors: Tianhong Li and Yunping Yang

Received: 10 December 2022
Revised: 17 January 2023
Accepted: 20 January 2023
Published: 23 January 2023

1. Introduction

With the rapid development of the social economy and people's increasing interest in environmental protection, the concept of ecology and environment has been integrated into the construction of traditional waterway projects in China. Therefore, ecological waterway projects have been proposed and become a trend and development direction in waterway project construction in the future [1]. During the full lifecycle of ecological waterway projects, the relationship between shipping development and river hydrodynamics, aquatic organisms and habitats are considered comprehensively. Eco-friendly technology, project management and ecological restoration measures have been adopted to realize the coordination between waterway construction and surrounding aquatic ecosystem [2]. The Yangtze River is known as China's significant waterway, connecting east and west, and the concept of ecology and the environment has been applied throughout the waterway project construction process in the middle reaches [3,4], the lower reaches [5,6], and the estuary [7] of the Yangtze River. These ecological waterway projects on the Yangtze River have relieved the adverse effects of the projects on hydrology, sediment, water environment quality and aquatic life, and have partly played a positive role in promoting the improvement of local habitat quality.

With the further development of ecological waterway projects, how to quantitatively evaluate the ecological effect of the projects has become an important research direction for scholars at present and in the future [8,9]. The current evaluation methods are as follows: (1) comparative analysis of the effects of ecological projects on improving water quality and increasing biomass through on-site ecological monitoring data [10,11]; (2) taking water depth, velocity, sediment and water temperature, which constitute aquatic habitat elements, as variables, the habitat fitness index model of target species was established to simulate the changes of habitat suitability values and ranges before and after the project [12,13]; (3) the ecological footprint method was adopted to evaluate the positive and negative effects of waterway engineering in the social economy, ecology and environment, and the comprehensive benefits and sustainability of engineering construction were analyzed by comparing the ecological footprint and ecological carrying capacity increment of the project [14,15]; (4) a multilevel ecosystem health assessment system was constructed for rivers with a navigation function to evaluate the river ecosystem health level at different time points [16,17]; and (5) an evaluation index system was established based on the pressure-state-response (PSR) model and its improved driver-pressure-state-impact-response (DPSIR) model [18] to integrate project construction with the surrounding environment, organisms, social economy, policy measures and others according to causal relationships, reflecting the interactions between the projects and the regional ecosystem.

The pressure-state-response (PSR) model is a popular environmental assessment model throughout the world. It is considered by many governments and organizations as the most effective framework for environmental indicator organization and environmental assessment. It was originally proposed to analyze the relationship between human and environmental pressure, status, and response [19]. On this basis, the European Environment Agency (EEA) proposed the driver-pressure-state-impact-response (DPSIR) model framework [20] to establish evaluation indicators at different levels, such as driving indicators (population growth, climate change); pressure indicators (resource utilization, pollution discharge); environmental state indicators (hydrology, geomorphology, water quality); impact indicators (individual organisms, populations, communities, ecosystems); social response indicators (policy system, environmental protection, ecological restoration); etc. However, the causal chain of the evaluation process of the ecological waterway project is as follows: (1) before the waterway regulation project is carried out, the state of the river ecosystem is taken as the background; (2) the waterway project is constructed in the river, which is a kind of artificial disturbance pressure; (3) with the completion of the project, the impact of the engineering then becomes apparent, including the aspects of environment, ecology, economy and society; and (4) in order to relieve the pressure and the negative impact of the engineering construction on the river ecology and environment, positive response measures are proposed and carried out, which creates a new state. Therefore, the abovementioned conceptual models (PSR and DPSIR) should be improved to be made suitable for the evaluation of the project before and after construction, as well as the ecological effects of the positive response during the project construction.

Taking a 12.5-m deep water waterway project in the Taicang-Nantong section of the lower reaches of the Yangtze River as the study object, this paper established a state-pressure-impact-response (SPIR) conceptual model based on the logical framework of PSR and DPSIR, which provided a clear idea for selecting relevant factors and indicators, organizing data and information, and ensuring that key factors and information are not ignored. It is helpful for systematic analysis and quantitative evaluation of the ecological effect after the policy measures are taken in the whole process of engineering design, construction, and operation to mitigate the adverse impact on river ecology and environment.

2. Assessment Indicator System

2.1. SPIR Conceptual Model

The research object of this paper is the 12.5 m deep water waterway project in the Taicang-Nantong section of the lower reaches of the Yangtze River, which was designed as an ecological waterway project. The specific methods of ecological construction included: (1) considering eco-friendly materials and structures in the design process; (2) the construction process strictly implemented the relevant environmental protection requirements; and (3) after construction, appropriate ecological compensation and restoration measures were actively carried out [21]. The evaluation mainly covered the whole process of the project construction (before, during and after the project) for about two years, and the spatial scope was the river section where the project is located.

Based on the engineering characteristics and the spatio-temporal scale of evaluation, the conceptual model took the river ecology and environment state as the main line, and described the disturbance pressure of the engineering construction on the river state, the impacts of the project on the river comprehensive function, and the positive responses taken in the full lifetime cycle of the project. Therefore, a state-pressure-impact-response (SPIR) was established including four criterion layers. In the model, the state refers to the situation of social and natural systems at a certain moment., including hydrology, water quality, organisms, habitats, engineering body and so on. The pressure refers to the stress of waterway construction on regional ecology and environment. The impact refers to the influence of the state of the system on human health, social and economic structure, and river ecosystem. The response process represents the countermeasures and policies taken by humans to reduce the negative effects of the project.

2.2. Indicator System

Based on the SPIR model of waterway engineering ecological effect evaluation, an evaluation index system was established by means of layer-by-layer refinement and then overall planning. The selection of indicators in the system considers the integrity, pertinence, and feasibility of the system, and pays attention to the main characteristic elements of each level and the effect evaluation function of the indicators. The first layer is the target layer, and that is the ecological effect evaluation of waterway engineering. The second layer is the criterion layer, including state, pressure, impact, response. The third and fourth layers are the element layer and the index layer, respectively. The hydrology element layer of the state includes two indicators: fluidity of water body and connectivity of rivers. The environment element layer includes composite water quality index, suspended sediment concentration, and sediment quality. Biological elements refer to the species diversity index. Habitat includes bank revetment type, riparian zone state, beach surface state and river morphology. The pressure mainly comes from the construction of the project, which is reflected in the discharge of pollutants, the destruction of vegetation, and the loss of benthic organisms by dredging. The impact includes the impact on the capacity of water bodies to carry pollution and the improvement of the navigation grade brought about by waterway construction. Based on the above pressures, the project construction made a positive response, including considering eco-friendly materials and structures in the design process, implementing strict environmental protection measures and management in the construction process, and ecological restoration and ecological compensation after construction. The evaluation index system of waterway engineering ecological effects based on the SPIR conceptual model is shown in Table 1.

Table 1. Evaluation index system of ecological effect of waterway engineering based on SPIR conceptual model.

Target Layer	Criterion Layer	Element Layer	Index Layer
Evaluation on ecological effect of waterway engineering	State	Hydrology	Fluidity of water body Connectivity of rivers
		Environment	Composite water quality index Suspended sediment concentration Sediment quality
		Biology	Species diversity index
		Habitat	Bank revetment type Riparian zone state Beach surface state River morphology
	Pressure	Engineering construction	Pollutant discharge Vegetation destruction rate Benthic loss rate
	Impact	Environment	Assimilative capacity
		Society	Guarantee rate of navigation
	Response	Engineering design period	Ecological materials and structures
		Engineering construction period	Environmental protection measures during construction
		Engineering operation period	Ecological restoration after the project

3. Construction of Evaluation Model

3.1. Data Normalization

The evaluation indexes of ecological effects of waterway engineering include qualitative and quantitative indexes, each of which has different dimensions and different impacts on the ecosystem. Therefore, the indexes cannot be compared directly. By normalizing the eigenvalue matrix of the evaluation index and the standard eigenvalue matrix of the index [22], the relative membership matrix can be obtained and the dimensionless of each index factor can be realized. The method is as follows.

With n sample groups identified by fuzzy set A, each sample is represented by m index eigenvalues, then the sample set can be represented as index eigenvalue matrix $X = \left(x_{ij}\right)$, where x_{ij} is the eigenvalue of index i of sample j, $i = 1, 2, \ldots, m$; $j = 1, 2, \ldots, m$. The sample set is identified according to m indexes and c levels of index standard eigenvalues, then there is index standard eigenvalue matrix $Y = (y_{ih})$, where y_{ih} is the standard eigenvalue of index i of level h.

Normalize the eigenvalue matrix X of the evaluation index and the standard eigenvalue matrix Y to calculate the relative membership degree r_{ij} of the eigenvalue of the index i of sample j to A [22]. Similarly, obtain the relative membership degree s_{ih} of the standard value of the index i of level h to A. Therefore, the index eigenvalue matrix X and index standard eigenvalue matrix Y are normalized to obtain the relative membership matrix $R = \left(r_{ij}\right)$, $S = (s_{ih})$.

3.2. Weight by Analytic Hierarchy Process

The weighting of indicators involved in multi-indicator evaluation is an important part of evaluation. The rationality and accuracy of indicator weights affect the reliability of evaluation results directly. Index weight determination methods can be divided into subjective weighting method, objective weighting method and combination weighting method [23]. The subjective weighting method is a method for decision-makers to determine the weight of each index according to their subjective value judgment, such as the

Delphi method, analytic hierarchy process (AHP), etc. [24,25]. The objective weighting method determines the weight of each index by mathematical and statistical methods based on the original information of each index, such as the entropy method, coefficient of variation method, etc. [26,27]. As a decision-making and intelligence-based empowerment method, the analytic hierarchy process [25] can make use of less quantitative data to mathematize and systematize people's thinking processes and solve the problem of multi-level and multi-objective evaluation of ecological effects of waterway engineering. The process of analytic hierarchy process (AHP) to determine the weight is as follows.

(1) Building a hierarchy

The construction of the evaluation index system considers the interaction between waterway engineering and river ecosystem and adopts the SPIR framework to divide the factors contained in the evaluation object into four levels: target level, criterion level, element level, and index level. See Section 2.2 for details.

(2) Construct judgment matrix

The index of the same level is compared in pairs, and the judgment matrix is constructed. The 1–9 scaling method [28] is used to assign the importance degree, and the consistency test is carried out. The feature vector corresponding to the maximum eigenvalue of the judgment matrix is the weight vector of each index. The weights of each index are obtained after the normalization of each value in the feature vector. Finally, the weight set of the first-level index and the hierarchical total ranking weight set of the second-level index are established.

(3) Calculate the weight

Calculate the weight vector of each judgment matrix and the composite weight vector of all judgment matrices. The sum value method is used to calculate the weight vector as follows.

① Normalize each column of the judgment matrix

$$\overline{a}_{ij} = \frac{a_{ij}}{\sum\limits_{j=1}^{n} a_{ij}} \qquad i, j = 1, 2, \ldots, n$$

② The normalized judgment matrix of each column is added by row

$$\overline{w}_i = \sum_{j=1}^{n} \overline{a}_{ij} \qquad i, j = 1, 2, \ldots, n$$

③ Normalization the vector quantity $w = (w_1, w_2, \ldots, w_n)^T$

$$\overline{w}_g = \frac{\overline{w}_i}{\sum\limits_{j=1}^{n} \overline{w}_j} \qquad i, j = 1, 2, \ldots, n$$

3.3. Fuzzy Evaluation Model

The fuzzy evaluation method approximates the qualitativeness of elements to quantification through fuzzy scale and simulates the human brain's judgment of fuzzy phenomena [29]. This method solves a series of problems, such as the complexity of evaluation factors, the hierarchy of evaluation objects, the fuzziness of evaluation criteria, and the uncertainty of evaluation influencing factors. The qualitative factors are processed quantitatively, and the combination of qualitative and quantitative factors is achieved, which not only takes into account the hierarchy of objects to reflect the fuzziness of evaluation criteria and influencing factors, but also gives full play to people's experience in the evaluation, so that the evaluation results are more in line with the actual situation.

By comparing the relative membership degree $r_{1j}, r_{2j}, \ldots, r_{mj}$ of sample j with the row vectors of the line 1, 2, ... , m in the relative membership matrix S of the standard value one by one, the upper-level limit b_j and lower-level limit a_j of sample j can be obtained.

Let the relative membership matrix of the sample set for each level of A be $U = \left(u_{hj}\right)_{c\times n}$, which satisfies the constraint conditions:

$$\sum_{h=a_j}^{b_j} u_{hj} = 1 \tag{1}$$

where u_{hj} is the relative membership degree of sample j to level h of set A, j = 1, 2, ... , n; h = 1, 2, ... , c.

If for different j, the weight of index i in the sample set is the same, that is $w = (w_1, w_2, \ldots, w_n)$, and the constraint conditions are satisfied $\sum\limits_{i=1}^{m} w_i = 1$, j = 1, 2, ... , n, the weighted generalized distance between sample j and level h can be defined as $D_{hj} = u_{hj} d_{hj} = u_{hj} \left\{ \sum\limits_{i=1}^{m} \left[w_i \left(r_{ij} - s_{ih} \right) \right]^p \right\}^{\frac{1}{p}}$, where p is distance parameter.

In order to solve the optimal relative membership degree of sample j to level h of fuzzy set A, the objective function is established as:

$$\min\left\{ F\left(u_{hj}\right) = \sum_{h=a_j}^{b_j} D_{hj}^2 \right\} \tag{2}$$

According to objective function (Equation (2)) and constraint condition (Equation (1)), the Lagrangian function is constructed, and the equation constraint extremum is changed into unconditional extremum problem. Let λ_j be the Lagrangian constant, then the corresponding Lagrangian function is as:

$$L\left(u_{hj}, \lambda_j\right) = \sum_{h=a_j}^{b_j} u_{hj}^2 d_{hj}^2 - \lambda_j \left(\sum_{h=a_j}^{b_j} u_{hj} - 1 \right) \tag{3}$$

The fuzzy evaluation model is obtained as:

$$u_{hj} = \begin{cases} 1 & h < a_j \text{or } h > b_j \\ \dfrac{1}{\sum\limits_{k=a_j}^{b_j} \left\{ \dfrac{\sum\limits_{i=1}^{m} \left[w_i \left(r_{ij} - s_{ih} \right) \right]^p}{\sum\limits_{i=1}^{m} \left[w_i \left(r_{ij} - s_{ik} \right) \right]^p} \right\}^{\frac{2}{p}}} & a_j \le h \le b_j, d_{hi} \ne 0 \\ 1 & d_{hi} = 0 \end{cases} \tag{4}$$

4. Model Application

4.1. Data Sources

The aquatic ecological survey data before (September 2012), during (July 2013) and after (July 2014) construction of the waterway engineering were adopted, including water quality, sediment, phytoplankton, zooplankton, benthic organisms, intertidal organisms and fishery resources, river flow and sediment, conditions of riparian zone, engineering design and management data of the waterway, etc. The above data were applied to carry out ecological effect evaluation of waterway construction. Among them, water quality is represented by the water quality composite index; the sediment quality was compared with the Standard for Soil Environmental Quality (GB15618-1995), and was divided into level I, level II and level III. The Shannon–Weiner index was used to calculate the species diversity index. The other indexes are given values by qualitative analysis.

4.2. Evaluation Criterion

The evaluation criteria adopted 5-level scores, which were mainly formulated according to relevant national, regional and industrial standards and norms, as well as the current ecology and environment status of the lower reaches of the Yangtze River, and then combined with the literature and expert knowledge. See Table 2 for details.

Table 2. Evaluation criteria for ecological effect of waterway engineering in the lower reaches of the Yangtze River.

Criterion Layer	Index Layer	Very Poor	Poor	Medium	Good	Excellent
		1	2	3	4	5
State	Fluidity of water body	No water body flows, forming stagnant water	Water flows slowly, making it difficult to tell if it is flowing	Water flow is slow, lack of change	Water flow is good	The water body is very fluid, varied and close to nature
	Connectivity of rivers	Very low (blocked)	low	Medium	High	Very high (unblocked)
	Composite water quality index	>2.0	1.5~2.0	1.0~1.5	0.5~1.0	<0.5
	Suspended sediment concentration (mg/L)	150	60	30	25	20
	Sediment quality	Level III	Level II~III	Level II	Level I~II	Level I
	Species diversity index	<0.75	0.75~1.5	1.5~2.0	2.0~2.25	>2.25
	Bank revetment type	Vertical reinforced concrete revetment	Stepped artificial revetment or masonry revetment	Hydrophilic platform revetment	Near- inartificial slope revetment	Inartificial soil revetment
	Riparian zone state	Non-vegetation	One layer vegetation	Two layers vegetation	Three layers vegetation	Various vegetation (more that three layers)
	Beach surface state	Completely artificial masonry	Most artificial masonry	Small part of artificial masonry	Near- inartificial beach protection	Inartificial soil beach surface
	River morphology	Straight line, horizontal no change	Slight bending, convection state has no obvious effect	More tortuous, there are deep pools and shoals	Meandering, there are deep grooves and shoals in the convex and concave banks	It is a serpentine distribution with abundant variations, obvious changes in velocity, and interphase distribution of beach trough
Pressure	Pollutant discharge (COD, kg/d)	50	40	30	20	10
	Vegetation destruction rate	20%	15%	10%	5%	0%
	Benthic loss rate	20%	15%	10%	5%	0%

Table 2. *Cont.*

Criterion Layer	Index Layer	Very Poor	Poor	Medium	Good	Excellent
		1	2	3	4	5
Impact	Assimilative capacity	No environmental capacity	20% environmental capacity left	50% environmental capacity left	80% environmental capacity left	Adequate environmental capacity and self-cleaning capacity
	Guarantee rate of navigation	50%	60%	70%	80%	90%
Response	Ecological materials and structures	Traditional materials and structures are used, regardless of ecology	A small part uses ecological materials and structures	Most of them use ecological materials and structures	Basically can use ecological materials and structures	The construction is carried out with ecological materials and ecological structure to the maximum extent
	Environmental protection measures during construction	Do not take any environmental protection measures, pollutants directly discharged	Pollutants are discharged directly after initial treatment	Environmental protection measures have been taken, and some pollutants are still discharged beyond the standard	Able to implement various environmental protection measures, various pollutants to meet the standards	Strictly implement to ensure zero emission of all pollutants
	Ecological restoration after the project	No ecological restoration measures	A small number of ecological restoration measures	Half of the ecological restoration measures will be taken	Most ecological restoration measures	Ecological restoration measures will be taken and full ecological compensation will be provided

4.3. Evaluation Results

The values of 18 indexes were compared with the evaluation criteria, and the data of different dimensions were normalized to obtain the characteristic values and relative membership of each index before, during, and after the project (Table 3). Similarly, the standard values were normalized, and the corresponding eigenvalues of the index standard excellent, good, medium, poor and very poor are, respectively, 5, 4, 3, 2 and 1, and the relative membership degrees are, respectively, 0, 0.25, 0.5, 0.75 and 1.

According to the principle of the analytic hierarchy process, the importance of the first level-state, pressure, impact, and response was calculated and the judgment matrix was obtained as Equation (5). The weight of the criterion layer and indicator layer were calculated, and the results are shown in Table 4. It can be seen that the weights of state, pressure, impact and response are 0.261, 0.177, 0.157, 0.405, respectively, where response has the most weight. In other words, environmental protection and ecological restoration measures have a very obvious promoting effect on the ecological waterway project. In terms of pressure, the main disturbance source was the pollutant discharge during the project construction.

$$\begin{Bmatrix} 1 & 3 & 5 & 1/4 \\ 1/3 & 1 & 3 & 1/7 \\ 1/5 & 1/3 & 1 & 1/8 \\ 4 & 7 & 8 & 1 \end{Bmatrix} \tag{5}$$

Table 3. Normalized index eigenvalue and relative membership degree.

Criterion Layer	Index Layer	Eigenvalue			Relative Membership Degree		
		Prior to the Project	During the Project	After the Project	Prior to the Project	During the Project	After the Project
State	Fluidity of water body	4	4	4	0.25	0.25	0.25
	Connectivity of rivers	4	4	4	0.25	0.25	0.25
	Water quality	4	3	4	0.25	0.50	0.25
	Suspended sediment concentration	3	2	3	0.50	0.75	0.50
	Sediment quality	4	4	4	0.25	0.25	0.25
	Species diversity index	2	2	3	0.75	0.75	0.50
	Bank revetment type	2	2	3	0.75	0.75	0.50
	Riparian zone state	4	4	4	0.25	0.25	0.25
	Beach surface state	5	5	4	0.00	0.00	0.25
	River morphology	4	4	4	0.25	0.25	0.25
Pressure	Pollutant discharge	5	3	4	0.00	0.50	0.25
	Vegetation destruction rate	5	3	4	0.00	0.50	0.25
	Benthic loss rate	5	2	2	0.00	0.75	0.75
Impact	Assimilative capacity	5	3	4	0.00	0.50	0.25
	Guarantee rate of navigation	4	4	5	0.25	0.25	0.00
Response	Ecological materials and structures	1	1	5	1.00	1.00	0.00
	Environmental protection measures during construction	1	5	1	1.00	0.00	1.00
	Ecological restoration after the project	1	1	5	1.00	1.00	0.00

Table 4. The weight calculation results of different levels of evaluation indexes.

Criterion Layer	Weight	Index Layer	Weight
State	0.261	Fluidity of water body	0.026
		Connectivity of rivers	0.026
		Water quality	0.026
		Suspended sediment concentration	0.026
		Sediment quality	0.026
		Species diversity index	0.027
		Bank revetment type	0.026
		Riparian zone state	0.026
		Beach surface state	0.026
		River morphology	0.026
Pressure	0.177	Pollutant discharge	0.071
		Vegetation destruction rate	0.053
		Benthic loss rate	0.053
Impact	0.157	Assimilative capacity	0.063
		Guarantee rate of navigation	0.094
Response	0.405	Ecological materials and structures	0.162
		Environmental protection measures during construction	0.081
		Ecological restoration after the project	0.162

The weight was substituted into the fuzzy identification model to obtain the membership degree corresponding to each ecosystem level before, during, and after the project. The maximum membership principle was adopted for the evaluation. The results are shown in Table 5. Prior to the project, the maximum membership was 0.368, corresponding to level 3/medium. During the project construction, the corresponding level of the maximum membership is level 2/poor. After the project, the ecosystem quality rises to level 4/good.

Table 5. Membership degrees corresponding to different ecosystem levels at each time node of waterway construction.

Level	Prior to the Project	During the Project	After the Project
Level 1/Very poor	0.113	0.221	0.045
Level 2/poor	0.269	0.346 *	0.081
Level 3/Medium	0.368 *	0.244	0.175
Level 4/Good	0.173	0.123	0.377 *
Level 5/Excellent	0.077	0.066	0.322
Evaluation results	Medium	Poor	Good

* Represents the maximum membership degree.

It can be seen from the evaluation results that the background the of river ecosystem quality is medium. During the construction, the system quality is reduced due to the discharge of wastewater, vegetation destruction, and the loss of benthic animals caused by dredging. After the project, with the gradual disappearance of the influence of the construction period, the positive effects of the ecological materials and structures, and the adoption of appropriate ecological restoration measures, the health of the ecosystem has been improved. In addition, the increase of the navigation guarantee rate after the project is also a part of its comprehensive effect. In general, the evaluation results are consistent with our expectation, which indicates that the SPIR model can be used for ecological effect evaluation of the ecological waterway project.

5. Conclusions

Among the conceptual models of the environmental assessment index system, PSR and DPSIR are the most commonly used models. However, their structure is not suitable for the effect evaluation of ecological waterway engineering. A conceptual state-pressure-impact-response (SPIR) was derived from PSR and DPSIR, and improved with the following features: (1) regarding the state as the logical starting point; (2) taking project construction as a disturbance pressure on the regional ecosystem; (3) with the construction of the project, the impact includes positive and negative effects, covering the scope of ecology, environment, economy, and society; and (4) the response reflects the efforts of the ecological waterway project compared to traditional waterway projects. The SPIR model was applied to evaluate the ecological effects of the ecological waterway project. Detailed conclusions can be drawn from this study as follows:

(1) A conceptual state-pressure-impact-response (SPIR) model of four criterion layers was constructed, and accordingly, an evaluation index system of the eco-environmental effects of waterway engineering was established for the lower reaches of the Yangtze River. According to the features of ecological waterway engineering and the characteristics of the aquatic ecosystem of the Yangtze River, a fuzzy AHP method combining qualitative and quantitative analysis was adopted to evaluate the ecological effects of the engineering. Taking the state as the main line, the changes to the river ecosystem health level under construction disturbance and its subsequent ecological restoration were analyzed;

(2) Before the project, the health level of the aquatic ecosystem was medium. Although strict environmental management measures were adopted during the construction period, it is still inevitable that the construction would cause wastewater discharge, vegetation destruction, benthic loss, and other conditions, leading to a slight decline in the health level of the ecosystem. After the project, with the influence of the construction period gradually subsiding, the application of ecological technology and the gradual implementation of ecological compensation measures, the health of river ecosystem was improved. The results of the evaluation explain the stress effect of different stages of project construction on the ecology and environment and the contribution of reducing the negative impact of the project to improve the health level of the system;

(3) In this paper, the state-pressure-impact-response model was established according to the logical relationship of the followings: the river background status; the disturbance pressure from the project; and the project's impact and the positive response to reduce the influence, which was well revealed in the criterion layer. However, the selection of evaluation indicators, and the formulation of evaluation level and evaluation criteria are still subjective, which brings uncertainty to the evaluation results. In future research, a multi-factor sensitivity analysis should be carried out as a reference basis for the identification of key indicators. In addition, the accumulation of long-term monitoring data for the project's reach is also crucial for the ecological effect evaluation of an ecological waterway project.

Author Contributions: Conceptualization, X.S.; methodology, X.S. and P.W.; model, X.S.; formal analysis, R.X.; investigation, Y.W. and C.J.; writing—original draft preparation, X.S. and P.W.; revision, X.S. and H.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Jiangsu Province Ocean Science and Technology Innovation Project (JSZRHYKJ202214), National Key Research and Development Plan Project (2021YFB2600204), Open Funds of Key Laboratory of Ocean Space Resource Management Technology, MNR (KF-2021-108).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Acknowledgments: We thank everyone who helped us during the completion of the thesis. We also thank the reviewers for their helpful comments and suggestions.

Conflicts of Interest: The authors declare no conflict of interest.

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