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Assessment of the Habitat Quality of Offshore Area in Tongzhou Bay, China: Using Benthic Habitat Suitability and the InVEST Model

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Abstract: Coastal zones, and in particular offshore areas, are coming under ever-increasing pressure from human development. Therefore, the evaluation of habitat quality is of vital importance for management of coastal zones. The InVEST model adopts a multi-module and multi-level design form, which has the advantages of strong visualization and fast calculation. As a result, this study used the InVEST-Habitat quality (HQ) model to assess the habitat quality of the Tongzhou Bay offshore area. Development activities were included in the classification of habitat types and the benthic habitat suitability index was used to describe the spatial variation in habitat quality of the offshore area. The results showed that the methodological approach mentioned above achieved a more detailed assessment of the spatial variation in habitat quality. The empirical model constructed based on the relationship between the Shannon–Weiner index and environmental factors performed well in revealing the suitability of habitat, with the regression equation showing an R^2 of 0.57 and R^2 of 0.5 significant at level of $p < 0.05$. The habitat suitability of Tongzhou Bay water was mainly influenced by aquaculture and industrial sea use. The habitat quality of Tongzhou Bay was relatively low due to disturbance by coastal development and a low water habitat suitability. The distribution of habitat quality in Tongzhou Bay was uneven and improved with the increase of the distance from the coast. Improvement of the habitat quality of Tongzhou Bay requires strict control of sea reclamation, optimization of the structure of offshore aquaculture, improvements to water quality and habitat suitability, and strengthening of the protection of areas of high habitat quality. This study provides a novel method for evaluating habitat quality of offshore areas.

Keywords: habitat suitability; habitat quality; InVEST model; offshore area; Tongzhou Bay

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Citation: Zhang, H.; Li, S.; Liu, Y.; Xu, M. Assessment of the Habitat Quality of Offshore Area in Tongzhou Bay, China: Using Benthic Habitat Suitability and the InVEST Model. *Water* **2022**, *14*, 1574. https://doi.org/10.3390/w14101574

Academic Editor: Dimitrios E. Alexakis

Received: 7 April 2022
Accepted: 11 May 2022
Published: 14 May 2022

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1. Introduction

Habitat quality refers to the ability of an ecosystem to provide appropriate conditions for the survival of individual organisms, populations of a particular species, and communities of species. Therefore, habitat quality can reflect biodiversity. The assessment and prediction of habitat quality are of great significance for biodiversity conservation and have become increasingly popular in recent ecological research [1]. Coastal zones experience intensive human activities. Approximately 60% of the global population live in coastal zones within 100 km from the shore. However, human activities and global climate change have significantly affected the ecosystems of coastal zones. Therefore, assessing the quality of habitat in coastal waters is of vital importance.

Several ecological models are currently used for the rapid assessment of habitat quality. These include the Multi-scale Integrated Models of Ecosystem Services (MIMES) [2], the Artificial Intelligence for Ecosystem Services model (ARIES) [3], and the Integrated

Valuation of Ecosystem Services and Tradeoffs model (InVEST). Among these models [4], the InVEST model is characterized by a wide range of functions, strong visualization capacity, easy operation, and clear data requirements. Consequently, the InVEST model has been widely used in the study of ecosystem protection and management under various scenarios, such as river basins [5], wetlands [6–8], and cities [9–11]. The InVEST-HQ model assesses habitat quality by classifying habitat types and measuring the habitat suitability of each type by overlaying degradation resulting from threat factors. The InVEST-HQ model assumes that a high habitat quality is an indicator of high biodiversity and that there is a decline in biodiversity with declining habitat quality [12].

However, most previous studies on habitat quality of coastal zones have focused on land areas, with the offshore area regarded as a single habitat due to the difficulty associated with intuitively identifying and classifying well-defined landscape types [7,9]. This approach does not objectively reflect development activities and spatial variations in habitat quality of offshore waters. Therefore, this approach performs poorly in guiding ecological protection of coastal and offshore areas within the context of increasingly intensified development of coastal areas. Some previous studies have attempted to overcome the problem of different habitat suitability values of the same habitat in different regions through the use of the normalized difference vegetation index (NDVI) to modify the assessment of habitat quality in land ecosystems [13]. Consequently, the stability, accessibility, and sensitivity of benthic biodiversity as well as its representativity of environmental and ecological conditions allows its use as an alternative landscape index for the assessment of habitat quality in offshore waters [14,15]. Thus, a benthic habitat suitability index can be used to reflect spatial variation in habitat quality in offshore waters.

A habitat suitability index model based on environmental factors can be used as a tool for indicating habitat suitability [16]. Recent studies have shown that several environmental factors, such as the water quality environment [17], water depth [18], and sediment characteristics [19], may affect benthic biodiversity. Therefore, the selection of important environmental factors can be helpful for the simplification of the model calculation and for improving the accuracy of the model.

Since the Tongzhou Bay offshore area is the access point to the Changjiang River, this area experiences intense development pressure and increasing threats to habitat quality. Given the lack of previous evaluations of habitat in the Tongzhou Bay offshore area, the present study adopted the Tongzhou Bay offshore area as a case study with the aim of providing a tool for the assessment of habitat quality in offshore and coastal areas; it is hoped that the current study can guide spatial planning and the sustainable development of the coastal zone and offshore area. More specifically, the objectives of the present study were to: (1) construct a classification of habitat types of Tongzhou Bay to allow the identification of coastal development activities; (2) identify the relationship between benthic biodiversity and environmental factors and establish an empirical model of the habitat suitability index of the Tongzhou Bay offshore water area; and (3) assess the habitat quality of the Tongzhou Bay offshore area.

2. Materials and Methods

2.1. Study Area

Tongzhou Bay is located in the southern part of Nantong City, Jiangsu Province, Eastern China, and is bordered by the estuary of the Changjiang River to the south. Since Tongzhou Bay lies at the intersection of the Jiangsu River economic belt and the coastal economic zone, the area experiences the majority of coastal development activities in Nantong City. The government of Nantong City proposed the "big Tongzhou Bay" development scheme in 2020 which planned to establish a new sea gate into Jiangsu Province to fully exploit the geographical advantages of Tongzhou Bay. However, the ecosystem of the Tongzhou Bay offshore area is currently under threat. The present study therefore selected a study area (within 32°0′–32°20′ N, 121°30′–121°40′ E) encompassing an area of 12.75 km^2 for the evaluation of the habitat quality of the Tongzhou Bay offshore area such as (Figure 1).

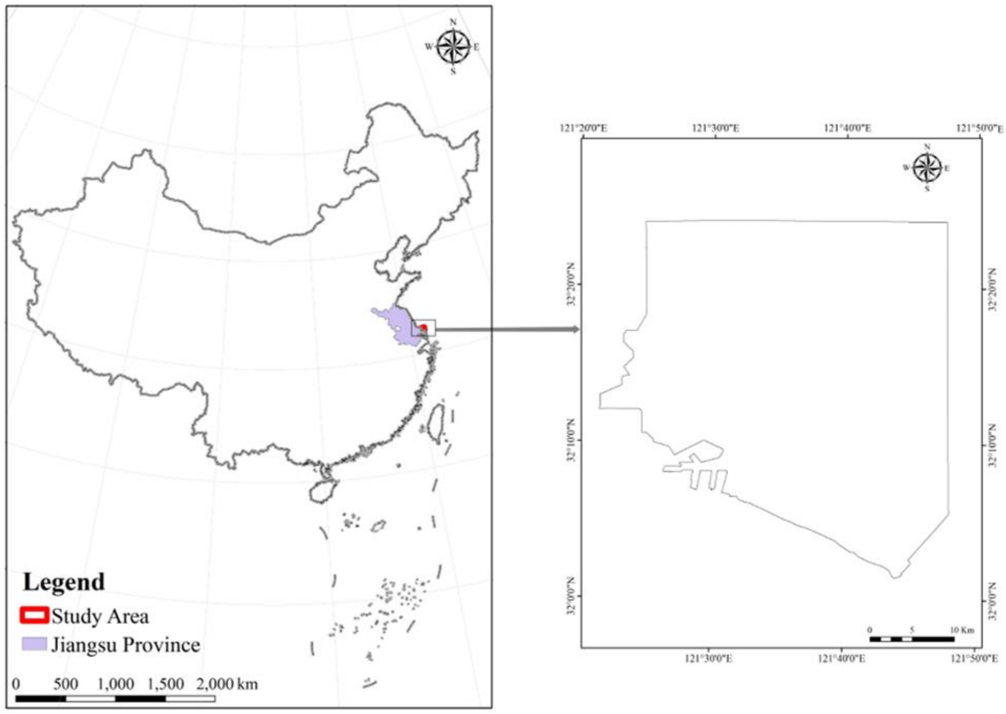

Figure 1. Geographic location of Tongzhou Bay, Nantong City, Jiangsu Province, Eastern China.

2.2. Data Sources

Samples were collected from 47 water quality stations and 28 ecological stations in the coastal waters of Tongzhou Bay during September and November 2018 and during January and April 2019 such as (Figure 2). Water samples and benthic samples were collected using a WB-PM water sampler and a grab sampler, respectively. The depths at which the water quality samples were taken depended on the water depth at the station. When the water depth at the station exceeded 10 m, samples were taken at a depth of 1 m as well as at the bottom, with the average measurements across the two samples used in the present study. Only surface water samples were taken when the water depth was less than 10 m. Water sample temperature, salinity, and pH were measured using a thermometer, salinometer, and pH meter, respectively. Chemical oxygen demand (COD), dissolved oxygen (DO), dissolved inorganic phosphate (DIP), nitrite, nitrate, and ammonium were measured using the potassium iodide alkaline permanganate, iodometric, phosphomolybdenum blue spectrophotometric, naphthalene ethylenediamine spectrophotometric, zinccadmium reduction, and hypobromite oxidation methods, respectively. Nitrite, nitrate, and ammonium were added up to represent the dissolved inorganic nitrogen (DIN). All the methods above followed the sea water monitoring standard of China [20].

Benthic sediment samples with an area of 0.1 m^2 were collected, screened, and fixed in a 5% formaldehyde solution in a polypropylene specimen bottle (PP), following which they were counted and weighed in the laboratory using a stereomicroscope and balance, respectively.

The present study obtained topographic data for the study area from 1:50,000 digital elevation model (DEM) data formed during multiple topographic surveys of the study area. Data for the development and utilization of the coastal area originated from field investigations and remote sensing images and were converted into 30 $\times$ 30 m raster data using ArcGIS 10.3 software.

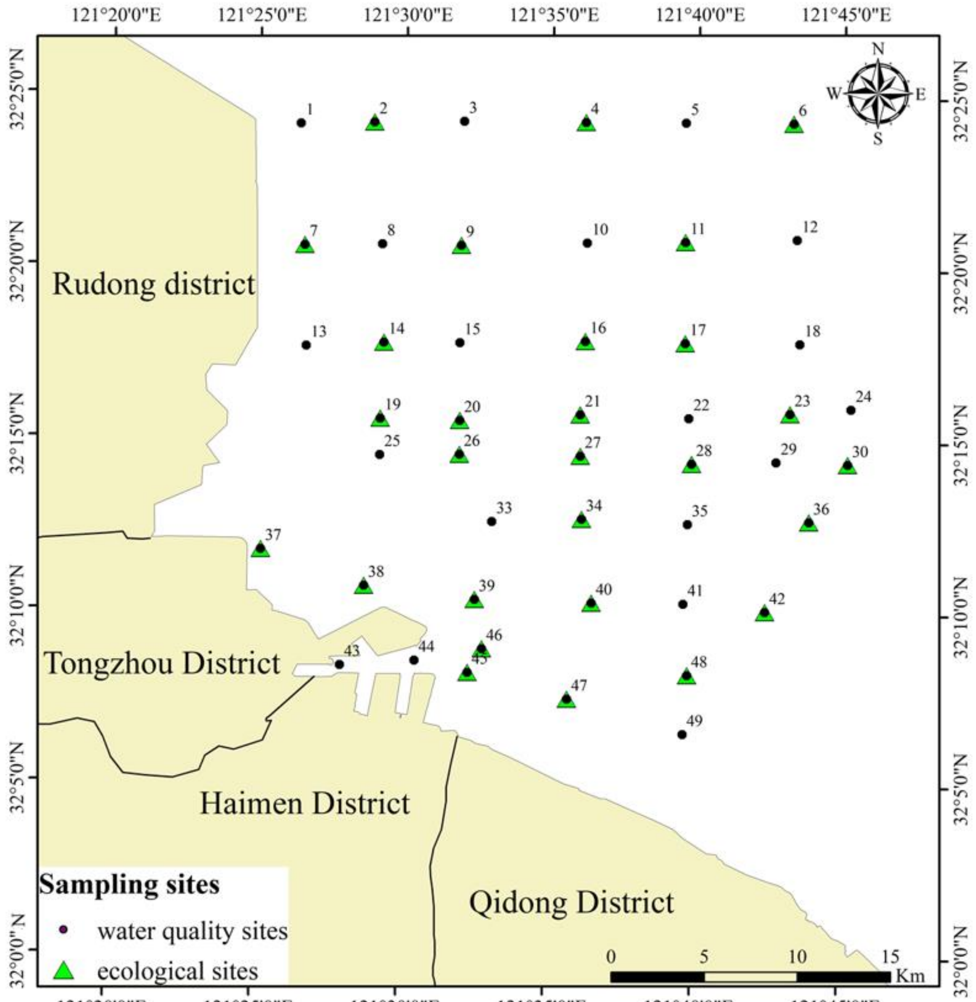

Figure 2. Map showing water sample sites in Tongzhou Bay, Nantong City, Jiangsu Province, Eastern China.

Landsat 8 image data was download from the United States Geological Survey (USGS) website (https://www.ngdc.noaa.gov/dmsp/maps.html (accessed on 21 July 2021)). Tide data were provided by the Lvsi tide-gauge station. Habitat types were determined by using topographic data, remote sensing images, development data, and tide level monitoring data.

2.3. Identification of the Major Environmental Factors Impacting Benthic Biodiversity

Pearson correlation analysis and ordination analysis were used to analyze the relationship between benthic biodiversity and environmental factors and for the selection of major environmental impact factors. Environmental factors were considered to be important when the significance index P was less than 0.05. The ordination analysis model was assessed according to the results of detrended correspondence analysis (DCA). Redundancy analysis (RDA) was selected when the result of DCA was less than 3 and canonical correlation analysis (CCA) was used when the result of DCA exceeded 4. Both methods were used when the result was between 3 and 4. Biodiversity was evaluated using the Shannon–Wiener index. Correlation analysis and ordination analysis were performed in SPSS 25.0 and Canoco 5.0 software packages, respectively.

2.4. Evaluation of the Habitat Suitability Index (HSI)

The habitat suitability index (HSI) was used to evaluate the habitat requirement to sustain the survival and growth of living organisms [21]. The present study established the HSI based on the relationship between environmental factors and biodiversity. The Shannon–Wiener index was used as the criterion with which to identify habitat suitability as according to previous studies and local conditions [22,23]. The values of the habitat suitability index were 0.2, 0.4, 0.6, 0.8, and 1 when the corresponding Shannon–Wiener index values were 0, 0–1, 1–2, 2–3, and >3, respectively. The ordinary least-squares (OLS) model was used to establish regression equations describing the relationships between environmental factors and the HSI. The empirical Bayesian kriging (EBK) interpolation method was used to construct a 30 × 30 m raster dataset for major environmental impact factors and the HSI for Tongzhou Bay was calculated using the empirical model. The interpolation and calculation of raster data was performed in Arc GIS 10.3 software.

2.5. Evaluation of Habitat Quality

The InVEST-HQ model was used to evaluate the habitat quality and regional biodiversity of the Tongzhou Bay nearshore area. Spatial variation in habitat quality was assessed by using the HSI to optimize the results of water habitat quality. Thus, the integrated model for the evaluation of habitat quality was:

$$Q = Q_{xJ} \times \mathrm{HSI} \quad (1)$$

In Equation (1), HSI represents the habitat suitability index constructed in Section 2.4 and Q_{xj} is the water habitat quality calculated by the InVEST-HQ model ([16]) as:

$$Q_{xJ} = \mathrm{H}_j\left(1 - \left(\frac{D_{xj}^z}{D_{xj}^z + k^z}\right)\right) \quad (2)$$

In Equation (2), H_j is the habitat score of habitat type j as determined by habitat suitability, k is the half-saturation constant, typically assigned a value of 0.5, z is a scaling parameter, and D_{xj} is the degree of habitat degradation of grid x in land-use type j:

$$i_{rxy} = \begin{cases} 1 - \frac{d_{xy}}{d_{rmax}}(linear) \\ \exp\left[-\frac{2.99}{d_{rmax}} \times d_{xy}\right](exponential) \end{cases} \quad (3)$$

In Equation (3), d_{xy} is the distance between the habitat and the threat and d_{rmax} denotes the maximum interference distance of threat r.

The identification of the types of habitats and the determination of parameters are of vital importance to the InVEST-HQ module. The study area was divided into water, tidal flat, and development area considering the development conditions of the study area. Coastal development activities were divided into light development (including cable and open aquaculture), medium development (including offshore wind turbines, pond aquaculture, harbors, and other permeable structures), and reclamation/roads (including reclamation and other impervious structures) with consideration of the impacts of coastal development activities on habitat. Light development and medium development were further classified into water and tidal flat components based on the type of occupied habitat, resulting in a total of seven habitat types such as (Table 1).

Table 1. Habitat types and relevant parameters.

Habitat Types	Habitat Score	Sensitivity to Threat Factors						
		Sewage Discharge	Reclamation	Pond Aquaculture	Open Aquaculture	Wind Turbines	Harbors	Trestles
Tidal flat	1	1	1	0.8	0.2	0.6	0.5	0.7
Water	1	1	0.7	0.7	0.2	0.5	0.3	0.5
Reclamation/road	0	0	0	0	0	0	0	0
Medium development (tidal flat)	0.6	0.6	0.4	0.4	0.12	0.3	0.18	0.3
Medium development (water)	0.6	0.6	0.4	0.4	0.12	0.3	0.18	0.3
Light development (tidal flat)	0.8	0.8	0.5	0.5	0.16	0.4	0.24	0.4
Light development (water)	0.8	0.8	0.5	0.5	0.16	0.4	0.24	0.4

As according to advice from experts and local conditions, sewage discharge, reclamation, pond aquaculture, open aquaculture, wind turbines, harbors, and trestles were considered factors posing a threat to habitat quality. Table 2 shows relevant parameters and habitat types considered.

Table 2. Threats and relevant parameters.

Threat Factors	Maximum Distance (d_{rmax}; km)	Weight (w_r)	Decay Type
Sewage discharge	5	1	Exponential decay
Reclamation	2	1	Exponential decay
Pond aquaculture	2	0.7	Exponential decay
Pond aquaculture	0.5	0.3	Linear decay
Harbors	2	0.7	Linear decay
Wind turbines	0.5	0.3	Exponential decay
Trestles	0.5	0.5	Linear decay

3. Results

3.1. Benthic Characteristics

Of all 122 samples, 7% (8), a total of 60 species of benthic organisms were identified in the remaining samples, with the value of the Shannon–Wiener index ranging from 0 to 3.08 such as (Figure 3).

3.2. Correlations between Benthic Biodiversity and Environmental Factors

As according to the results of the DCA (log = 0.8), the RDA model was used to analyze the relationship between environmental factors and biological data. Figure 4 and Table 3 shows that the Shannon–Wiener index of benthic organisms was mainly positively affected by temperature and dissolved inorganic phosphorus (DIP). Pearson correlation analysis showed that the biodiversity of benthic fauna was positively correlated with temperature ($p < 0.01$, R = 0.323) and negatively correlated with COD ($p < 0.05$, R = −0.226).

The results of the Pearson correlation analysis and RDA indicated different relationships between DIP and biodiversity. Since there was a wide range in DIP among the samples, the samples were separated into one group with DIP concentrations less than 0.045 mg L^{-1} (threshold value of the Chinese sea water quality standard) [24] and another group containing the remaining samples. Pearson correlation analysis was then conducted on each group separately.

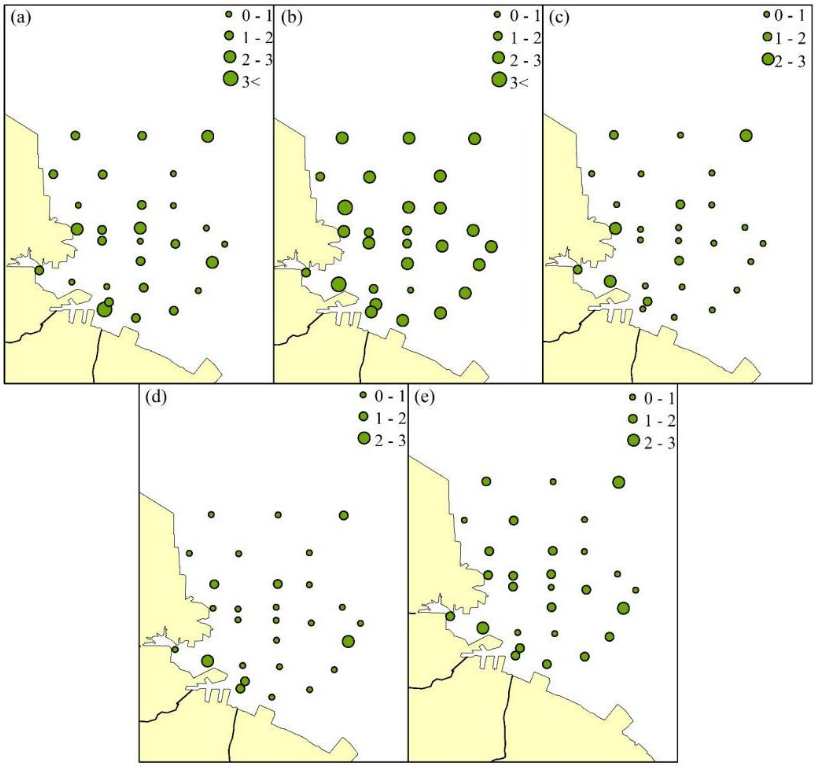

Figure 3. Spatial distribution of the values of the Shannon–Wiener index in Tongzhou Bay, Nantong City, Jiangsu Province, Eastern China. (**a**) September 2018; (**b**) November 2018; (**c**) January 2019; (**d**) March 2019; (**e**) mean value.

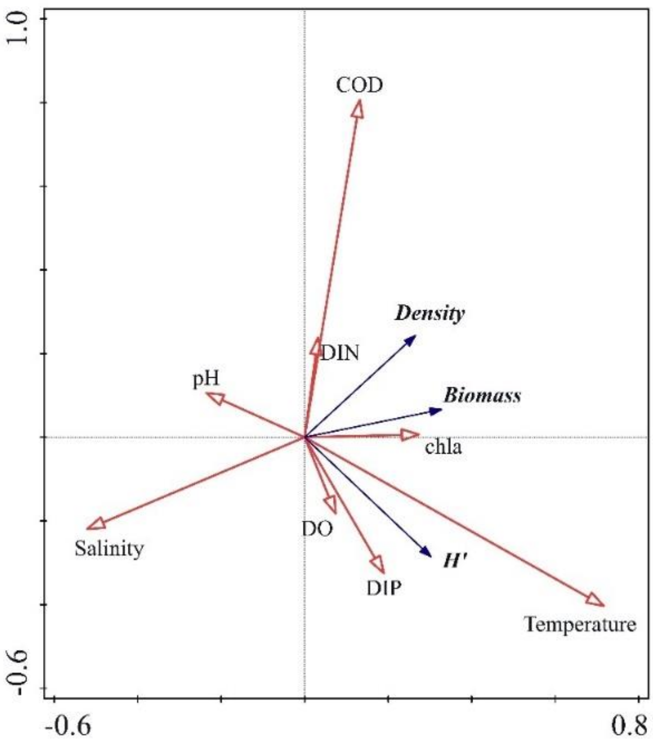

Figure 4. Redundancy analysis (RDA) between environmental factors and benthic characteristics for water samples from Tongzhou Bay, Nantong City, Jiangsu Province, Eastern China.

Table 3. Correlations between benthic Shannon–Wiener index values and environmental factors for water samples from Tongzhou Bay, Nantong City, Jiangsu Province, Eastern China.

	Temperature	pH	Salinity	COD	DO	DIP	DIN	CHLA
All samples	0.323 **	−0.099	−0.054	−0.226 *	0.049	0.133	−0.096	0.076
DIP < 45 (mg/L)	0.650 **	−0.156	−0.105	−0.268 *	0.036	0.322 **	−0.210	−0.108
DIP > 45 (mg/L)	−0.044	−0.002	0.110	−0.090	0.023	0.012	−0.064	0.104

Abbreviations: COD: chemical oxygen demand; DO: dissolved oxygen; DIP: dissolved inorganic phosphorus; DIN: dissolved inorganic nitrogen; CHLA: chlorophyll-a. (*: $p < 0.05$, **: $p < 0.01$)

As shown in Figure 5, pearson correlation analysis showed no significant correlations between biodiversity and the second group of samples (DIP > 0.045 mg L^{-1}). COD, DIP, and temperature had the largest effects on benthic biodiversity in the first group of samples (DIP $\leq$ 0.045 mg L^{-1}) in which the Shannon–Wiener index was negatively correlated with COD ($p < 0.05$, R = −0.268) and positively correlated with DIP and temperature, respectively ($p < 0.01$, R = 0.322; $p < 0.01$, R = 0.65).

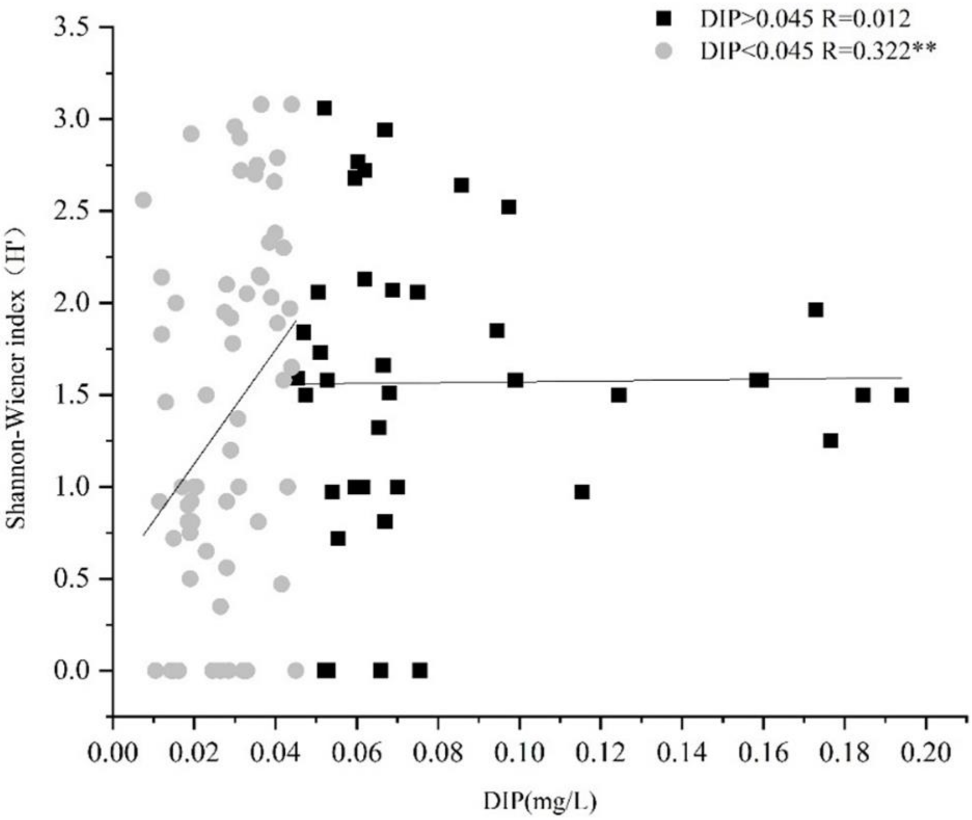

Figure 5. Correlation between dissolved inorganic phosphorus (DIP) and the Shannon–Wiener index for water samples from Tongzhou Bay, Nantong City, Jiangsu Province, Eastern China. (**: $p < 0.01$).

3.3. The Empirical Benthic Habitat Suitability Index (HSI) Model

The empirical model for calculating the benthic habitat suitability index was constructed based on the relationship between biodiversity and major environmental impact factors (DIP, temperature, and COD). The relationship between environmental factors and biodiversity was not clear when the concentration of DIP exceeded 0.045 mg L^{-1}. Therefore, the HSI was set as 0.6 in these cases by comparing the measured data and with reference to the advice of experts.

The OLS model was used to construct the habitat suitability model for the first group of samples (DIP < 0.045 mg/L). As shown in Table 4, the natural break method was conducted to divide the three major environmental impact factors into several grades for the establishment of a single evaluation factor. The regression equation used was:

$$\mathrm{HSI} = 0.119 + 0.13 * V_T + 0.023 * V_{COD} + 0.008 * V_{DIP} \quad (4)$$

Table 4. Criteria of environmental factors.

Environmental Factors	Score of Single Factors				
	1	2	3	4	5
Temperature	0–7	7–13.4	13.4–18	18–30	<30
COD	<1.12	0.85–1.12	0.7–0.85	0.61–0.7	0–0.61
DIP	0–0.015	0.015–0.03	-	-	0.03–0.045

In Equation (5), V_T, V_{COD}, and V_{DIP} represent the single factor evaluation results of temperature, COD, and DIP, respectively. Table 5 shows the results of the regression analysis in which the R^2 was 0.57 and the analysis result was statistically significant. Accordingly, the empirical model of benthic HSI in Tongzhou Bay was:

$$\mathrm{HSI} = \begin{cases} 0.119 + 0.13 * V_T + 0.023 * V_{COD} + 0.008 * V_{DIP} & C_{DIP} < 0.045\mathrm{mg/L} \\ 0.6 & C_{DIP} > 0.045\mathrm{mg/L} \end{cases} \quad (5)$$

Table 5. Results of the ordinary least squares (OLS) regression model.

	Sum of Squares	df	Mean Square	F	Sig.	R^2
Regression	1.965	3	0.655	26.562	0.000	0.57
Residual	1.479	60	0.025			
Total	3.444	63				

3.4. Evaluation of the Habitat Suitability Index

The benthic habitat suitability ranged between 0.59 and 0.62 with an average of 0.6, thereby indicating a medium habitat suitability. Figure 6 shows the spatial distribution of HSI in which the area situated far from shore, particularly in the central parts, showed high values, whereas low values were simultaneously concentrated in the nearshore and north area.

3.5. Evolution of the Habitat Quality of Tongzhou Bay

3.5.1. Habitat Types

Undeveloped water accounted for the largest proportion in the study area (51.44%), followed by undeveloped tidal flat (12.18%), collectively encompassing 63.62% of the study area such as (Figure 7 and Table 6).

The proportion of developed area to undeveloped area was 48.54%, among which light development was mainly concentrated in the northern nearshore area, accounting for 20.84% of the study area (10.75% in the tidal flat and 10.09% in the water area). Medium development accounted for 10.04% (4.92% in the tidal flat and 5.12% in the water area) of the study area. Reclamation/road area did not possess habitat quality and showed the smallest proportion of the study area.

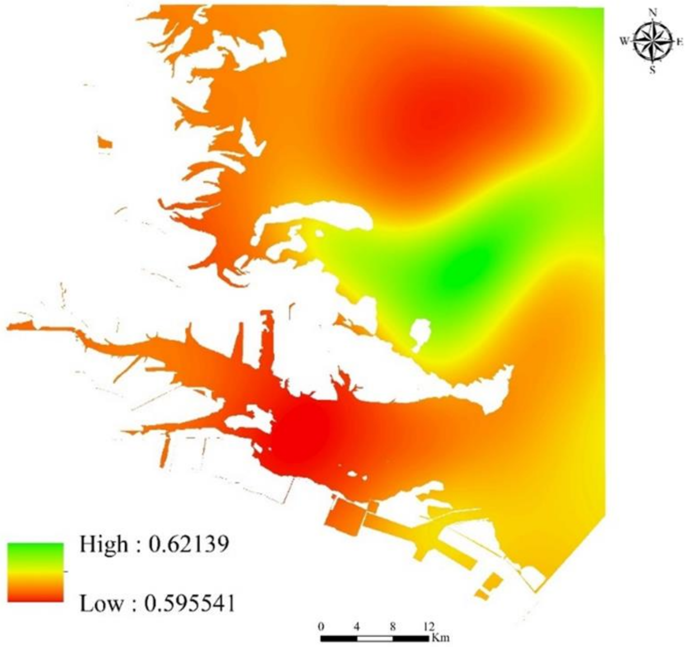

Figure 6. Spatial distribution of habitat suitability index within water samples from Tongzhou Bay, Nantong City, Jiangsu Province, Eastern China.

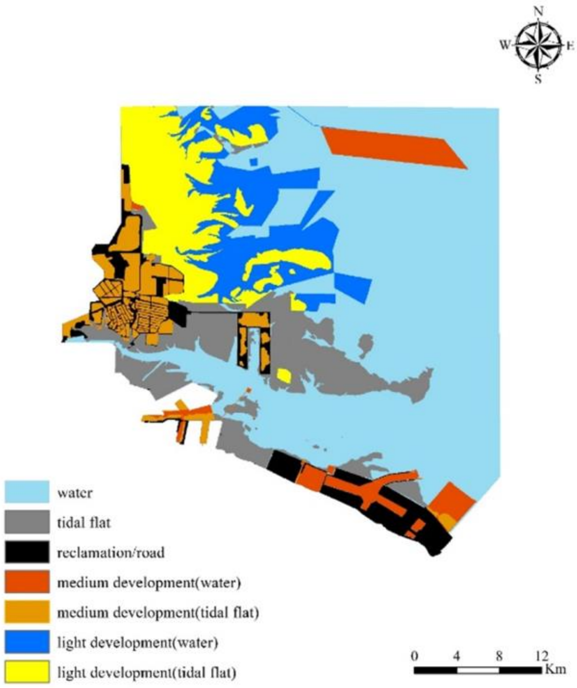

Figure 7. Habitat types of Tongzhou Bay, Nantong City, Jiangsu Province, Eastern China.

Table 6. Results of the ordinary least squares (OLS) regression model.

Tidal Flat	Water	Reclamation/Road	Medium Development (Tidal Flat)	Medium Development (Water)	Light Development (Tidal Flat)	Light Development (Water)
12.18%	51.44%	5.5%	4.92%	5.12%	10.75%	10.09%

3.5.2. Evaluation of Habitat Quality

Habitat quality was calculated based on a 30 × 30 m grid using Equation (2), whereas the results of the water area were modified using Equation (1).

In comparison with merely considering the sea area as a single habitat type, the habitat quality of Tongzhou Bay as indicated by the HSI showed an obvious spatial distribution with an average value that decreased by 29% (Figure 8b). As shown in Table 7, the area falling in the IV class replaced that in the V class as the largest area, with this area distributed in most of the water space. After adjustment, the V class was mainly distributed in the central tidal flat area, whereas class I representing the poorest habitat quality showed no change in proportion and was mainly distributed in the coastal area (Figure 9).

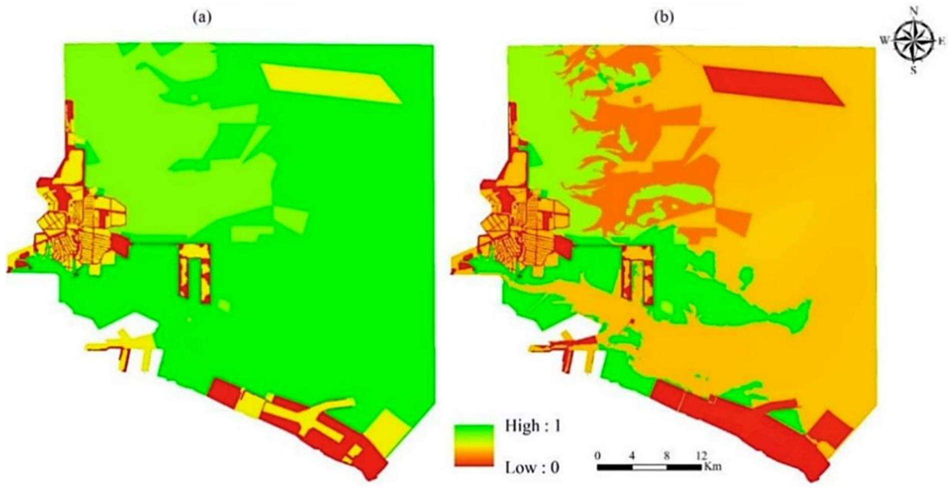

Figure 8. Spatial distribution of habitat quality of Tongzhou Bay, Nantong City, Jiangsu Province, Eastern China. (**a**) without HSI; (**b**) with HSI.

Table 7. Proportion of different levels of habitat quality in Tongzhou Bay, Nantong City, Jiangsu Province, Eastern China.

	Average	I	II	III	IV	V
Without HSI	0.86	5.93%	-	9.60%	20.79%	63.68%
With HSI	0.61	5.93%	4.91%	27.89%	49%	12.27%

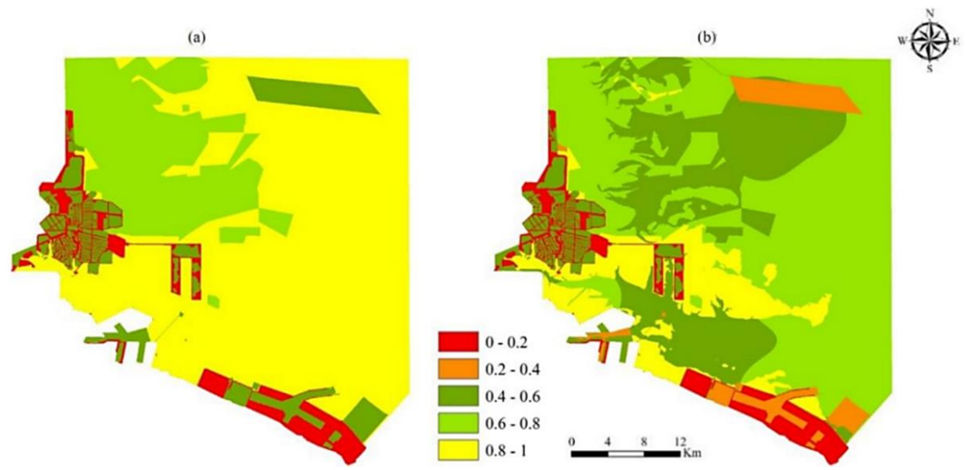

Figure 9. Proportions of different levels of habitat quality in Tongzhou Bay, Nantong City, Jiangsu Province, Eastern China. (**a**) without HSI; (**b**)with HSI.

4. Discussion

4.1. Habitat Quality Model

The present study used the InVEST-HQ model to calculate the habitat quality of Tongzhou Bay. The first step required to calculate habitat quality using this model is the classification of habitat types. Current methods of classifying habitats in sea areas ignore the impacts of human activities on habitat patterns [25]. Development activities in the sea area showed a scattered distribution due to the vast extent of the sea area, and there was only a small disturbance to the sea habitat. In contrast to the total loss of habitat quality of the occupied area of a land ecosystem resulting from development activities, sea development areas, such as open aquaculture and offshore wind turbines, can still be regarded as usable habitat. Thus, the present study included light and medium sea development activities in the habitat classification system of nearshore sea areas to fully express the patterns of sea habitat under the influence of human activities.

Since various sea development types exist, based on expert opinion, the degree of change in habitat was included in the classification. The present study divided open aquaculture and cables fully covering the sea bottom into light development. Partly enclosed areas, including pond aquaculture, harbors, offshore wind turbines, and other permeable structures were categorized as medium development. Reclamation and impervious structures that convert sea areas to land were classified as reclamation/road and were no longer regarded as habitats. The application of this classification method showed that the coastal habitat types in Tongzhou Bay simultaneously reflect the differences between natural attributes and human activities (Figure 7), which is helpful for objectively reflecting the habitat status in the nearshore waters.

The present study used the habitat suitability to reflect the ability of habitat to provide suitable conditions for biological survival. The benthic community shows characteristics of a living area that is relatively fixed and sensitive to environment variations; therefore, the benthic community has been widely used to represent water habitat conditions [26,27]. The results of the present study also revealed that the benthic community of Tongzhou Bay showed significant spatial variation (Figure 3). Thus, the benthic HSI could be used to reflect the habitat quality of Tongzhou Bay. The present study used the benthic habitat suitability index (HSI) to describe the difference in suitability of the same type of habitat, with this method overcoming the problem of a lack of distinction in habitat quality that is encountered when the offshore sea area is taken as a single habitat (Figure 8).

4.2. The Habitat Suitability Model

In contrast to previous studies, a habitat suitability model was constructed in the present study based on the relationship between the Shannon–Wiener index of the benthic community and environmental variables instead of on the relationship between species abundance and environmental factors.

The results of the present study showed that the sea area of Tongzhou Bay is rich in benthic species. It is hoped that the results of the present study can reflect the overall level of diversity of the sea area, rather than the ecological status of a particular species, thereby illustrating the advantage of using the Shannon–Wiener index to reflect suitability. The results of correlation analysis also indicated a significant correlation between the Shannon–Wiener index of benthic organisms and environmental factors in Tongzhou Bay (Figure 4 and Table 3). Therefore, the construction of an empirical model of HSI based on the Shannon–Wiener index was reasonable from a statistical perspective.

The present study used the Pearson correlation analysis, RDA, and OLS to analyze the qualitative and quantitative relationships between benthic biodiversity and environmental factors. These methods have been widely applied in previous studies of habitat suitability [28,29]. The results of the present study showed that the benthic organisms in Tongzhou Bay have adapted to living in an environment with high water temperature, rich nutrients, and clean water. The results also found that DIP, as the main nutrient, promoted the improvement in benthic biodiversity in Tongzhou Bay when the fourth-grade water quality standards were met (DIP < 0.045 mg L^{-1}). However, this trend became less obvious when concentrations of DIP exceeded 0.045 mg L^{-1}. A study by Savage et al. (2002) of Himmerfjaerden Bay similarly showed a continuous increase in benthic biodiversity with increasing nutrients during an early stage, but with significant inhibition of biodiversity with further increases in the nutrient level. Therefore, expert knowledge was used in the current study to perfect the empirical equation for concentrations of DIP exceeding the threshold of 0.045 mg L^{-1}.

The regression equation based on DIP, COD, and temperature showed a high goodness-of-fit and significance for concentrations of DIP less than the threshold of 0.045 mg L^{-1} (Table 5). Accordingly, the empirical equation can be used to calculate the suitability of habitat in Tongzhou Bay.

In addition, the HSI model was established using the water quality factors. However, many other environmental factors not considered in the present study could also influence the biodiversity of the benthic community [30,31]. The most important advantage of selecting water quality factors to calculate the HSI is that water quality factors can be combined with remote sensing data for more rapid and convenient monitoring, thereby facilitating future research on habitat suitability and habitat quality. The improvements in data acquisition methods allow the opportunity for other factors to be incorporated into the empirical model to better reflect habitat suitability.

It is important to note that as the HSI model presented in the current study is a simple empirical model created specifically for Tongzhou Bay, and this model cannot simply be applied to other areas in which the relationships between benthic biodiversity and environmental factors are different. However, this does not preclude the use of the model to calculate the habitat suitability and habitat quality of Tongzhou Bay.

4.3. Habitat Suitability of Tongzhou Bay

A habitat suitability map of Tongzhou Bay was constructed based on the measured water quality factor data and the empirical equation constructed in the present study.

The results showed a low habitat suitability in the northern and southern waters of Tongzhou Bay, which can be related to the influences of aquaculture and industrial activities. Habitat suitability was slightly higher in the central part of Tongzhou Bay compared to that in other areas, which could be attributed to a lower degree of pollution and levels of DIP that generally fell within the fourth-grade water quality standards. Industrial activities and the harbor are concentrated in the southern sea area of Tongzhou Bay. Therefore, discharge from human activities in this area will increase the concentration of chemical oxygen demand (COD) in the adjacent sea area, resulting in a low habitat suitability.

Low habitat suitability of the northern waters can mainly be attributed to aquaculture activities. Previous studies have shown that bait delivery, metabolic waste water generated during the process of breeding, and emissions of breeding residue greatly increase the concentrations of nitrogen, phosphorus, and COD in adjacent waters [32]. These trends are particularly prominent in shellfish breeding in which 80% of produced metabolic substances are soluble [33]. Approximately 267 ha of open aquaculture can be found in the northern waters of Tongzhou Bay, consisting mainly of shellfish aquaculture. This area of aquaculture results in a high concentration of DIP, leading to the inhibition of biodiversity and a low benthic habitat suitability.

Although the results of the present study showed spatial differences in the suitability of benthic habitats in Tongzhou Bay, the average habitat suitability was roughly 0.6. This result can be attributed to the excessive concentrations of DIP in Tongzhou Bay. The results of the current study showed that the average concentration of active phosphate in Tongzhou Bay was 0.05 mg L^{-1} and that the annual average concentration of active phosphate in more than 50% of the sampling sites exceeded the fourth-grade water quality standards. Therefore, the HSI was assigned a value of 0.6 for most of the sea areas according to expert opinion. The continued study of the response mechanisms of benthic biodiversity to concentrations of DIP exceeding the fourth-grade water quality standards can allow the improvement and perfection of the habitat suitability calculation method in the future.

4.4. Habitat Quality of Tongzhou Bay

Habitat quality is an important indicator of regional biodiversity. The present study used the InVEST model and the benthic HSI to calculate habitat quality. The habitat quality of Tongzhou Bay according to the results of the present study was low in comparison with previous estimates that considered the sea area as a single habitat. This result could mainly be attributed to a low benthic habitat suitability. Meanwhile, the modified results showed obvious spatial variations in habitat suitability in the water area (Figure 8, Table 7).

The distribution of habitat quality in Tongzhou Bay was uneven and improved with the increase of the distance from the coast. The overall habitat quality of the sea area was less than that of the tidal flat area due to a lower habitat suitability. With a gradual increase in the distance from shore, there was a gradual decrease in ocean development. Medium development near to the shore consisted mainly of the harbor as well as pond aquaculture and reclamation/road. Development further from shore consisted mainly of opening aquaculture. Therefore, degradation resulting from human activities decreased with increasing distance from shore, resulting in a low habitat quality nearshore area transforming to a higher habitat quality in the far offshore area.

At present, disturbance to the quality of the offshore habitat in Tongzhou Bay mainly occurs in the nearshore area. However, the results of the present study showed that the offshore wind turbines had an impact on the quality of the habitat in the northeastern waters situated far from the shore. Offshore wind power plants have taken up a lot of coastal habitats in Jiangsu Province in recent years due to technical development and government support. On one hand, offshore wind power plants will affect the environment and quality of habitat in waters far offshore [34], whereas on the other hand, the presence of these wind turbines may improve regional habitat quality through providing artificial reefs and habitat [35]. The integrated impact of offshore wind power on offshore habitats remains unclear. Regardless, it remains the case that human activities have begun to disturb habitats over a longer range offshore of Tongzhou Bay.

4.5. Implications for Future Management

The results of the current study showed that the habitat quality in the nearshore area of Tongzhou Bay is facing the greater pressure. Therefore, some suggestions for protecting and improving the habitat quality in the coastal zone of Tongzhou Bay can be suggested. Firstly, the direct occupation of habitats through sea reclamation will result in a great loss in habitat quality. Therefore, the management of land reclamation activities should be strengthened to avoid new land reclamation activities. In addition, ecological restoration activities should be conducted in the existing land reclamation areas to improve the quality of the habitat.

Secondly, open aquaculture is the main form of development and exploitation of the nearshore area. This type of development has had a serious impact on nearshore habitat quality. Therefore, it is suggested that nearshore aquaculture activities be reduced by encouraging pelagic fishing and putting in place a fishing moratorium in summer to alleviate the pressure on the nearshore habitat.

Third, the poor habitat quality in Tongzhou Bay can be mainly attributed to the poor suitability of sea habitats. Continuous monitoring and enhanced management of discharge can effectively improve water quality and habitat suitability in Tongzhou Bay, thereby improving habitat quality.

Finally, the natural tidal flat and the central waters of Tongzhou Bay provide high habitat quality. Therefore, more attention should be focused on the protection of these areas by establishing protected areas to maintain the current habitat quality.

4.6. Limitations and Outlook

The present study used the InVEST model to calculate the quality of the habitat in the offshore area of Tongzhou Bay. Moreover, an empirical model was established for calculating the HSI of benthic fauna to modify the habitat quality results of the water area. The present study provides a novel approach to obtaining a detailed and accurate estimation of the quality of offshore habitats. However, many shortcomings in the present study remain.

The present study used environmental factors to calculate the benthic HSI. However, since there is a lack of relevant survey data for this area, sampling data from 2018 to 2019 were used to analyze the qualitative and quantitative relationships between biodiversity and environmental factors. The short time span of the measured data was insufficient to fully reveal these relationships. In particular, the response of benthic diversity to environmental variations when concentrations of DIP in the study area exceeded 0.045 mg L^{-1} remained unclear. Therefore, perfecting the HSI model requires follow-up field monitoring and surveys of the sediment environment to fully understand the response mechanisms of biodiversity to changes to the environment.

Secondly, the current study determined habitat types, threat factors, and related parameters in the sea area based on expert knowledge. This approach is relatively subjective due to the lack of related research in the water area. Thus, studies on classifying sea habitat types and determining relevant coefficients should be further strengthened to establish a complete classification system for sea habitat types.

Finally, the present study provided detailed estimates of habitat quality through the construction of the benthic HSI model. A similar approach could be applied to the tidal flats. However, measurements of the habitat in the tidal flats were not possible in the current study due to limitations in the experimental conditions. Future collection of ecological data for the tidal flats can allow a similar tidal flat habitat suitability calculation model to be established, thereby further improving the accuracy of the habitat model.

5. Conclusions

The results showed that the inclusion of development activities into the habitat types and the modification of the water habitat quality using a benthic habitat suitability model allowed spatial variation in habitat quality to be revealed in greater detail. The empirical model of benthic HSI established based on the relationship between benthic biodiversity and environmental factors in Tongzhou Bay could be used to reflect the quality of sea habitats.

The results of the current study suggest that habitat quality of Tongzhou Bay can be improved by the strict control of sea reclamation, optimization of offshore aquaculture, improvement of water quality to improve habitat suitability, and the strengthening of the protection of high habitat quality areas. The present study optimized the application of the InVEST-HQ model in the offshore area and provided a novel approach for the calculation of habitat quality of the coastal zone and offshore area.

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

Funding: The Marine Science and Technology Innovation Research of Jiangsu Province (Grant No. JSZRHYKJ202002).

Institutional Review Board Statement: This study did not involve human or animal studies.

Informed Consent Statement: All authors have read and agreed to the published version of the manuscript.

Data Availability Statement: Since all the data of this study are from field sampling, which costs a lot of manpower, material resources and financial resources, all authors decided not to disclose the data temporarily after discussion.

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

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