water

MDPI

Article

Construction of a Near-Natural Estuarine Wetland Evaluation Index System Based on Analytical Hierarchy Process and Its Application

Jiajun Sun [1,2,3,†], Yangyang Han [4,†], Yuping Li [1,*], Panyue Zhang [5], Ling Liu [4], Yajing Cai [5], Mengxiang Li [4] and Hongjie Wang [4,*]

1 Beijing Engineering Research Center of Process Pollution Control, Institute of Process Engineering, Chinese Academy of Sciences, Beijing 100190, China; sunjiajun2020@163.com
2 University of Chinese Academy of Sciences, Beijing 100049, China
3 China Xiong'an Group Co. Ltd., Baoding 071000, China
4 Xiong'an Institute of Eco-Environment, Hebei University, Baoding 071002, China; hanyy315@163.com (Y.H.); liuling@hbu.edu.cn (L.L.); limengxiang_19951@163.com (M.L.)
5 College of Environmental Science and Engineering, Beijing Forestry University, Beijing 100083, China; panyue_zhang@bjfu.edu.cn (P.Z.); cyj_96born@bjfu.edu.cn (Y.C.)
* Correspondence: ypli@ipe.ac.cn (Y.L.); Wanghj@hbu.edu.cn (H.W.)
† Jiajun Sun and Yangyang Han contribute equally to the article.

Abstract: Nutrients carried in upstream rivers to lakes are the main cause of eutrophication. Building near-natural estuarine wetlands between rivers and lakes is an effective way to remove pollutants and restore the ecology of estuarine areas. However, for the existing estuarine wetland ecological restoration projects, there is a lack of corresponding evaluation methods and index systems to make a comprehensive assessment of their restoration effects. By summarizing a large amount of literature and doing field research, an index system was constructed by combining the characteristics of the near-natural estuarine wetlands themselves. It covered environmental benefits, technical management and maintenance, and socio-economic functions, and contained 3 systems, 7 criteria, and 16 indicators. The analytical hierarchy process (AHP) was used to determine the weights of each indicator. The top 5 indicators in order of importance were habitat diversity, total phosphorus (TP), coverage of aquatic plants, ammonia nitrogen (NH_3-N), and adaptation to the surrounding landscape. The above evaluation system was used for the comprehensive evaluation of the water purification project in the Fuhe estuarine wetland, Hebei Province, as an example. The results showed that the comprehensive score of the Fuhe estuarine wetland at this stage was 4.1492, and the evaluation grade was excellent. The effect of water purification and ecological restoration was good, and the selected technology was suitable and stable in operation. It had a greater positive impact on the surrounding economy and society and can be promoted and applied. The research results were important for clarifying the advantages and defects of the project and developing efficient and advanced restoration technologies.

Keywords: Fuhe estuarine wetland; analytical hierarchy process; water purification; engineering evaluation

Citation: Sun, J.; Han, Y.; Li, Y.; Zhang, P.; Liu, L.; Cai, Y.; Li, M.; Wang, H. Construction of a Near-Natural Estuarine Wetland Evaluation Index System Based on Analytical Hierarchy Process and Its Application. *Water* **2021**, *13*, 2116. https://doi.org/10.3390/w13152116

Academic Editors: Christos S. Akratos and Andreas N. Angelakis

Received: 21 June 2021
Accepted: 27 July 2021
Published: 31 July 2021

1. Introduction

Wetlands play an important role in protecting biodiversity and regulating regional climates [1]. However, with the rapid socio-economic development, more and more nutrients have entered the wetlands. The eutrophication of water bodies has become a worldwide problem attracted great concern [2,3]. The nutrients carried by upstream rivers into wetlands are the main exogenous pollution. Wang et al. found that harmful algal blooms in Lake Erie were mainly caused by exogenous pollution from rivers [4]. Pei et al. concluded that pollutants in the Fuhe River could threaten the water quality and

ecosystem of Baiyangdian Lake [5]. The control of nutrients in rivers is essential to control eutrophication and restore the ecosystem.

An estuarine wetland buffer area can be defined as a transitional zone between terrestrial and aquatic ecosystems, consisting mainly of plants, substrates, and microorganisms [6]. Adsorption by substrate, uptake by plants, and transformation by microorganisms are the main processes of water purification in estuarine wetlands [7]. In addition to reducing nutrient concentration, the construction of wetlands also brings benefits to flow regulation, ecosystem stability, and landscape improvement [8]. Since the 21st century, China has established lots of near-natural estuarine wetlands in Dianchi Lake, Erhai Lake, Chao Lake, and Fuxian lake, which have effectively reduced pollutants such as nitrogen and phosphorus and restored the ecology of estuarine areas [9–11].

Many scholars have done plenty of research on substrate selection, plant and microbial purification mechanism, and operational parameters adjustment of estuarine wetlands for a long time [12–15]. However, there is a lack of studies on the evaluation of estuarine wetland projects. Several indices including the water quality index, biological index, and land type index are used to evaluate the water quality and ecology of estuarine wetlands [16–18]. The application of these methods only evaluates one aspect and does not provide a comprehensive method and system for evaluating the technology and engineering of near-natural estuarine wetlands so far. Therefore, it is important to establish a comprehensive set of index evaluation system to analyze accurately and scientifically the advantages and defects and develop efficient and advanced ecological restoration techniques for estuarine wetlands. AHP is a multi-criteria way of thinking, which combines qualitative analysis and quantitative analysis, to hierarchize and quantify the evaluation process [19]. The group decision-based hierarchical analysis can synthesize the knowledge and information of different experts and reduce the subjective influence with the help of group wisdom. AHP has become one of the most widely used methods for the practical solution of multi-criteria decision problems such as evaluate the suitability of coastal zone reclamation [20,21], but the application in the evaluation of near-natural estuarine wetlands has not been reported.

In this study, a four-level evaluation index system was constructed containing environmental benefits, engineering, technology, and socio-economics aspects. The indicators were assigned weights using group decision hierarchy analysis and the evaluation thresholds were determined to form a complete estuarine wetland evaluation system. To verify the effectiveness of this evaluation system, the largest near-natural estuarine wetland in North China, the Fuhe estuarine wetland, was evaluated as a case. The evaluation results are beneficial for the long-term management and sustainable operation of the Fuhe estuarine wetland. They are also significant for the subsequent clarification of the advantages and defects of other near-natural estuarine wetland projects and help to develop efficient and advanced ecological restoration techniques for estuarine wetlands.

2. Materials and Methods

2.1. Construction of the Indicator Hierarchy

The selection and determination of indicators should follow the following principles: scientific and reasonable, comprehensive and systematic, highlighting the focus, and the method follows the target.

We organized and analyzed domestic and foreign cases of ecological restoration project evaluation and ecological health evaluation for rivers and lakes. Based on that, in the implemented projects, the evaluation index only targeted the water purification effectiveness. Therefore, the evaluation results only reflected the water quality of water bodies and could not cover the condition of the whole ecosystem. In addition, the socio-economic and engineering technical indicators were not comprehensive enough, and the expression of restoration effect evaluation was not rich enough [22,23]. In this study, a hierarchical structure model of the evaluation index system was established by using hierarchical analysis. The model incorporated three aspects of ecological environment, engineering technology,

and socioeconomics and combined with the frequency of literature indicators and the expert scoring. Combined with the frequency of literature indicators, four layers of target layer (A layer), system layer (B layer), criterion layer (C layer), and indicator layer (D layer) were constructed. Among them, the system layer included ecological benefits, technical management, and maintenance as well as socio-economic functions. Seven criterion layers of water quality, biology, technology, engineering, maintenance, society, and economy were set under the system layer. The evaluation index system of water quality purification project of near-natural wetlands in estuaries was constructed from multiple aspects and perspectives. Table 1 shows the indexes and calculation methods.

Table 1. Evaluation index system and description.

Target Layer	System Layer	Criterion Layer	Index Layer	Index Description and Calculation Method
A Evaluation of near-natural estuarine wetland	B1 Environmental benefits	C1 Water quality index	D1 Chemical oxygen demand (COD_{Cr})	Reflect the pollution of organic matter in the water body, mg/L.
			D2 NH_3-N	Refers to nitrogen in water in the form of free ammonia and ammonium ions, which exists in water ecosystems and is the main oxygen-consuming pollutant in water bodies, mg/L.
			D3 Dissolved oxygen (DO)	An indicator reflecting the recovery of the self-purification capacity of a water body. Obtain the data on site or online, mg/L
			D4 TP	Phosphorus is the most important factor in the eutrophication of water bodies. Monitoring the phosphorus content of water bodies plays an important role in water quality evaluation, mg/L
		C2 Biological indicators	D5 Coverage of aquatic plants	The coverage of aquatic plants is maintained at a moderate level to achieve a better water purification effect, coverage of aquatic plants = area covered by aquatic plants/water surface area × 100%, %.
			D6 Habitat diversity	The diversity of habitat will affect the stability of the wetland ecosystem. Qualitative indicators need to be evaluated by multiple experts.
	B2 Technical management and maintenance	C3 Technical index	D7 Technical advancement	The technology has achieved great improvement or improvement in water quality treatment effect, economic cost, maintenance cost, project life, etc., and has certain advanced nature. Qualitative indicators need to be evaluated by multiple experts.
			D8 Technical maturity	Maturity refers to the extent to which the technology has been applied to the actual project, and a technology with a high degree of maturity means that the technology has been operating stably in several projects. Qualitative indicators need to be evaluated by multiple experts.

Table 1. *Cont.*

Target Layer	System Layer	Criterion Layer	Index Layer	Index Description and Calculation Method
		C4 Engineering index	D9 Engineering operability	To evaluate the operability of the project, it is necessary to comprehensively consider the difficulty of the project, the economic cost, and the comprehensive factors of local geography, geology, economic development, and material supply, and finally select a project with strong operability. Qualitative indicators need to be evaluated by multiple experts.
			D10 Engineering stability	Stability is an important indicator for evaluating an engineering technology. Whether an engineering operates stably for a long time will have a great impact on the investment, operation, management and maintenance of the project. Qualitative indicators need to be evaluated by multiple experts.
		C5 Maintenance management	D11 Maintenance complexity	Relatively easy maintenance and management can be beneficial to the long-term operation of the project. Qualitative indicators need to be evaluated by multiple experts.
			D12 Maintenance duration	Regular maintenance is time-consuming and labor-intensive, which directly affects the investment in maintenance costs, and the noise and smell generated during the maintenance process have a significant negative impact on the landscape and comfort. Therefore, the shorter the single maintenance time, the better. Data obtained through field investigation, h.
	B3 Social and economic functions	C6 Social influence	D13 Adaptation to the surrounding landscape	Reflect whether the overall environment is organically integrated with the surroundings and whether it is abrupt. Qualitative indicators, issuing questionnaires combined with multi-industry expert assessments, and obtaining results.
			D14 Impact on the surrounding economy	The impact of the project implementation on the surrounding economic development. Qualitative indicators, issuing questionnaires combined with multi-industry expert assessments, and obtaining results.
		C7 Economic input	D15 Cost of investment	Reflect the investment size of the restoration project. If the same restoration effect is achieved, the smaller the investment, the more advantageous. Data obtained through field investigation, unit: $\$/m^2$.
			D16 Operating expenses	Reflect the cost of the later operation and management of the restoration project. If the same repair effect is achieved, the smaller the operating cost, the more advantageous. Data obtained through field investigation, $\$/(m^2 \cdot a)$.

2.2. Determination of Indicator Weights

AHP is a method that organically combines qualitative and quantitative indicators. It treats the research object as a system and assigns weights according to decomposition, comparative judgment, and synthesis, quantifying the degree of influence of each factor in each level on the results [24]. In this paper, a hierarchical analysis based on group decision making was used to determine the weights of each indicator. Seventeen experts in the same field from universities, research institutes and design institutes and 12 senior engineers from ecological restoration project construction companies participated in the evaluation process. Based on the two-by-two judgment of the experts on the indexes, a consistent aggregated judgment matrix was constructed. The judgment matrix construction method and consistency test are as follows.

2.2.1. Construction of Judgment Matrix

The importance of each element in the same level to the upper level was compared pairwise and the judgment matrix was constructed. The expert scoring uses the '1–9 scale method' proposed by Professor Saaty [25]. This method can determine the importance among the indicators and can reduce the influence of subjectivity of experts and other uncertainties [26]. Let m expert groups consisting of S1, S2, . . . , Sm score the n indicators B_1, B_2, . . . , B_n. Let the i-th expert score the j-th indicator B_j as: x_{ij} ($0 \le x_{ij} \le 100$, $x_{ij} \in Z$), and the average value of each expert's score on the j-th indicator is x_j according to Equation (1), and the n-dimensional vector $x = (x_1, x_2, \ldots, x_n)$ is obtained. Take $A = (a_{ij})$ as the judgment matrix of the expert group, where $a_{ij} = x_i/x_j$, $i, j \in (1, 2, \ldots \ldots, n)$, and the judgment form is as in Equation (2):

$$x_j = \frac{1}{m}\sum_{i=1}^{m} x_{ij} \tag{1}$$

$$A = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix} = \begin{pmatrix} 1 & \cdots & \frac{x_1}{x_n} \\ \vdots & \ddots & \vdots \\ \frac{x_n}{x_1} & \cdots & 1 \end{pmatrix} \tag{2}$$

2.2.2. Weight Calculation and Consistency Test

According to the judgment matrix of subfactors at a certain level, the weight of subfactors at that level was calculated. The eigenvalues of the judgment matrix A were solved to find the maximum eigenvalue λ_{max}, and put λ_{max} into Equation (3) to solve for x, and normalize x to get eigenvector ω^T, where ω^T was the weight value of subfactors at a certain level. The weights from the target level to the system level, the system level to the criterion level, and the criterion level to the indicator level were calculated sequentially. The consistency test was done using the consistency index $C.I.$ and the consistency ratio $C.R.$ where $C.I.$ and $C.R.$ were calculated by the formulas by Equations (4) and (5). When $C.R. \le 0.1$, the consistency of the judgment matrix is considered good. Otherwise, experts need to be asked to reconsider and confirm the scores of each index. Note that when $n = 1, 2$, $R.I.$ takes 0, at this time, there is no need to calculate $C.R.$ again, and it can be considered to satisfy the consistency.

$$(A - \lambda E)x = 0 \tag{3}$$

$$C.I. = \frac{\lambda_{max} - n}{n - 1} \tag{4}$$

$$C.R. = \frac{C.I.}{R.I.} \tag{5}$$

where, E is the identity matrix with all diagonals being 1 and other elements being 0; n is the order of the judgment matrix; $R.I.$ is the average random consistency index corresponding to n, which is obtained by looking up the Table S1.

Using the above method to calculate the indicator weights at each level. The final assignment results are shown in Table 2. The system layer to target layer, criterion layer to system layer, and indicator layer to criterion layer consistency parameters *C.R.* are all less than 0.1, indicating that the results meet the consistency requirements. The weight ranking from the indicator layer to the target layer indicates the importance ranking of the indicators in the system. In this index system, the top 5 indexes in order of weight are: habitat diversity, TP, coverage of aquatic plants, NH_3-N, and adaptation to the surrounding landscape.

Table 2. The weight of each level of indicators.

B Layer		C Layer		D Layer			
System Layer	**A–B Weight**	**Criterion Layer**	**B–C Weight**	**Index**	**C–D Weight**	**A–D Weight**	**Order**
B1	0.4618	C1	0.5461	D1	0.161	0.0406	13
				D2	0.318	0.0802	4
				D3	0.165	0.0416	11
				D4	0.356	0.0898	2
		C2	0.4539	D5	0.4253	0.0891	3
				D6	0.5747	0.1205	1
B2	0.2485	C3	0.3862	D7	0.568	0.0545	9
				D8	0.432	0.0415	12
		C4	0.3264	D9	0.471	0.0382	14
				D10	0.529	0.0429	10
		C5	0.2874	D11	0.525	0.0375	15
				D12	0.475	0.0339	16
B3	0.2897	C6	0.5250	D13	0.515	0.0783	5
				D14	0.485	0.0738	6
		C7	0.4750	D15	0.464	0.0638	8
				D16	0.536	0.0738	6

2.3. Indicator Thresholds and Evaluation Methods

2.3.1. Determination of Indicator Thresholds

The evaluation indicators selected for the indicator system are both qualitative and quantitative indicators. Referring to the Environmental Quality Standard for Surface Water (GB3838-2002) and combining with a large amount of ecological restoration project evaluation information, the quantitative indicators were divided, and the evaluation thresholds of the indicators were determined (Table 3). In the evaluation of the qualitative indicators, the grades were divided according to Table S2. The setting of the thresholds in this paper has been proofread by experts, which is scientific and can ensure the accuracy of the evaluation results.

Table 3. Threshold value and score of evaluation system.

Score	1	2	3	4	5
COD_{Cr} (mg/L)	>50	40–50	30–40	20–30	≤20
NH_3-N (mg/L)	>1.5	1.0–1.5	0.5–1.0	0.15–0.5	≤0.15
DO (mg/L)	<2	2–3	2–5	5–6	≥6
TP (mg/L)	>0.3	0.2–0.3	0.1–0.2	0.02–0.1	≤0.02
Coverage of aquatic plants (%)	<10 or >90	10–20 or 70–80	20–30 or 60–70	30–40 or 50–60	40–50
Habitat diversity	very bad	bad	average	good	excellent
Technical advancement	very bad	bad	average	good	excellent
Technical maturity	very bad	bad	average	good	excellent

Table 3. *Cont.*

Score	1	2	3	4	5
Engineering operability	very bad	bad	average	good	excellent
Engineering stability	very bad	bad	average	good	excellent
Maintenance complexity	very difficult	difficult	average	simple	very simple
Maintenance duration (h)	>24	12–24	8–12	4–8	≤4
Adaptation to the surrounding landscape	very bad	bad	average	good	excellent
Impact on the surrounding economy	inhibit	slight inhibit	no effect	slight promote	promote
Cost of investment ($/m^2)	>123.68	77.30–123.68	46.38–77.30	15.46–46.38	≤15.46
Operating expenses ($/(m^2·a))	>7.73	3.09–7.73	1.55–3.09	0.77–1.55	≤0.773

2.3.2. Evaluation Result Grading

The final score was calculated by direct weighting method, referring to the following Formula (6). According to the scores of each index, the final evaluation results are divided into 5 levels: poor, relatively poor, average, good, and excellent. Based on the characteristics of each level and combined with the actual research, the evaluation results are outlined for each level of status. It should be ensured that the evaluation results can clearly and intuitively reflect the restoration status, and the evaluation grading is shown in Table 4. In order to further analyze the benefits of each system layer of the estuarine wetland and accurately analyze the impact of water quality, technology, engineering, economy, and society on the evaluation results, the system layer was divided into three levels: poor, average, and excellent. The division Criteria and descriptions are shown in Table 5, F_e, F_t, F_s are the scores of environmental benefits, technical management and maintenance, social and economic functions, respectively. A range of system level scores was obtained by multiplying the system level weights with the lowest score of 1 and the highest score of 5, respectively. Afterwards, this range was averaged into three ranges to obtain the range of scores for each level of the system layer.

$$\mathrm{F} = \sum_{i=1}^{n} W_i \cdot F_i \quad (6)$$

where F is the evaluation score; F_i is the score of the i-th evaluation index; W_i is the weight of the i-th evaluation index; n is the total number of evaluation indexes; and n = 16 in this evaluation system.

Table 4. Classification of evaluation results of ecological restoration projects.

Level	Score	Status
very bad	F ≤ 1	The structure of the aquatic ecosystem is severely damaged, and basically no improvement; the selected engineering technology is not suitable; personnel and economic investment are too high; it has a serious negative impact on the surrounding environment; the project is in urgent need of renovation.
bad	1 < F ≤ 2	The structure of the aquatic ecosystem has been restored; some of the selected engineering technologies are suitable; personnel and economic investment are relatively high; it has no positive impact on the surrounding environment; the project needs partial renovation.
average	2 < F ≤ 3	The structure of the aquatic ecosystem is basically restored; the selected engineering technology is basically suitable; personnel and economic investment are high; it has a certain positive impact on the surrounding environment; the project can be optimized.
good	3 < F ≤ 4	The structure of the water ecosystem is well restored; the selected engineering technology is appropriate; personnel and economic investment are moderate; it has a greater positive impact on the surrounding environment; the project can be promoted after optimization.
excellent	4 < F ≤ 5	The structure of the water ecosystem is complete; the selected engineering technology is very suitable; the personnel and economic input are economical and efficient; it has a great positive impact on the surrounding environment; the project can be promoted.

Table 5. Classification of evaluation results of system level.

System Layer		Bad	Average	Good
Environmental benefits	score	$0.4618 \leq F_e < 1.0775$	$1.0775 \leq F_e < 1.6933$	$1.6933 \leq F_e < 2.3090$
	status	The effect of ecological restoration is poor, the concentration of COD_{Cr}, NH_3-N, TP and other pollutants in the water body is high, the self-purification ability of the water body is poor, and the water body is eutrophication.	The effect of ecological restoration is moderate, the concentration of COD_{Cr}, NH_3-N, TP and other pollutants in the water body is relatively high, the self-purification ability of the water body is average.	The effect of ecological restoration is good, the concentration of COD_{Cr}, NH_3-N, TP and other pollutants in the water body is low, the self-purification ability of the water body is good.
Technical management and maintenance	score	$0.2485 \leq F_t < 0.5798$	$0.5798 \leq F_t < 0.9112$	$0.9112 \leq F_t < 1.2425$
	status	The technological advancement is poor, the stability is low, the later maintenance cost is high, time-consuming, and the operating cost is high.	The technological advancement and stability are average, the later maintenance costs are relatively high, the time-consuming is moderate, and the operating costs are relatively high.	The technology is advanced and stable, and the later maintenance and operation are simple and easy.
Social and economic functions	score	$0.2897 \leq F_s < 0.6759$	$0.6759 \leq F_s < 1.0622$	$1.0622 \leq F_s < 1.4485$
	status	Social and economic functions are poor, which has a negative impact on society and restrains the economy, and the satisfaction rate of the masses is low.	The social and economic functions are average, the positive impact on the society and the economy is average, and the mass satisfaction rate is average.	The social and economic function is good, it has a positive impact on the society and promotes the economy, and the mass satisfaction rate is high.

3. Case Study

3.1. Overview

Baiyangdian Lake, known as the "Kidney of North China", is crucial as a critical node for maintaining the ecological balance of North China, regulating the climate of the Hebei Plain and even the Beijing-Tianjin region, supplementing groundwater sources, regulating floods, and protecting biodiversity and rare species resources [27]. With socio-economic development, the volume of water entering Baiyangdian Lake has gradually shrunk, resulting in serious fragmentation of the wetland ecological landscape, gradual reduction of the ecological function and the decrease of biological species year by year [28,29]. The PuRiver, Cao River and the Fu River are the three upstream rivers of Baiyangdian Lake. As they flow through towns and cities, the discharge of agricultural non-point source pollution, domestic sewage, and tailwater from sewage treatment leads to poor water quality of the rivers [30]. These are the main pollution source of Baiyangdian Lake, especially in the western part. The water quality is directly related to the water safety of Baiyangdian Lake [31]. In September 2020, the construction of the water quality purification project at Fu River estuary was completed. Its function is to purify the three rivers and increase the stability of the ecosystem of estuary. The project is located in the north of Anxin Jianchang Village, near Zhaili Town, where three rivers converge. The geographical location is shown in Figure 1.

Figure 1. Location map of the Fuhe estuarine wetland.

The project adopted the combination process of "pre-ecological sedimentation pond + subsurface flow constructed wetland + macrophyte pond", covering 3.15 km^2 in total, with a daily processing capacity of 250,000 tons. It was divided into three parts and covering area of 0.82 km^2, 1.02 km^2 and 1.31 km^2, respectively, as shown in Figure 2. The pre-sedimentation pond was the first treatment unit of the water purification project in the Fuhe estuarine wetland. Its main function was to precipitate the suspended matter and reduce the sand content in the river, at the same time, degrade the complex pollutants initially under the action of microorganisms and plants to further improve the biodegradability of the pollutants for the subsequent biochemical treatment of pollutants. The subsurface-flow wetland took over the effluent of the ecological sedimentation pond and relied mainly on the action of the roots of macrophytes, microorganisms and substrates to remove pollutants. The aquatic plant pond consisted of two parts, the front part is the submerged plant area, and the back end is the emerged plant area, which purified the water through the action of microorganisms and plants.

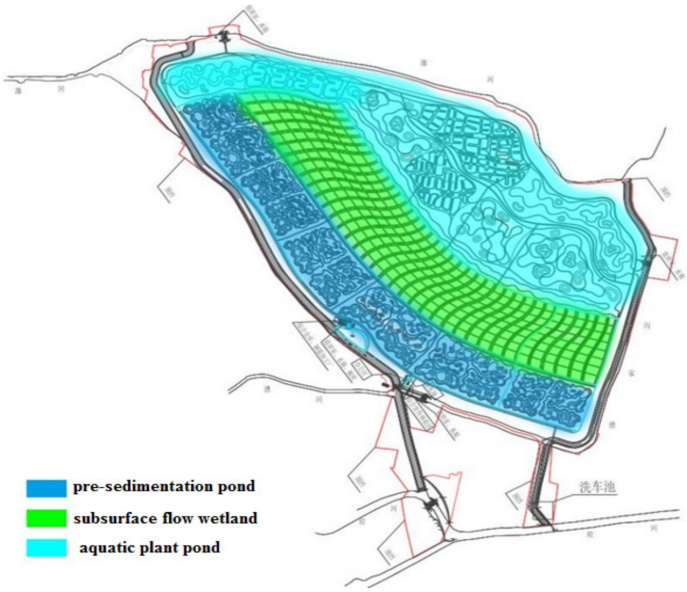

Figure 2. Wetland water purification unit.

3.2. Date Acquisition

3.2.1. Quantitative Indicators

On-site water quality monitoring was conducted for the purification project. Sampling points were set up at the inlet and outlet of three units, respectively. The specific sampling points were shown in Figure 3. Sampling was conducted once a month for 3 consecutive days during October 2020 to March 2021, once a day. Water samples were collected at 0.5 m below the water surface using sample apparatus. Water quality parameters included pH, DO, COD_{Cr}, TP, NH_3-N, etc. We used the quadrat method to select a total of 9 points of 2 m × 2 m in the three-water purification units and used the formula "Coverage of aquatic plants = aquatic plant coverage area/4 m^2 × 100%" to calculate the aquatic plant coverage of each plot. The average "coverage of aquatic plants" of the 9 plots was calculated as the current month's data. Parameters such as maintenance duration, investment costs and operating costs were obtained from the project design documents and verified with the managers of Fuhe wetland. Quantitative indicator data are shown in Table 6. Six months data of the wetland outlet were used in the evaluation process to score water quality indicators.

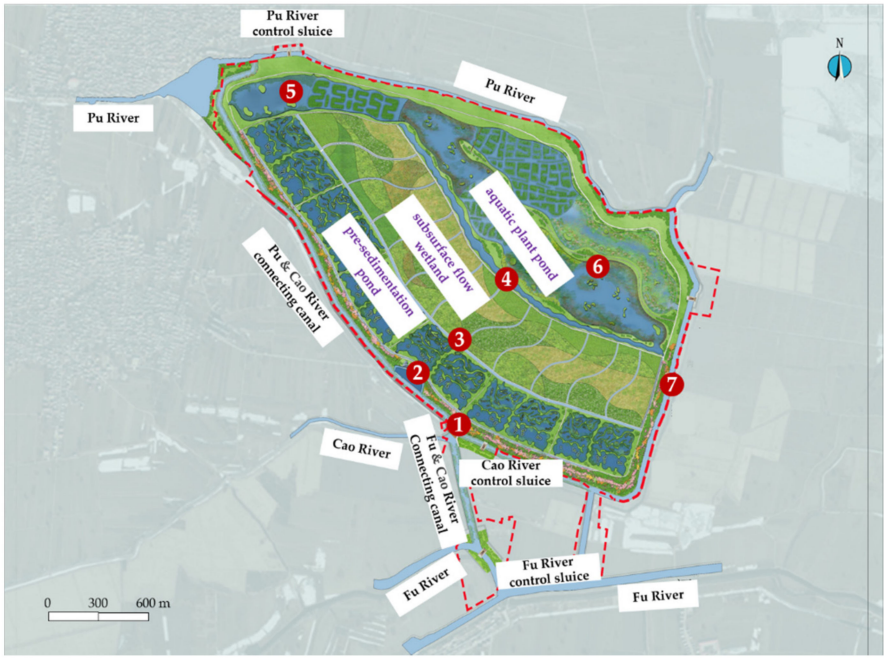

Figure 3. Location map of sampling points.

Table 6. Quantitative index data.

Index	Date						
	2020.10	**2020.11**	**2020.12**	**2021.01**	**2021.02**	**2021.03**	**Average**
COD_{Cr} (mg/L)	24.30	18.01	16.62	11.70	13.00	17.00	16.77
NH_3-N (mg/L)	0.144	0.246	0.090	1.012	0.273	0.174	0.32
DO (mg/L)	8.6	7.3	9.7	6.8	11.6	10.9	9.15
TP (mg/L)	0.028	0.041	0.033	0.053	0.050	0.057	0.04
Coverage of aquatic plants (%)	32.45	26.51	21.45	23.26	32.65	36.24	28.76
Maintenance duration (h)				4–8			
Cost of investment ($/$m^2$)				22.47			
Operating expenses ($/($m^2$·a))				0.02			

3.2.2. Qualitative Indicators

In order to make the qualitative indicators more credible, different people and approaches were selected for evaluation for different qualitative indicators (Table 7). For habitat diversity, technical advancement, technical maturity, engineering operability, and engineering stability, 20 experts and senior engineers who were more knowledgeable about the Fuhe estuarine wetland were invited. The adaptation to the surrounding landscape and the economic impact on the surrounding area were obtained by means of a questionnaire survey. A total of 50 people living around the wetland were given questionnaires, and 50 valid questionnaires were obtained. The maintenance complexity was evaluated by 15 operation and maintenance personnel of Fuhe estuarine wetland.

Table 7. Qualitative index evaluation results.

Index	Results
Habitat diversity	good
Technical advancement	good
Technical maturity	excellent
Engineering operability	good
Engineering stability	good
Maintenance complexity	average
Adaptation to the surrounding landscape	excellent
Impact on the surrounding economy	slight promote

4. Results and Discussion

4.1. Fuhe Estuarine Wetland Evaluation Results

In this case evaluation stage, the overall score of Fuhe estuarine wetland was 4.1492, and the evaluation result was "excellent". The indicator scores and final evaluation results were shown in Table 8; Table 9, respectively.

Table 8. Evaluation data and score.

Index	Date	Score
COD_{Cr}	16.77 mg/L	5
NH_3-N	0.32 mg/L	4
DO	9.15 mg/L	5
TP	0.04 mg/L	4
Coverage of aquatic plants	28.76%	3
Habitat diversity	good	4
Technical advancement	good	4
Technical maturity	excellent	5
Engineering operability	good	4
Engineering stability	good	4
Maintenance complexity	average	3
Maintenance duration	4–8 h	4
Adaptation to the surrounding landscape	excellent	5
Impact on the surrounding economy	slight promote	4
Cost of investment	22.47 \$/m^2	4
Operating expenses	0.02 \$/(m^2·a)	5

Table 9. Evaluation results of the Fuhe estuarine wetland.

Index Layer	Score	A–D Weight	Index Score	Criterion Layer	Criterion Level Score	System Layer	System Level Score	Target Layer	Result
COD_{Cr}	5	0.0406	0.2030	C1	1.0910	B1	1.8403	A	4.1492
NH_3-N	4	0.0802	0.3208						
DO	5	0.0416	0.2080						
TP	4	0.0898	0.3592						
Coverage of aquatic plants	3	0.0891	0.2673	C2	0.7493				
Habitat diversity	4	0.1205	0.4820						
Technical advancement	4	0.0545	0.2180	C3	0.4255	B2	0.9980		
Technical maturity	5	0.0415	0.2075						
Engineering operability	4	0.0382	0.1528	C4	0.3244				
Engineering stability	4	0.0429	0.1716						
Maintenance complexity	3	0.0375	0.1125	C5	0.2481				
Maintenance duration	4	0.0339	0.1356						
Adaptation to the surrounding landscape	5	0.0783	0.3915	C6	0.6867	B3	1.3109		
Impact on the surrounding economy	4	0.0738	0.2952						
Cost of investment	4	0.0638	0.2552	C7	0.6242				
Operating expenses	5	0.0738	0.3690						

4.2. System-Level Evaluation

4.2.1. Environmental Benefits

The Fuhe estuarine wetland scored 1.8403 in environmental benefits, with an evaluation grade of excellent. The Fuhe estuarine wetland had a good effect on pollutant removal, a strong self-purification ability of the water body and a stable ecosystem. The score of water quality indexes was 1.065, among which four indexes, COD_{Cr}, NH_3-N, DO and TP score 5, 4, 5, and 4 respectively, indicating that the wetland performs well for the removal of COD_{Cr}, TP, and NH_3-N and the enhancement of DO.

Comparing the effluent of Fuhe estuarine wetland with the Environmental Quality Standard for Surface Water (GB3838-2002) (Figure 4), COD_{Cr} reached Class III water in five months during the monitoring period and met the design requirements. The removal performance of each unit on COD_{Cr} was analyzed based on the monitoring of influent and effluent of the three units (Figure S1 in Supplementary Material). The removal rates of COD_{Cr} in the pre-sedimentation pond and subsurface-flow wetland were 3.3% and 14.7%, respectively, while in the aquatic plant pond COD_{Cr} content increased slightly. The main reason for this phenomenon was the release of organic substances caused by the decomposition of aquatic plants during autumn and winter of monitoring time [32]. In general, the Fuhe estuarine wetland could remove COD_{Cr}, and the subsurface-flow wetland was the main reduction unit of COD_{Cr}. However, it was more influenced by the growth and decomposition of aquatic plants. Figure 4b shows the effluent content of NH_3-N. It can be seen that water quality in terms of NH_3-N reached Class III for only one month during the monitoring period, and the rest of the months were better than Class III. The average influent concentration of NH_3-N in the Fuhe estuarine wetland was 0.48 mg/L and the

average effluent concentration was 0.32 mg/L. The overall removal rate of NH_3-N was 33.33% (Figure S2). The removal rates of NH_3-N in the pre-sedimentation pond, subsurface-flow wetland, and aquatic plant pond were 23.33%, 26.03%, and 42.37%, respectively. The aquatic plant pond contributed main for NH_3-N removal. TP of effluent during the monitoring period all reached Class II. TP of influent was 0.071 mg/L averagely and the effluent concentration was 0.044 mg/L. The removal rates of the pre-sedimentation pond, subsurface-flow wetland and aquatic plant pond were 20.29%, 37.27%, and 50.66%, respectively (Figure S3). In terms of effluent quality and removal rate, the Fuhe estuarine wetland was effective in TP treatment. DO is an important parameter for the self-purification ability. A high level of dissolved oxygen in water and the short time required to return to the initial state after being consumed indicates a strong self-purification ability of the water body [33]. As shown in Figure 4c, the high DO level reached Class I-II, indicating that good self-purification ability of Fuhe estuarine wetland.

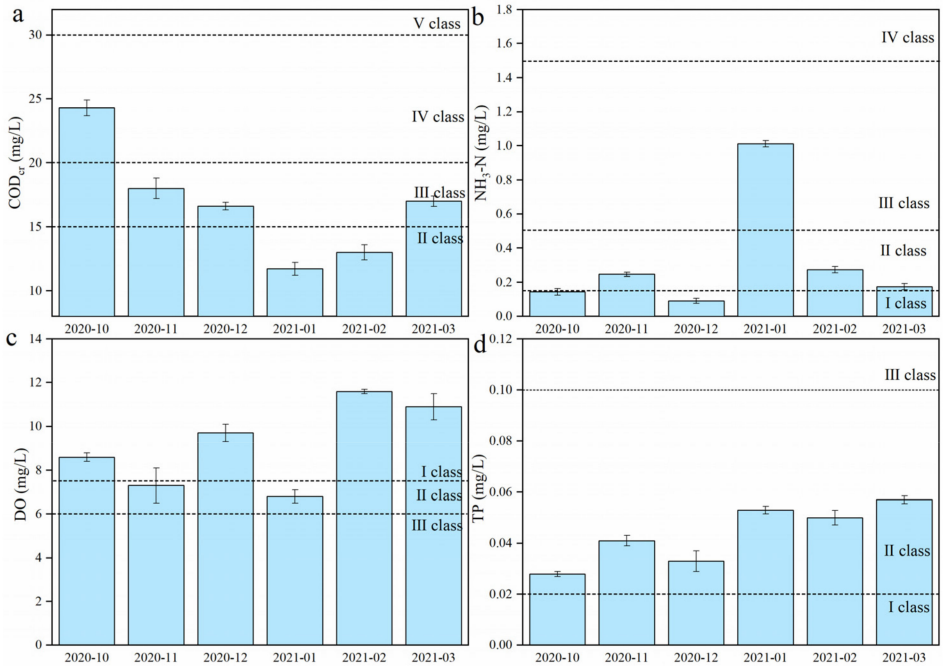

Figure 4. Water quality of the effluent from Fuhe estuarine wetland ((**a**) COD_{Cr}, (**b**) NH_3-N, (**c**) DO, (**d**) TP).

The aquatic plant coverage of the Fuhe estuarine wetlands was 28.76% during the monitoring period. The purifying effect of aquatic plants on pollutants mainly contains both plant uptake and metabolism of rhizosphere microorganism. The decomposition of aquatic plants themselves also release nutrients to the water body. Therefore, the amounts of aquatic plants should be moderate. According to the evaluation results, the habitat diversity of Fuhe estuarine wetland is good, wetland has constructed habitats such as the lotus pond area and the reed area, and combined with the growth needs of plants, the wetland plants have been restored, and have created a variety of healthy wetland habitats such as bird and fish habitats. The overall service quality of the region has been improved, and the resilience and stability of the wetland ecosystem has been enhanced.

4.2.2. Technical Management and Maintenance

The system layer for technical management and maintenance scored 0.998 with a evaluation grade of "excellent". The technical indicators, engineering indicators, and maintenance management indicators contributed 0.4255, 0.3244 and 0.2481 points respectively. The technical advancement scored 4, indicating that the Fuhe estuarine wetland has improved in some respects such as water treatment, ecological restoration, and maintenance

cost. As for substrate selection, gravel, zeolite, and steel slag were selected as carrier for the subsurface-flow wetland. The adsorption and precipitation effects of steel slag in phosphorus removal were less dependent on season and temperature [34]. And high-quality steel slag was abundant in the vicinity. The choice of substrate not only achieved stable TP removal but also reduced the investment. The technology maturity score was the highest score of 5. The near-natural water purification process of "pre-sedimentation pond + subsurface-flow wetland + aquatic plant pond" in this project was mature and reliable, which has been applied in the practice of many wetlands and has been operating stably [9,35].

The project operability and stability both scored 4, indicating that the geological, hydrological, and topographical conditions meet the project requirements, and the project can operate stably in the long term. The maintenance of the Fuhe estuarine wetland relied on a digital maintenance management system, which requires 22 people to operate. The management system made comprehensive use of automated control technology, modern information, and telecommunications technology. The water quality from the upstream and the water level inside the wetland were monitored in real time through an automated monitoring system. The water depth and flow inside the wetland were adjusted through a remote-control system, ultimately realizing mechanization and automation for management and maintenance. The maintenance time scored 4. From the field survey, the single maintenance time was around 4 to 6 h, which mainly included the control of water distribution, vegetation maintenance and site monitoring.

4.2.3. Social and Economic Functions

The system layer of socio-economic function scored 1.3109, and the evaluation grade was "excellent". The social impact and economic input contributed 0.6867 and 0.6242 points respectively. In this case, not only the effect of water purification, but also the landscape was considered in the matching and selection of plants. On the basis of the original plants, plants with high ornamental value were added appropriately. The landscape value was improved and the disturbance to the ecological environment of this site was less. The constructed reed terraces and lotus ponds, forming a unique reed and lotus ocean landscape, were suitable for the Baiyangdian Lake.

The indicator of economic impact on the surrounding area scored 4, indicating that the surrounding residents recognized the good contribution of wetland project to the local economy. During the construction period, the purchase of plants and padding was dominated by local businesses, contributing to the growth of the related economy. In addition, employment increased during construction and the sequent maintenance. The capital and operational cost of the project were 22.47 \$/m^2 and 0.02 \$/(m^2·a), respectively, which were in a reasonable range.

4.3. Target-Level Evaluation

The evaluation results showed that the water quality has been better after the pre-sedimentation pond, subsurface-flow constructrd wetland and aquatic plant pond, for the good removal performance of NH_3-N, TP and COD_{Cr}. In terms of habitat construction, the wetland increased biodiversity, enhanced the resilience and stability of the ecosystem, and improved the service quality of the overall region. The Fuhe estuarine wetland performed well in terms of engineering for the technology adopted, which was stable. The improvements in substrate, plant configuration and topography construction made the wetland more effective in removing pollutants and restoring the ecosystem. The construction of this project met local development requirements and promoted the local economy. However, according to the index layer scores, the indicators of coverage of aquatic plants and maintenance complexity scored lowest. Therefore, we suggested the following: (1) increase the amounts of aquatic plants in the treatment units or the available lakeshore to enhance the water purification efficiency and landscape appreciation value; (2) further improve the mechanization and automation of management and reduce maintenance

personnel. In summary, the Fuhe estuarine wetland performance well in water purification, ecological restoration, engineering technology and socio-economic aspects, and could be popularized.

5. Conclusions

Based on the characteristics of near-natural estuarine wetlands, an evaluation index system was constructed covering the aspects of environmental benefits, technical management and maintenance, and socio-economic functions, containing 1 target layer, 3 system layers, 7 criterion layers, and 16 indicator layers. The weight of indicators in different layers was determined by group decision-based hierarchical analysis and a fuzzy evaluation was used as the evaluation algorithm. A case evaluation was conducted using the Fuhe estuarine wetland project in Xiong'an New Area of Hebei Province as an example. The water purification project of Fuhe estuarine wetland was evaluated and the result was "excellent", indicating that Fuhe estuarine wetland had good effect on pollutants removal. The technology adopted had good effect in practical application, for the improvement in ecological restoration and investment reduction. The project site was suitable, and it had a positive impact on the surrounding environment, economy, and social development. The Fuhe estuarine wetland can be optimized and improved by increasing the coverage of aquatic plants and improving the efficiency of maintenance and management. The traditional evaluation of water purification and ecological restoration projects was mostly limited to the evaluation of restoration effects. However, the evaluation system constructed in this study added qualitative and quantitative indicators on various aspects such as technical, engineering, social and economic impacts, to build a more scientific and comprehensive evaluation system for evaluating near-natural estuarine wetlands, which provided an accurate way to analyze. It provides strong support to accurately analyze the advantages and defects of water purification and ecological restoration projects, and to develop advanced and efficient technologies.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/w13152116/s1. Table S1: Random consistency index table; Table S2: Basis for qualitative index evaluation; Figure S1: Reduction of COD_{Cr} in Fuhe estuarine wetland (a: pre-ecological sedimentation pond; b: subsurface flow constructed wetland; c: macrophyte pond); Figure S2: Reduction of NH_3-N in Fuhe estuarine wetland (a: pre-ecological sedimentation pond; b: subsurface flow constructed wetland; c: macrophyte pond); Figure S3: Reduction of TP in Fuhe estuarine wetland (a: pre-ecological sedimentation pond; b: subsurface flow constructed wetland; c: macrophyte pond).

Author Contributions: Conceptualization, J.S. and Y.H.; methodology, J.S.; software, Y.H.; validation, P.Z., H.W. and Y.C.; formal analysis, L.L. and M.L.; investigation, M.L.; resources, H.W. and P.Z.; data curation, Y.C.; writing—original draft preparation, Y.H.; writing—review and editing, J.S.; visualization, J.S.; supervision, H.W. and Y.L.; project administration, P.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Major Science Technology Program for Water Pollution Control and Treatment of China (2018ZX07110).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We are thanks to our all colleagues and research staff members for their constructive advice and help.

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

References

1. Ji, Z.; Zhang, H.; Zhang, Y.; Chen, T.; Long, Z.; Li, M.; Pei, Y. Distribution, ecological risk and source identification of heavy metals in sediments from the Baiyangdian Lake, Northern China. *Chemosphere* **2019**, *237*, 124425. [CrossRef] [PubMed]
2. Ramsar Convention on Wetlands (RCW). *Global Wetland Outlook: State of the World's Wetlands and their Services to People*; Ramsar Convention Secretariat: Gland, Switzerland, 2018.
3. Hu, S.; Niu, Z.; Chen, Y.; Li, L.; Zhang, H. Global wetlands: Potential distribution, wetland loss, and status. *Sci. Total Environ.* **2017**, *586*, 319–327. [CrossRef] [PubMed]
4. Wang, Y.; Zhang, T.; Zhao, Y.; Ciborowski, J.; O'Halloran, I.; Qi, Z.; Tan, C. Characterization of sedimentary phosphorus in Lake Erie and on-site quantification of internal phosphorus loading. *Water Res.* **2021**, *188*, 116525. [CrossRef] [PubMed]
5. Qi, Y.; Wang, Z.; Pei, Y. Evaluation of water quality and nitrogen removal bacteria community in Fuhe River. *Procedia Environ. Sci.* **2012**, *13*, 1809–1819. [CrossRef]
6. Sudarsan, J.S.; Annadurai, R.; Mukhopadhyay, M.; Chakraborty, P.; Nithiyanantham, S. Domestic wastewater treatment using constructed wetland: An efficient and alternative way. *Sustain. Water Resour. Manag.* **2018**, *4*, 781–787. [CrossRef]
7. Li, D.; Chu, Z.; Huang, M.; Zheng, B. Multiphasic assessment of effects of design configuration on nutrient removal in storing multiple-pond constructed wetlands. *Bioresour. Technol.* **2019**, *290*, 121748. [CrossRef] [PubMed]
8. Dørge, J. Modelling nitrogen transformations in freshwater wetlands. Estimating nitrogen retention and removal in natural wetlands in relation to their hydrology and nutrient loadings. *Ecol. Model.* **1994**, *75–76*, 409–420. [CrossRef]
9. Chen, H. Impacts of exotic plant invasions on soil biodiversity and ecosystem processes. *Biodivers. Sci.* **2005**, *13*, 555–565. [CrossRef]
10. Liu, X.; Zhao, Y.; Zhang, X.; Kong, H.; Lin, Y. Plant community diversity in Dengbeiqiao constructed wetland and ecological revetment of Yonganjiang River in Erhai Region in 2012. *Wetland Sci.* **2018**, *16*, 45–50. [CrossRef]
11. Li, J.; Chen, J.; Xia, F. A pollutant removal rule of constructed wetland on the Dianchi Lake lakeshore. *Environ. Sci. Technol.* **2012**, *35*, 98–101.
12. Parde, D.; Patwa, A.; Shukla, A.; Vijay, R.; Killedar, D.J.; Kumar, R. A review of constructed wetland on type, treatment and technology of wastewater. *Environ. Technol. Innov.* **2021**, *21*, 101261. [CrossRef]
13. Li, Y.; Zhu, S.; Zhang, Y.; Lv, M.; Kinhoun, J.J.R.; Qian, T.; Fan, B. Constructed wetland treatment of source separated washing wastewater in rural areas of southern China. *Sep. Purif. Technol.* **2021**, *272*, 118725. [CrossRef]
14. Wang, Y.; Li, Q.; Zhang, W.; Wang, S.; Peng, H. Pollutants removal efficiency assessment of constructed subsurface flow wetlands in lakes with numerical models. *J. Hydrol.* **2021**, *598*, 126289. [CrossRef]
15. Wu, H.; Gao, X.; Wu, M.; Zhu, Y.; Xiong, R.; Ye, S. The efficiency and risk to groundwater of constructed wetland system for domestic sewage treatment—A case study in Xiantao, China. *J. Clean. Prod.* **2020**, *277*, 123384. [CrossRef]
16. Jiang, M.; Chen, H.; Chen, Q.; Wu, H.; Chen, P. Wetland ecosystem integrity and its variation in an estuary using the EBLE index. *Ecol. Indic.* **2015**, *48*, 252–262. [CrossRef]
17. Zhang, H.; Cui, B.; Ou, B.; Lei, X. Application of a biotic index to assess natural and constructed riparian wetlands in an estuary. *Ecol. Eng.* **2012**, *44*, 303–313. [CrossRef]
18. Su, F.; Liu, H.; Zhu, D.; Li, L.; Wang, T. Sustainability assessment of the Liaohe Estuary wetland based on emergy analysis. *Ecol. Indic.* **2020**, *119*, 106837. [CrossRef]
19. Ghosh, A.; Maiti, R. Development of new Ecological Susceptibility Index (ESI) for monitoring ecological risk of river corridor using F-AHP and AHP and its application on the Mayurakshi river of Eastern India. *Ecol. Inform.* **2021**, *63*, 101318. [CrossRef]
20. Chan, F.T.; Chan, M.; Tang, N. Evaluation methodologies for technology selection. *J. Mater. Process. Technol.* **2000**, *107*, 330–337. [CrossRef]
21. Feng, L.; Zhu, X.; Sun, X. Assessing coastal reclamation suitability based on a fuzzy-AHP comprehensive evaluation framework: A case study of Lianyungang, China. *Mar. Pollut. Bull.* **2014**, *89*, 102–111. [CrossRef] [PubMed]
22. Zhang, D.; Ge, W.; Zhang, Y. Evaluating the vegetation restoration sustainability of ecological projects: A case study of Wuqi County in China. *J. Clean. Prod.* **2020**, *264*, 121751. [CrossRef]
23. Zhang, R.; Liu, C.; Gu, Y.; Sun, D.; Qi, F. Evaluation method of water ecological restoration technologies in urban river and lake supplied by reclaimed water established by analytical hierarchy: Establishing and application. *Chin. J. Environ. Eng.* **2017**, *11*, 3545–3554. [CrossRef]
24. Chen, Z.-Y.; Dai, Z.-H. Application of group decision-making AHP of confidence index and cloud model for rock slope stability evaluation. *Comput. Geosci.* **2021**, *155*, 104836. [CrossRef]
25. Lu, Y.; Xu, H.; Wang, Y.; Yang, Y. Evaluation of water environmental carrying capacity of city in Huaihe River Basin based on the AHP method: A case in Huai'an City. *Water Resour. Ind.* **2017**, *18*, 71–77. [CrossRef]
26. Tung, S.; Tang, S. A comparison of the Saaty's AHP and modified AHP for right and left eigenvector inconsistency. *Eur. J. Oper. Res.* **1998**, *106*, 123–128. [CrossRef]
27. Yang, W.; Yan, J.; Wang, Y.; Zhang, B.-T.; Wang, H. Seasonal variation of aquatic macrophytes and its relationship with environmental factors in Baiyangdian Lake, China. *Sci. Total Environ.* **2020**, *708*, 135112. [CrossRef]
28. Zhang, Y.; Cui, B.; Lan, Y.; Han, Z.; Wang, T.; Guo, A. Four terrestrialization characteristics of Baiyangdian Lake, China. *Procedia Environ. Sci.* **2012**, *13*, 645–654. [CrossRef]

29. Xu, F.; Yang, Z.; Chen, B.; Zhao, Y. Development of a structurally dynamic model for ecosystem health prognosis of Baiyangdian Lake, China. *Ecol. Indic.* **2013**, *29*, 398–410. [CrossRef]
30. Hu, G.; Xu, Z.; Dai, J.; Mai, B.; Cao, H.; Wang, J.; Shi, Z.; Xu, M. Distribution of polybrominated diphenyl ethers and decabromodiphenylethane in surface sediments from Fuhe River and Baiyangdian Lake, North China. *J. Environ. Sci.* **2010**, *22*, 1833–1839. [CrossRef]
31. Zhou, Z.; Zhang, P.; Zhang, G.; Wang, S.; Cai, Y.; Wang, H. Vertical microplastic distribution in sediments of Fuhe River estuary to Baiyangdian Wetland in Northern China. *Chemosphere* **2021**, *280*, 130800. [CrossRef]
32. Reina, M.; Espinar, J.; Serrano, L. Sediment phosphate composition in relation to emergent macrophytes in the Doñana Marshes (SW Spain). *Water Res.* **2006**, *40*, 1185–1190. [CrossRef] [PubMed]
33. Guo, W.; Yang, F.; Li, Y.; Wang, S. New insights into the source of decadal increase in chemical oxygen demand associated with dissolved organic carbon in Dianchi Lake. *Sci. Total Environ.* **2017**, *603–604*, 699–708. [CrossRef] [PubMed]
34. Lee, M.S.; Drizo, A.; Rizzo, D.M.; Druschel, G.; Hayden, N.; Twohig, E. Evaluating the efficiency and temporal variation of pilot-scale constructed wetlands and steel slag phosphorus removing filters for treating dairy wastewater. *Water Res.* **2010**, *44*, 4077–4086. [CrossRef] [PubMed]
35. Barco, A.; Borin, M. Treatment performance and macrophytes growth in a restored hybrid constructed wetland for municipal wastewater treatment. *Ecol. Eng.* **2017**, *107*, 160–171. [CrossRef]