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Spatio-Temporal Heterogeneity and Cumulative Ecological Impacts of Coastal Reclamation in Coastal Waters

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Abstract: The coastal reclamation, as one of the most extreme transformations of the ocean space by humans, still lacks scientific quantitative evaluating methods to a large extent, compared with the evolution of land use patterns. A cumulative ecological impacts of reclamation (RCEI) was established in our study based on ecological influence characteristics of different reclamation types, and the attenuation effect of reclamation on adjacent areas. It was characterized by spatio-temporal features in decades. Here, we estimated that the cumulative reclamation area in the Bohai Sea from 1985 to 2018 was 5839.5 km^2. Under the influence of human activity, proportions of the industrial and urban boundary, marine construction boundaries (e.g., ports, wharves, and bridges), and protective dams were increased significantly, which led to a sharp increase of the RCEI. In addition, spatio-temporal changes of reclamation were affected by the combination of population growth, economic development, urbanization, industrialization, and marine industry development in coastal cities. These results provided an important historical reference for tracking future development of the Bohai Sea by humans and provided basic data support for the development and protection of the ocean.

Keywords: coastal water; movable water bodies boundary (MWBB); cumulative ecological impact; reclamation; driving factor; spatio-temporal heterogeneity

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1. Introduction

The Circum-Bohai-Sea region has one of the densest populations and the highest degrees of urbanization and industrialization in China. At the end of 2019, the Circum-Bohai-Sea region had a total population of 0.25 billion, accounting for 17.1% of the population of China, with an annual GDP of 1.8×10^5 billion yuan, 20.8% of the GDP of China [1]. Rapid economic expansion and accelerated population growth in the Bohai Sea have caused a sharp increase in land reclamation [2,3]. Between the 1950s and 1980s, reclamation of cultivated land in succession for the coastal area was focused on agricultural development and food production. Between the 1980s and 2000s, coastal reclamation was aimed at increasing salt and agricultural production. In recent decades, driven by the fast-growing economy from 2000 to 2018, Bohai Rim city aggressively expanded coastal industries and urbanization, which resulted in an increasing demand for reclamation. Along with the rapid development of the Bohai Sea, the high-intensity reclamation activities have already caused severe challenges to its ecological environment and the ecosystem service functions, especially the widely distributed and typical coastal wetlands of the Bohai Sea [4]. According to the 2018 Bulletin of China's Marine Ecological Environment, Ministry of Ecology and Environment of the People's Republic of China (2019), the Bohai Sea—as a part of the Western Pacific Ocean and China's inland sea, with land from three directions, surrounded by Liaoning Province, Hebei Province, Shandong Province, and Tianjin City, and connected with the Yellow Sea through the Bohai Strait—is the sea area with the most prominent marine ecological problems, e.g., pollutant emission, oil exploitation, and coastal reclamation in northern China [5,6]. The ecological degradation problems of the Bohai Sea are mainly within its coastal waters, especially those near the Liaodong Bay, Bohai Bay, and Laizhou Bay [7,8]. Therefore, since the "Action Plan for the Integrated Management of the Bohai Sea" jointly issued by the Ministry of Ecology and Environment, the National Development and Reform Commission, and the Ministry of Natural Resources in November 2018, the most stringent management and control of sea reclamation has been implemented in the Bohai Sea area in order to continually improve its coastal ecological functions and gradually restore its fishery resources.

In order to protect the fragile coastal ecosystem that has been severely affected by human activities and global climate change, recently, the assessment on the spatio-temporal evolution of coastal reclamation and its impacts on marine ecosystem has attracted the attention of marine management departments and has been studied from different perspectives in different regions. For example, Chu et al. [9] investigated how reclamation activities altered the coastal morphology and hydro-oceanography, resulting in the deterioration of the tidal flat in Lingding Bay. Bi et al. [10] showed that reclamation changed the natural properties of sea areas and coastlines with varying degrees of impacts on the health of coastal and marine ecosystems, including ocean hydrodynamic conditions, water quality, sediment environment, noise, food chain, biome structure, and diversity. However, the existing research on reclamation has focused on descriptive statistics and habitats affected (tidal flats, coastal sand dunes, freshwater bodies, sand reclaimed from the seabed, seagrass meadows, rocky reefs, etc.) [11], always considering the entire coastal regions as the research unit; thus, little attention has been paid to the spatial and temporal variation in ecological impact factors.

Research on reclamation change has employed a range of methods and approaches, including remote sensing (RS), geographic information system (GIS) mapping, and field surveys. For example, the remote sensing has been widely used to quantify coastal zone changes, and fine-resolution orbital sensors (e.g., Landsat and Sentinel) are very advantageous [12]. Most scientists use remote sensing images to extract coastlines (the boundary between land and sea) to simulate the coastal erosion-siltation process and the dynamic process of human reclamation development, which can then reveal the effects of the ecological and economic impacts of coastal reclamation [13,14]. Shen et al. [15] established an indicator system to investigate the cumulative impact of reclamation, so that the strategies of ecosystem-based management can be applied in the Bohai Sea of China. Nevertheless, research on cumulative impact of coastal reclamation characterized by spatio-temporal features in decades remain insufficient. The current study provides an integrated approach of the GIS technique and remotely sensed satellites data images for the objectives of coastal topography analysis and ecological impacts of coastal reclamation assessment. The spatial distribution characteristics of coastal reclamation were revealed, and their cumulative impacts on the ecological were investigated.

In this paper, studies were focused on the development process, cumulative ecological effects, and driving mechanism of reclamation in near coastal waters, and the conceptual framework is shown in Figure 1. The goals were: (1) to establish a method to define and identify the boundary of movable water bodies (MWBB) in coastal waters; (2) to draw a diagram of the spatio-temporal changes of near coastal reclamation in typical coastal waters; (3) to reveal the characteristics of the spatio-temporal changes of ecology with the coastal reclamation; and (4) to identify the driving forces of reclamation.

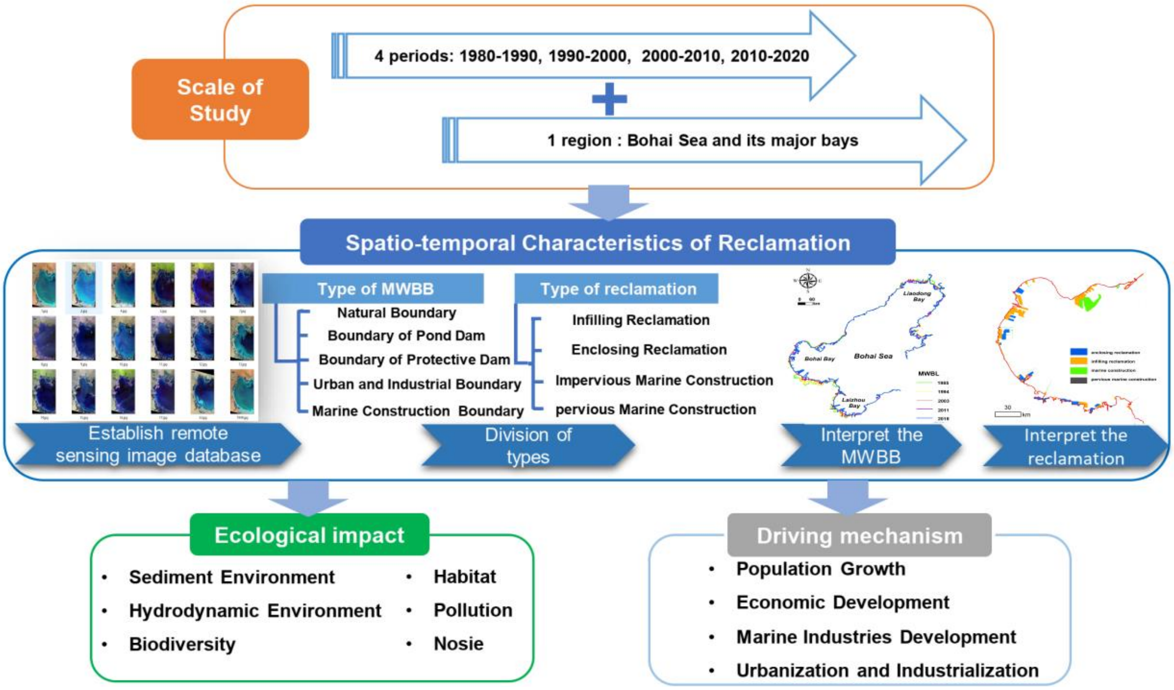

Figure 1. Conceptual framework of study.

2. Materials and Methods

2.1. Study Area

The Bohai Sea is a near-closed continental shelf in the Northwest Pacific between 37–41°N and 117–122°E and is separated from the Yellow Sea with a line between Laotieshanjiao on the Liaodong Peninsula and Penglaijiao on the Shandong Peninsula. Its sea area is approximately 77×10^3 km^2, with a coastline of close to 3800 km. It has several bays, including Liaodong Bay (the north of 40°N), Bohai Bay (the west of 118°E), and Laizhou Bay (the south of 37°N), as well as Central Bohai Sea and Bohai Strait. There are 13 cities along its coastline, namely Dalian, Yingkou, Panjin, Jinzhou, Huludao, Qinhuangdao, Tangshan, Cangzhou, Tianjin, Binzhou, Dongying, Weifang, and Yantai (Figure 2).

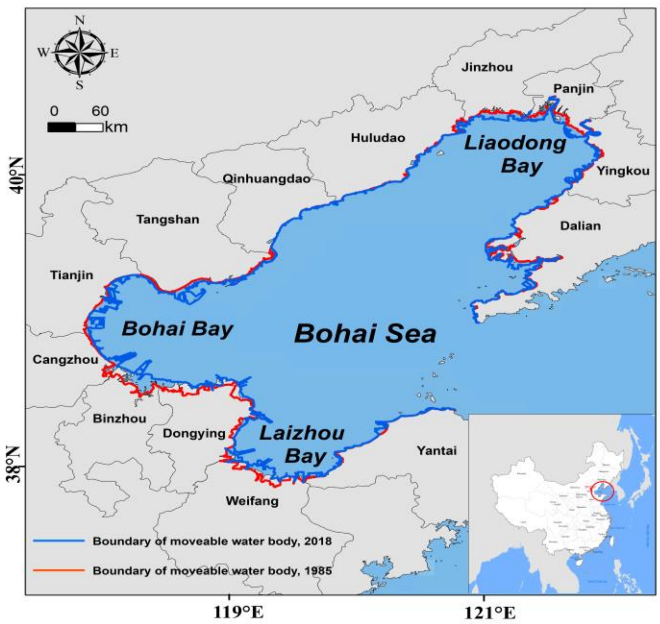

Figure 2. Location and change in boundary of movable water bodies of the study area.

2.2. Data Source

The data used in this study were obtained mainly from the following four resources: remote sensing images from the Landsat 5 satellite in June 1985, May 1994, and July 2003, as well as the Landsat 8 satellite in May 2011 and June 2018, with no or little cloud cover, were used to assess changes in the Bohai Sea's coastal reclamation (Table 1); the vector data, including data extracted from the geographic information system (the length of MWBB, reclamation area, and its utilization types); the statistical data from the China Marine Statistical Yearbook (1995–2018), the statistical yearbooks of Liaoning, Tianjin, Hebei, and Shandong (1998–2018) [16–19]; and Google Earth Pro 7.3 data as a geographic reference for correcting marine constructions such as ports, breakwaters, and cross-sea bridges.

Table 1. List of land satellite image data of Bohai Sea.

Region	Year	Image Sensor	Path/Row	
Bohai Sea	1985, 1994, 2003, 1998–2018	Landsat5 TM, Landsat8 OLI.	120/034, 122/033, 121/032, 120/033,	121/034, 121/033, 120/032, 119/033

2.3. Defining and Identifying Method of the MWBB

2.3.1. A New Definition of the 'Coastline'

The coastline is the boundary between the sea and the land, namely the outline of a coast [20]. In this study, the MWBB was defined as the solid boundary (for example, breakwaters, bridges, and artificial reefs) blocking the movement of the sea and destroying its connectivity at the intersection of land and sea. The main difference between coastline and MWBB is in their natural attributes. The natural attributes of land and sea, which are emphasized by traditional coastlines, are important indicators of ocean management. For example, in the sea surrounding the areas used for mariculture, the sea is still the sea, but it has changed from a naturally moving water body to a basically non-moving one, indicating that its physical and chemical properties have not changed, but its movement characteristics have changed. However, the hydrodynamics, as an important factor affecting the ecological health of the coastal water, is not reflected in the definition of traditional coastline. Therefore, studies based on traditional coastline changes cannot reveal the impact of human activities in the coastal water, which makes ocean management based on ecosystems impossible to implement. On the contrary, with the method of defining and extracting the spatial position of the MWBB in the coastal water, it takes into account whether the sea area reclamation has hydrodynamic conditions and seawater exchange capacity as the foundation to reveal the ecological effect and development of the reclamation and allows for the study of the marine ecological and environmental protection. In this paper, according to Suo et al.'s coastline extraction method, the spatial positions of the two lines were described under the same remote sensing image, and the two lines showed significant spatial heterogeneity, as in Laizhou Bay (from the Yellow River Mouth to Qimujiao), shown in Figure 3 [21].

2.3.2. The Method for Identifying the MWBB

On the basis of the knowledge of the morphological features, vegetation types, and the development and utilization status, we established the relationships between the remote sensing image shape, size, color or tone, shadow, location, structure, texture, and other features and the corresponding interpretation types. Then, the MWBB types were classified as bedrock, sandy, sand–powder silt, lagoon, estuary, pond, industrial and urban land, port, or marine construction through visual interpretation of the remote sensing images. The details are shown in Table 2.

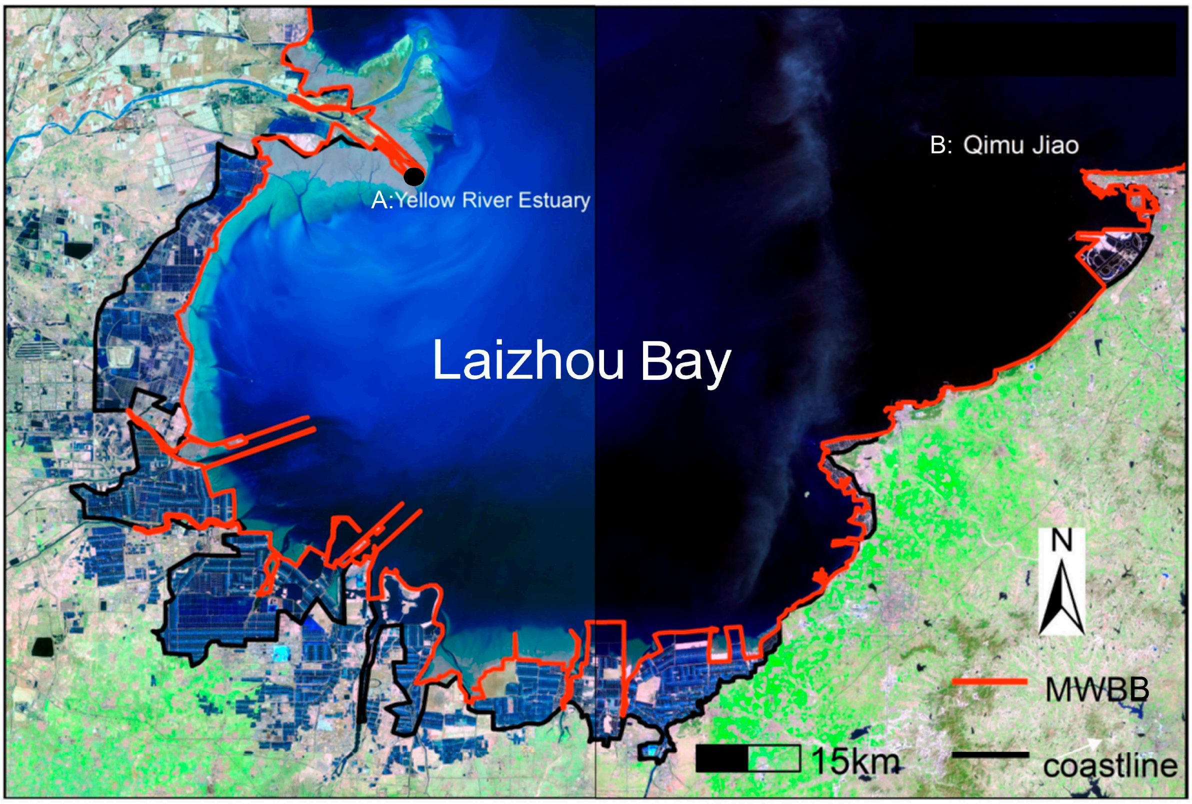

Figure 3. Comparison of positions of the MWBB and coastline in Laizhou Bay (from the Yellow River Mouth to Qimujiao).

Table 2. Boundary defining methods of MWBB with different utilization types.

Boundary Types of Movable Water Bodies		**Spatial Location**	**Remote Sensing Information (Fusion of Bands 3, 4, and 5)**
Natural boundary (including bedrock boundary and sandy boundary)		Trace line of direct meeting of land and water	Bedrock boundary: The remote sensing images have a high reflectivity white color tone and are surrounded by vegetation [21]. Sandy boundary: The reflection on remote sensing images of sandy gravel bank and beach, which are formed over time, is higher than that of other features, and their textures are white and uniform [22].
Reclamation boundary	Boundary of the pond dam	Boundary of the pond dam	If there are engineering facilities that protect salt pans, aquaculture ponds, and reservoirs, the aquaculture pond is dark blue on the remote sensing image, with uniform color, clear texture, flaky or striped distribution [22]; the salt field is uneven bright blue, with a clear texture, flaky distribution, and vegetation coverage; the boundary of reservoir is clear, with a gray dam.
	Boundary of protective dam	Contour line of the dam on the sea side	If there are engineering facilities and linear dams that protect the reclaimed land area, the land reclamation has uneven color and clear internal textures; the linear dams have clear and gray textures, with generally small widths, and are distributed in places where water and land meet directly.

Table 2. *Cont.*

Boundary Types of Movable Water Bodies		Spatial Location	Remote Sensing Information (Fusion of Bands 3, 4, and 5)
	Industrial and urban boundary	Contour line on the sea side	The boundaries are clear, including urban residential areas, industrial areas, and roads, with clear internal texture and uneven color, which is easy to identify on remote sensing images.
	Marine construction boundary	Extracted contour line on the sea side if there is a port wharf or an impervious offshore structure	The boundaries are clear and easy to identify, with ports and wharves, impervious offshore structures (breakwaters and submarine tunnels), and permeable marine structures (cross-sea bridges) included, which are distributed mainly near urban and industrial areas; offshore structures have blurred, gray textures that are mostly in strips and perpendicular to the land. On the basis of the projected images of the offshore buildings from Google Maps and the continuity of the water waves on both sides, the water permeability is identified.

2.4. Ecological Cumulative Impact Assessment Model of Reclamation

2.4.1. Assessing System

Local extent and effects of coastal reclamation projects are increasingly reported, which supports our judgment of the strength of the impact intensity and looks more holistically at impacts of coastal reclamation on spatio-temporal scales through large-scale survey work to interpret these impacts (Table 3). Based on the supporting data of Table 3, the reclamation can change the original seabed topography, affect the tidal capacity of the bay, and alter sediment dynamics [23]. If habitat is destroyed, biodiversity decreases. The same holds true for pollution. For example, a port area would collect a large amount of oily wastewater discharge from ships docking in it. These pollutants will aggravate the seawater eutrophication, reducing biodiversity. In this study, according to the 6 aspects of reclamation effects on the ecosystem of the near coastal water (sedimentation environment, hydrodynamic conditions, biodiversity, habitat, pollution, and noise), a systematical assessment system was established (Figure 4).

In this system, the impact intensity and attenuation distance were used to reflect the difference in the impact of different reclamation types. If the ecological impact was great, the impact intensity was set to 1. If the ecological impact was moderate, the impact intensity was set to 0.5. The impact intensity with limited ecological impact was set to 0 [24]. The ecological impact assessment grade is divided using the equal interval breakpoint method. The values '0', '0.5', and '1' represent high, medium, and low impact, respectively.

The reclamation through infilling, with an engineering process similar to that of impervious marine construction, will change the natural properties of the ocean significantly, such as changing the sedimentary environment and hydrodynamic conditions, encroaching on the biological habitats, destroying the marine biodiversity, and generating noise and pollutants during the construction and development. However, the area of impervious marine construction is usually very small, and it has a high impact only on the sedimentary environment through noise pollution [15,25]. The enclosing reclamation and pervious marine constructions (dams or buildings in the reclaimed area) can partially change the natural properties of the ocean, and the enclosing reclamation has a high impact on the hydrodynamic conditions, marine biodiversity, and pollutant emission. Most pervious marine constructions are cross-sea bridges. During their construction and usage, pollutants can be produced which threaten the biodiversity [5]. Additionally, noise pollution caused by shipping activity in ports and marinas showed the greatest extent of modification. Compared with ports, the noise pollution caused mainly by vehicles on the road, bridges, industries, and urban areas, is relatively weak compared with ports and marinas [26].

Therefore, in this study, the cumulative ecological impact values of infilling reclamation, enclosing reclamation, impervious marine construction, and pervious marine construction were set as 6.0, 4.5, 4.0, and 1.4, respectively (Figure 4).

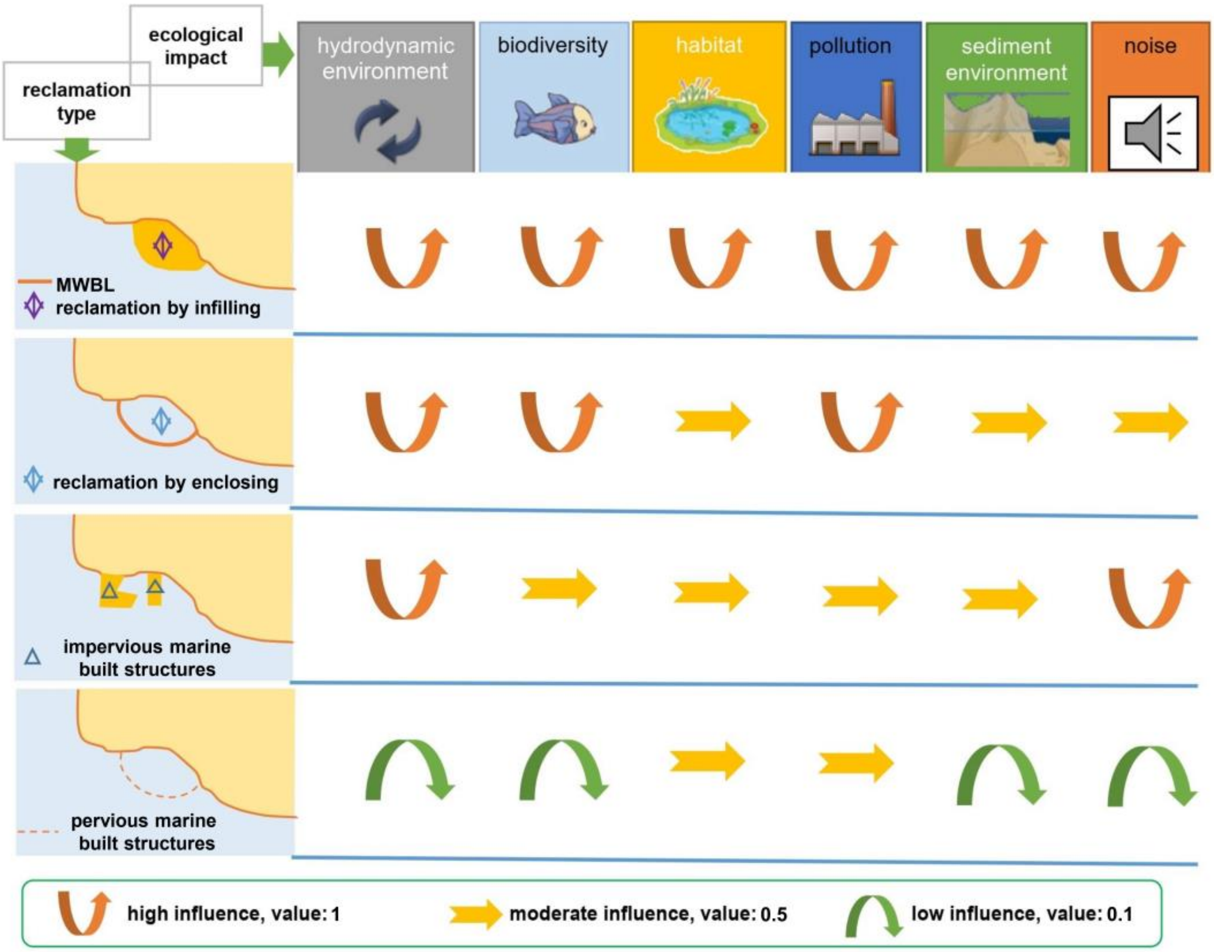

Figure 4. Assessment system of impacts of different reclamation types on the coastal ecosystem.

Table 3. Supporting data for the reclamation impact intensity on the ecosystem.

Reclamation Types	Evaluation and Survey Work of the Researcher
Infilling reclamation (e.g., industrial and urban area)	1. Shifts in the spatial extent, configuration, and dynamics of natural habitats by altering sediment dynamics and geomorphic connectivity [26]. 2. Permanent change of the geomorphology of the coastal line and the physical processes of the coastal system [27]. 3. Production of pollutants from ports and factories as well as nutrients and pesticides from croplands, resulting in deterioration of inshore and oceanic environments and severely reduced biodiversity [11]. 4. Habitat loss and sediment burial [28]. 5. Sediment dynamics and hydrodynamics were weakened [15]. 6. Destruction of habitats for fish; reduced water purification ability from narrowing and even disappearance of gulf and bay area, increased water pollution, and frequent harmful algal blooms [29]. 7. Shrinking of the tidal mudfats; loss of marine habitat; reduction of the adaptive capacity of shoreline ecological communities to sea level rise [10].

Table 3. *Cont.*

Reclamation Types	Evaluation and Survey Work of the Researcher
Enclosing reclamation (e.g., pond)	8. Same as article 6. 9. Same as article 7. 10. Production of pollutants from ponds and chemicals, such as antibiotics, resulting in deterioration of inshore and oceanic environments [29]. 11. Modification of flows of energy and materials [30]. 12. In mariculture ponds, large number of residual bait, dead fish, and shrimp would sink to the bottom of the ponds, and high-concentration organic wastes would be discharged into the surrounding water bodies [31].
Marine construction (e.g., harbor, seawall, bridge)	13. Same as article 4. 14. Port area would collect discharge large amount of oily wastewater from ships docking in [32]. 15. Noise pollution caused by shipping activity in ports and marinas showed the greatest extent of modification, affecting seascapes at regional scales [32]. 16. Physical barriers to the movement of organisms, materials, and/or energy within and among habitats [31]. 17. The hydrodynamic is significantly modified by a bridge piling [32].

2.4.2. Spatial Mapping

Previously, it was reported that coastal reclamation and development affected the occupied and the adjacent areas, with a gradual attenuation of the RCEI when the distance from the reclamation area was increased. In this study, an inverted "S"-shaped attenuation function was used, and the attenuation effect was applied to the spatial mapping [33].

Typically, steps in the mapping were: with human–computer interaction recognition as the method and the interpretation signs as reference, the different utilizations of coastal reclamation was interpreted to obtain the vector data and to determine the size of the unit according to the pixel size and the area of the evaluation area. In this study, the remote sensing data in pixel was 30 m × 30 m, the area of the Bohai Sea in 2018 was 82,404 km^2, and the unit size should meet the demand of spatial heterogeneity with sufficient area and pixel number. With the "Fishnet" tool in ArcGIS, a 3 km × 3 km cell grid was generated; thus, the Bohai Sea had 9156 cell points, and the cell size met the demand for spatial heterogeneity [34].

With the "Euclidean Distance", the distances from the 4 types of reclamation utilization to all unit points on the adjacent sea area were determined. The influence of the attenuation distance was determined according to the established attenuation formula (Formulas (1) and (2))—a theoretical model in which the ecological impact exhibits an inverted "S"-shaped attenuation as the distance increases. The attenuation effect of the RCEI on coastal waters is expressed by (x, y), and the spatial mapping is carried out. Additionally, the (x, y) was calculated by simple averaging of each of the 4 reclamation utilization's RCEI and calculated following the formula below [35].

$$f_k(x,\ y) = \frac{P_k}{1 + D_k(x,\ y)/\mathrm{w}} \tag{1}$$

$$I(x,\ y) = 0.25 \sum_{k=1}^{4} f_k(x,\ y) \tag{2}$$

where P_k is the upper limit reference value of ecological impact of the k-th type of reclamation. $D_k(x, y)$ represents the Euclidean distance from any point (x, y) in the sea to the area where the k-th reclamation type is located, w is the half-attenuation coefficient that is set to 20 km uniformly after repeated attempts, and $I(x, y)$ is the cumulative ecological impact value.

In order to realize the spatial heterogeneity expression of the RCEI, "Kriging" was used to spatially interpolate the cumulative ecological impact values of all unit points, and the cumulative ecological impact grade (I) was divided according to the equal interval breakpoint method, including low impact ($0 \leq I < 2$), moderate impact ($2 \leq I < 4$), and high impact ($I \geq 4$).

2.5. Analysis of Driving Factors of Reclamation

It is well known that the Structural Equation Modeling (SEM) is a widely used statistical analysis model. In this model, through the analyses on direct and indirect relationships between/among variables and on variables that cannot be directly measured (latent variables), the interaction strength of multiple variables and the influence transmission path can be better determined, which can effectively overcome the shortcomings of traditional statistical methods. Therefore, this model has significant application importance in biology, ecology, social sciences, education, economics, management, and other fields [36]. Meanwhile, Path Analysis (PA) is one of the main SEM models that is still currently in use. As an application model of SEM without latent variables, it tests the significance of the relationship between/among variables, and the positive and negative signs of Pearson's coefficient (r) represent the positive and negative correlations, respectively.

In the past four decades, the need for economic development and agricultural requirements have been the primary drivers cited for coastal reclamation projects, such as urban construction, port construction, oil extraction, fishery production, and saltern reclamation, in many of the coastal cities in the Bohai Sea [3,22]. Additionally, the rising human population in the coastal cities is also driving coastal expansion [37]. On the basis of the preceding description, the PA was used to construct a complex relationship between the cumulative reclamation area and the driving factors, including economy, population, marine industry, and urban and industrialization degree. The expected model of causal factors upfront is shown in Figure 5. The economic development is composed of two variables: GDP of primary industry and GDP of secondary industry. Population growth is composed of two variables: population growth rate and urbanization degree. Economic development and population growth on accelerating coastal reclamation were regarded as the most relevant indicators of accelerating coastal reclamation [37]. Given the more local land use of reclamation in the present stage, some of the reclaimed areas are used for mariculture pond, but most of them are used for ports and industrial areas, so the cargo throughput of major ports and the mariculture production were elected as access to provide for the relationship between marine industry development and reclamation [33].

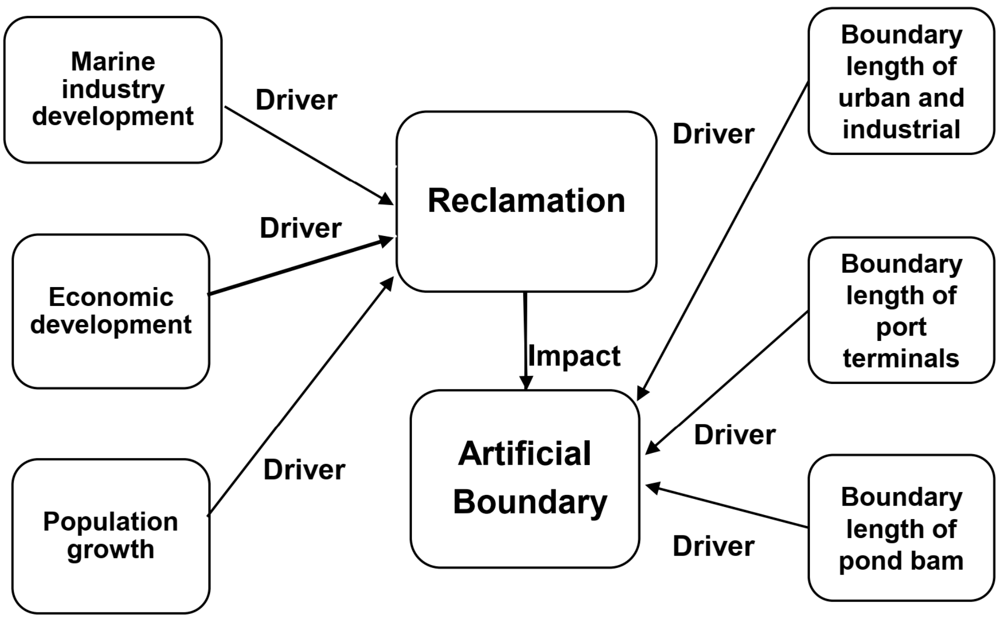

Figure 5. The expected model of causal factors upfront.

3. Results

3.1. Spatio-Temporal Characteristics of Reclamation

3.1.1. Changes in the MWBB in Near Coastal Waters

During the past 40 years, the reclaiming of the Bohai Sea has already resulted in significant spatio-temporal changes of MWBB. Marine constructions, such as ports and wharves, are bulging along the coast and extending rapidly toward the ocean, and the boundaries tend to be complex. This phenomenon is particularly obvious in Laizhou Bay, Bohai Bay, and Liaodong Bay (Figure 6).

As shown in Figure 7, in the 1980s, the MWBB was mainly natural landforms, such as bedrock, beaches, and estuaries, accounting for 74.5% of the total length of the Bohai Sea (1985). Marine aquaculture was the main development activity near the Bohai Sea, and its pond dams accounted for 21% of its boundary. In the 1990s, the types of Bohai Sea boundaries began to diversify. The length and proportion of the urban and industrial boundary and protective dams increased significantly, and the increase in the pond dams was the most significant, which jumped from 21% to 44%. Since the 21st century, the urbanization and industrialization in the coastal areas of the Bohai Sea has been accelerated, leading to a decline in the ratio of natural boundaries of the Bohai Sea to 27.4% in 2018. The proportions of urban and industrial, marine construction, and protective dam boundaries were increased, respectively, from 4.1%, 5.2%, and 2.8% in 2003 to 10.4%, 14.7%, and 12.6% in 2018.

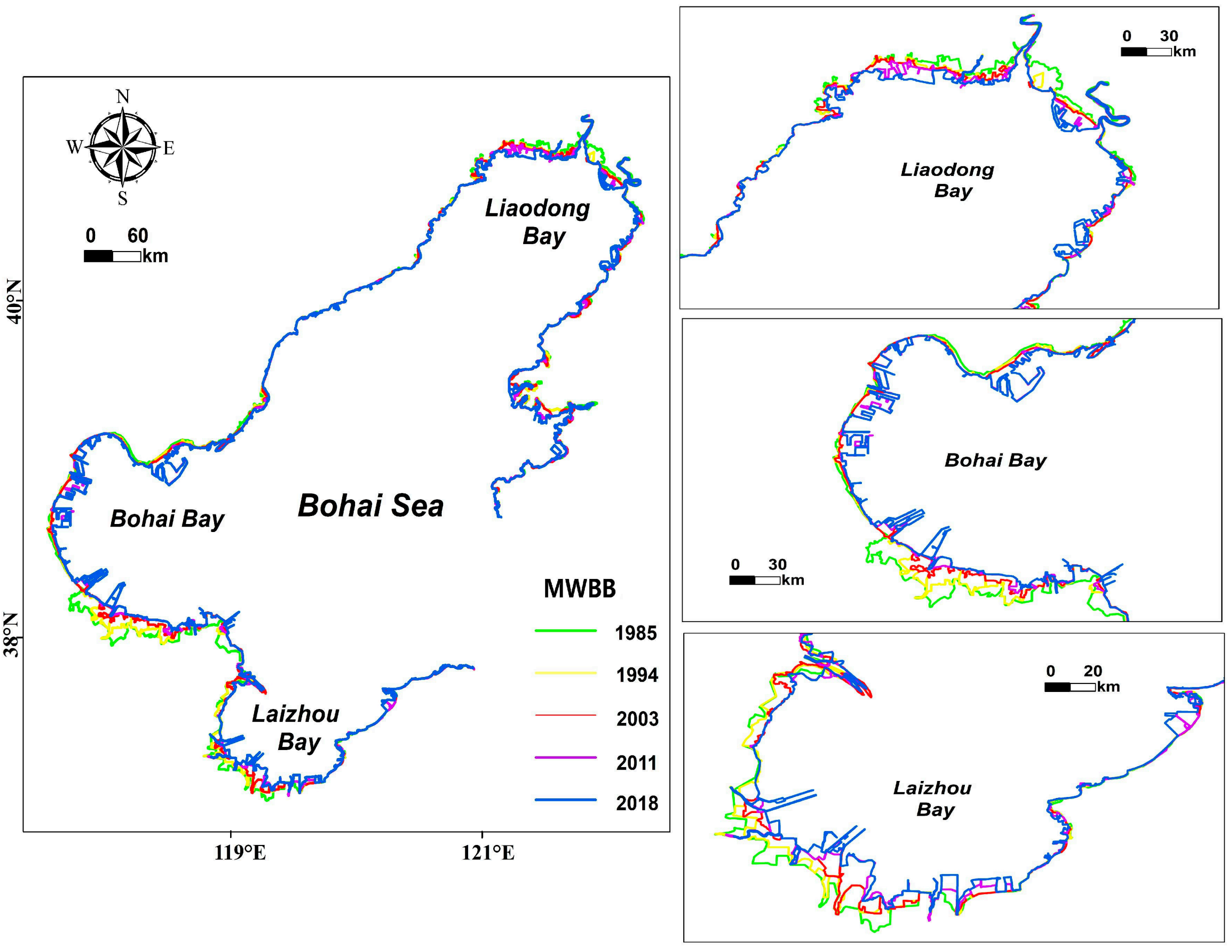

Figure 6. Spatio-temporal changes of the MWBB in the Bohai Sea.

3.1.2. Changes in Reclamation

Four development periods of Bohai Sea reclamation are shown in Figure 8a. The first period (1985–1994) was the rise of large-scale reclamation activities in the aquaculture and salt industries, which was most significant in Bohai Bay and Laizhou Bay. In the second period (1994–2003), reclamation activities were converged to some degree, because the reclamation in the first period occupied many large and small bays, and its "cutting and straightening" of the MWBB drove the limited development space close to its saturation. The third period (2003–2011) was the peak of reclamation activities. Coastal projects such as ports, wharves, and cross-sea bridges bulged along the coast, and large-scale industrial areas from reclamation settled down and were scattered in the Bohai Sea. The fourth period (2011–2018) was one of strict management and control of reclamation, and the area of newly built offshore construction was reduced. For example, according to statistics, from 1985 to 2018, the cumulative increase of reclamation area in the Bohai Sea was 5839.5 km^2, which was equivalent to half the area of Tianjin, the continuous growth rate was 3.3% per year, and 55% of the Bohai Sea reclamation could be attributed to aquaculture field and salt field. From 2003 to 2018, the area of impervious marine constructions jumped from 0.9% to 9.2%, especially for the port and wharf, which accounted for 5.8% (Figure 8b).

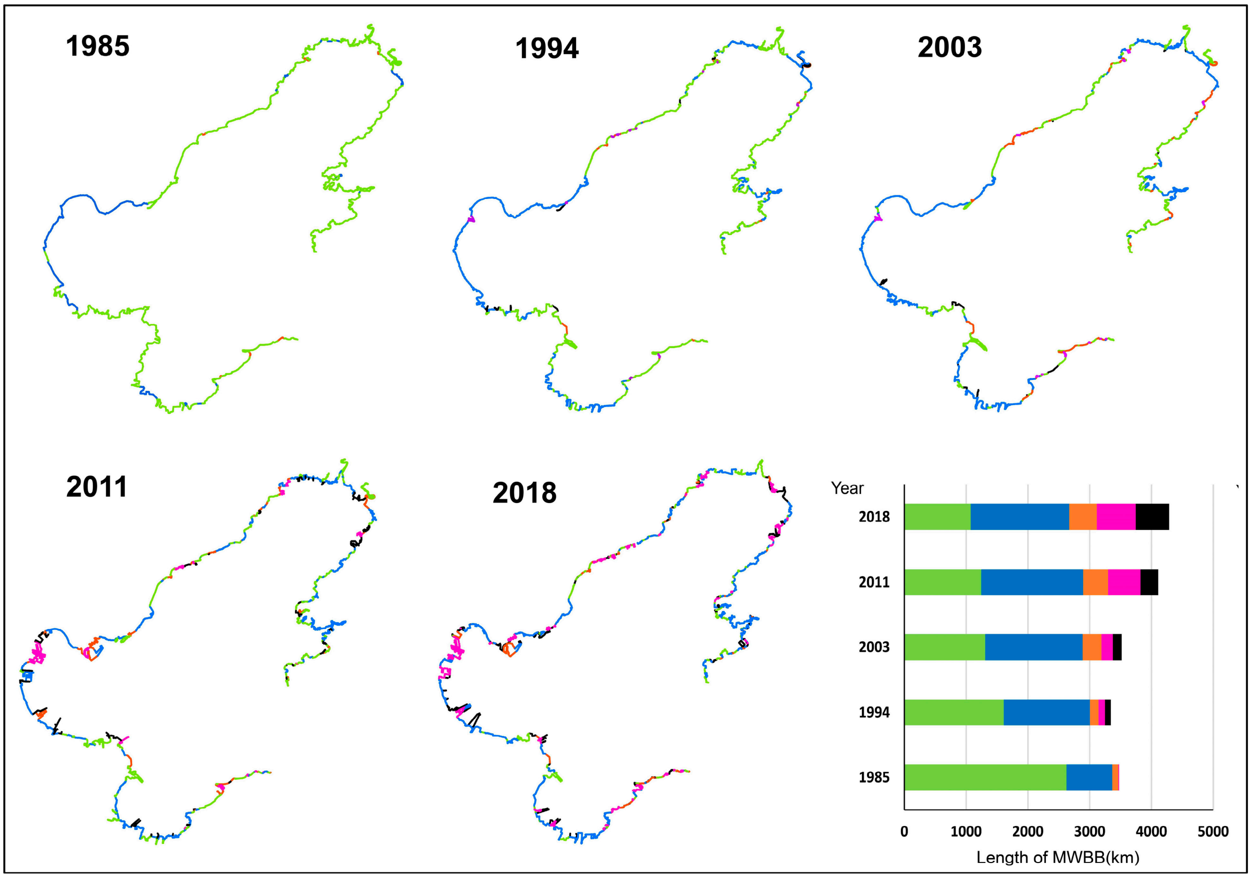

Figure 7. Spatio-temporal changes of the boundary types of the Bohai Sea in Phase 5. Green, blue, orange, red, and black denote the natural boundary, pond dam, industrial and urban area, marine construction, and protective dam, respectively.

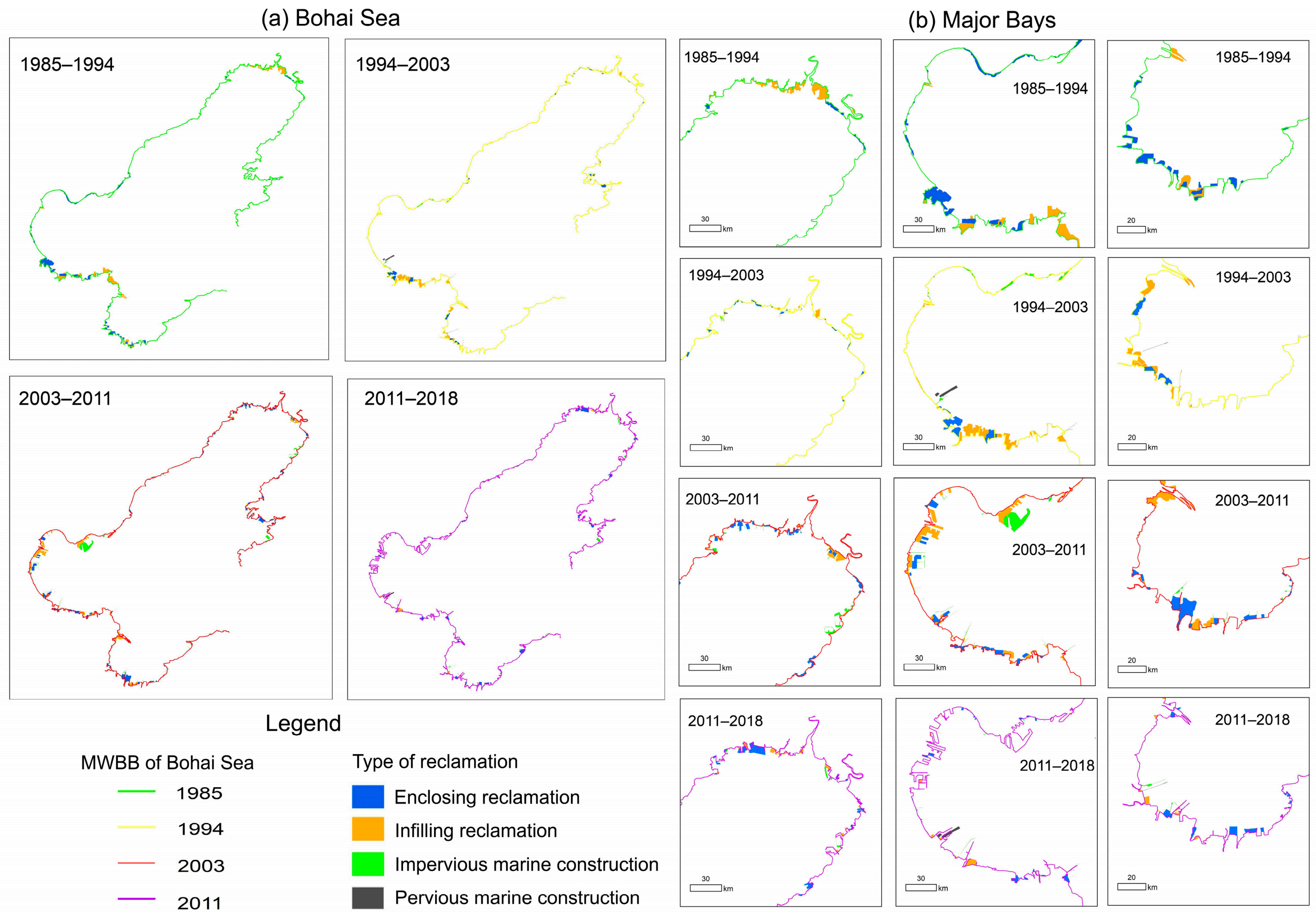

Figure 8. The development process of reclamation in the Bohai Sea.

3.2. Assessment on the RCEI

3.2.1. Evaluation Results

The RCEI scores in the Bohai Sea in 1994, 2003, 2011, and 2018 were 1.3, 1.6, 2.0, and 2.2, respectively, which exhibited a continual increase. The ecological impact level changed from low impact in 1994 and 2003 to moderate impact in 2011 and 2018. The spatial distributions of RCEI changed greatly from 1985 to 2018. In 1985, the proportions of the moderate and high impact zones were all lower than 6% and were distributed mainly in the coastal water of the Laizhou Bay and Bohai Bay. In 2018, the moderate impact zone surrounded the high impact zone, with a proportion of 22.3%. According to RCEI's contribution and the proportion of reclaimed area caused by various utilization methods in the Bohai Sea from 1985 to 2018 (Figure 9b), it was found that the completed impervious marine constructions (mainly ports and seawalls) and pervious marine constructions (cross-sea bridges) accounted for only 9.1% and 0.9% of the total reclaimed area within the Bohai Sea, whereas they had contributions of 24.4% and 4.3% of their RCEI; therefore, they were the main factors that caused the Bohai Sea's RCEI to jump from a low impact (1.3) to a moderate impact (2.2) in 2018.

3.2.2. Evaluation and Verification Results

In this study, the RCEI assessment results of the studied area were compared with the distribution diagram of the water quality status of the seas under China's jurisdiction from the China Ecological and Environmental Status Bulletin and the global marine health score published by Halpern et al. [38] over the same period. According to the 2018 China Marine Ecological Environment Bulletin, the area in the Bohai Sea that did not meet the first-class seawater quality standard in 2019 was 21.6 × 10^3 km^2, with an equivalent reclamation area of 17.4 $\times$ 10^3 km^2 having a high ecological cumulative impact, indicating that reclamation and pollution were the two most important ecological pressures in the Bohai Sea. According to the comparison of spatial distribution, the significantly affected areas in the Bohai Sea in 2018 and the areas with inferior Grade IV water quality distribution under China's jurisdiction in the summer of 2018 showed that both of them were concentrated in the main bays (Laizhou Bay, Bohai Bay, and Liaodong Bay). However, their spatial locations were heterogeneous. The significantly affected areas were concentrated in reclamation areas and ports, and the areas with inferior Grade IV water quality were concentrated in the sea entrance [12,19]. According to the global ocean health distribution map from Halpern in 2012, the scores of the Bohai Sea were relatively low at 30–40. Because the lower score means worse ocean health, the ocean health in the studied area was of low quality. With the method established in this study, the calculated cumulative ecological impact values of reclamation in the Bohai Sea from 1985 to 2011 was 47.9. Because the higher score indicates a larger marine ecological impact, these results showed that the ecological health of the Bohai Sea was of low quality.

3.3. Analysis on the Driving Mechanism of Reclamation

According to the PC-based analysis model of driving factors of reclamation (Figure 10), in Bohai Bay (the coastal water of Tianjin, Tangshan, and Cangzhou), the GDP of secondary industry, its cargo throughput of major ports, the boundary length of urban and industrial, and the boundary length of pond all showed a positive influence relationship with the cumulative reclamation area, and their path coefficients were 0.616, 0.282, 0.742, and 0.324, respectively. In the coastal waters of Laizhou Bay, the GDP of secondary industry, its urbanization degree, and the boundary length of ports terminals all showed a positive relationship with the cumulative reclamation area as well. Their path coefficients were 0.237, 0.279, and 0.673, respectively. These findings indicated that the spatio-temporal changes in Bohai Bay reclamation were caused by the combined effects of economic development, and marine industry development, whereas the spatio-temporal changes in Laizhou Bay reclamation were caused by the combined effects of economic development, urbanization, and marine industry development.

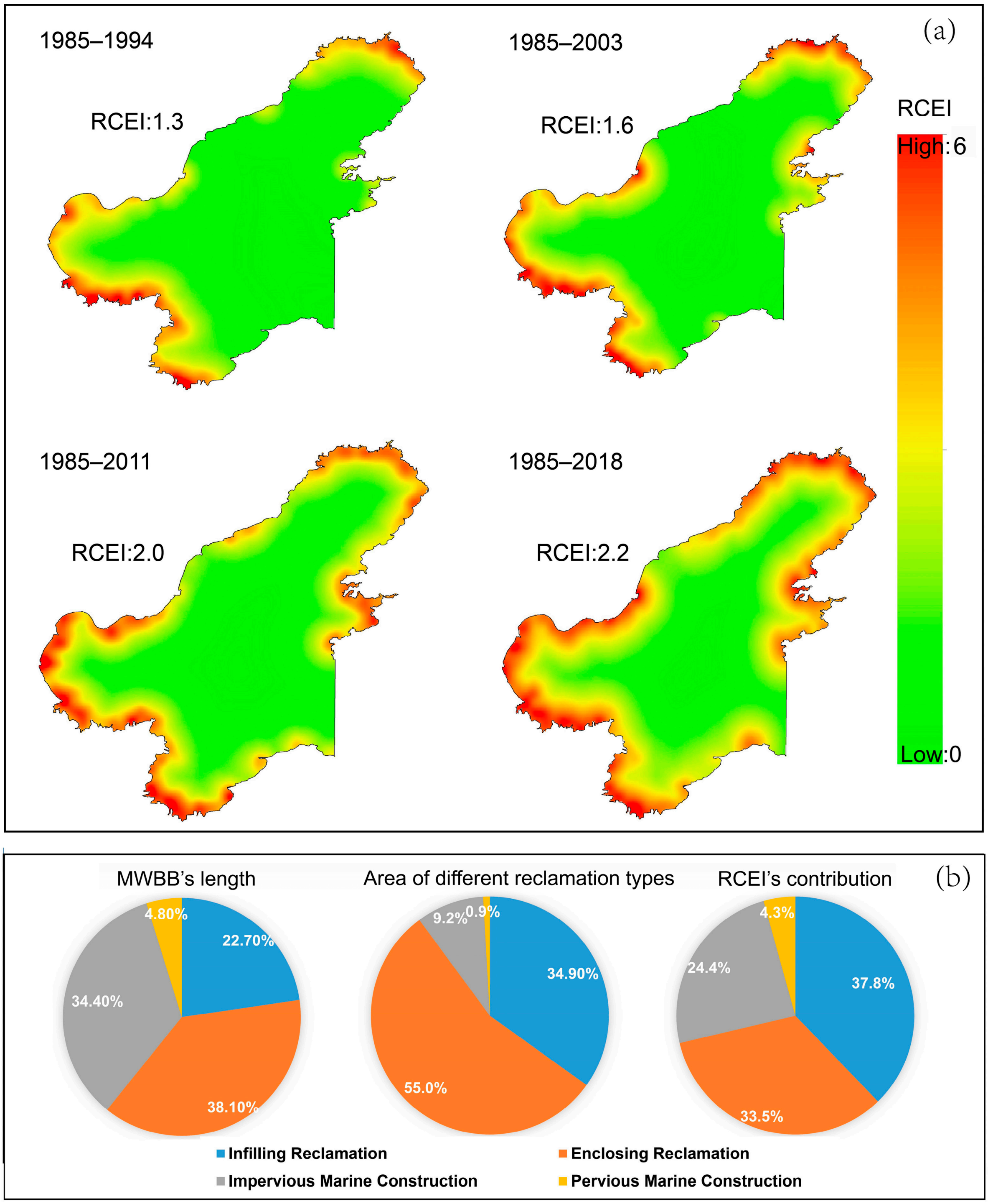

Figure 9. Spatio-temporal changes of the RCEI in the Bohai Sea (**a**) and the ratio of MWBB's length, RCEI' s contribution, and the area of different reclamation types (**b**).

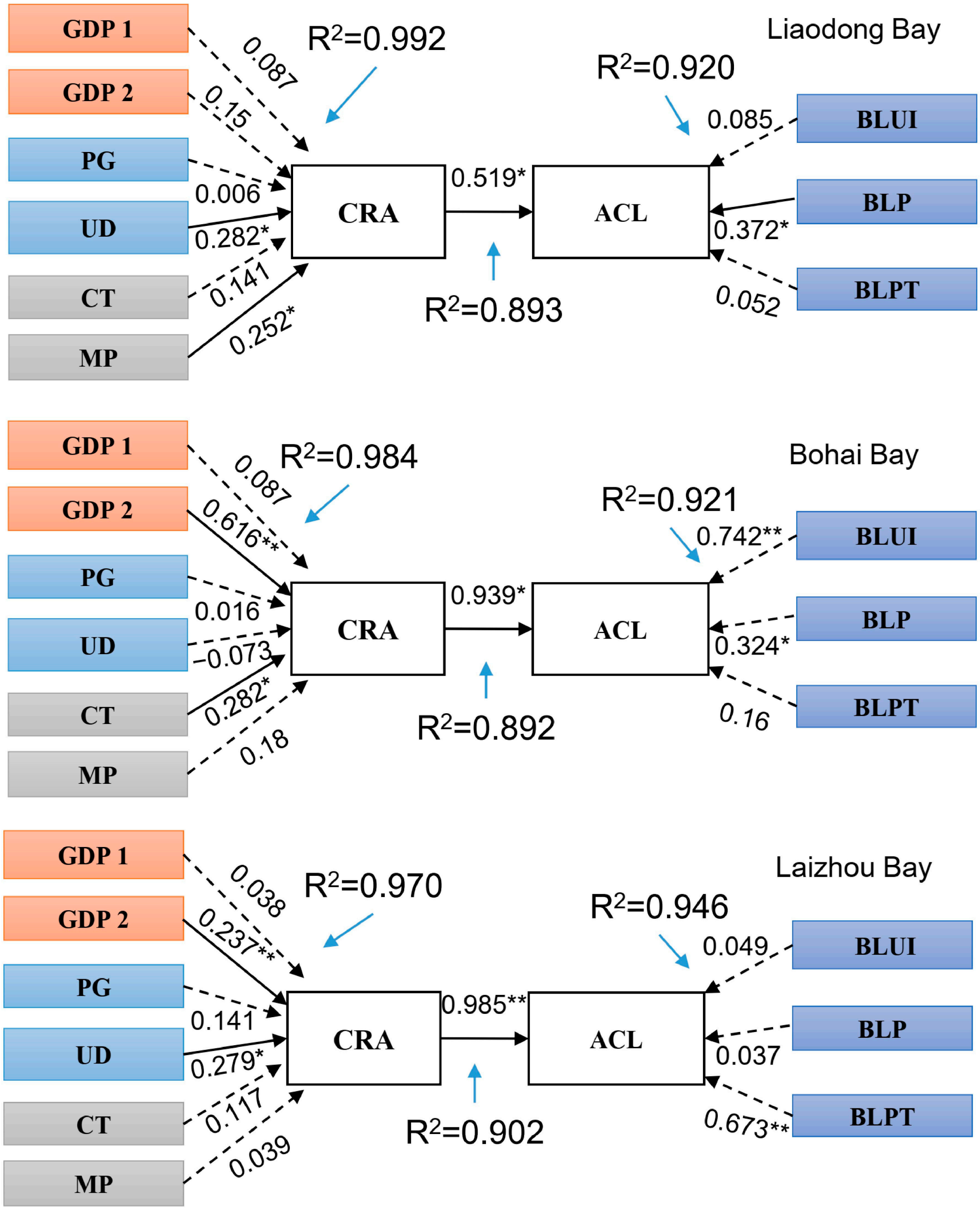

Figure 10. PC-based analysis model of driving factors of reclamation. Numbers show the standardized coefficients. Solid line indicate that the effect is significant, dotted line indicate that the effect is insignificant. The R^2 values for all the equations were high and ranged between 0.892 and 0.992, which indicate good performance. (Note: GDP1—GDP of primary industry, GDP2—GDP of secondary industry, PG—population growth rate, UD—urbanization degree, CT—cargo throughput of major ports, MP—mariculture production, BLUI—the boundary length of urban and industrial, BLPT—the boundary length of port terminals, and BLP—the boundary length of pond). * $p < 0.05$, ** $p < 0.01$.

4. Discussion

4.1. Uncertainty of RCEI

4.1.1. The Applicability and Limitation of Model

With the established model, the RCEI can be simulated with the consideration of the historical cumulative effects of reclamation on the coastal ecosystem and the influence degree of different reclamation utilization types. Through the attenuation function, the spatial heterogeneity was revealed to show the ecological impact of human activities on different locations in the coastal water. As the distance increases, the cumulative impact of reclamation development on the marine ecology gradually decreased, which was the marginal effect of the cumulative impact.

RCEI was established in our study. The features of RCEI are as follows: fixed values of different reclamation types were determined by their ecological influence characteristics (Figure 4); an inverted "S"-shaped attenuation effect was considered to represent the ecological impact of reclamation area on adjacent areas. Because the connectivity of marine ecosystems is much better than that of land—whereas roads, residential areas and cities on land often interfere with terrestrial ecological impact assessment—the assumption that the cumulative impact decayed with the distance in the RCEI study here is reasonable [39]. The reclamation types and their RCEI in the Bohai Sea indicated that the distribution of reclamation exhibited specific characteristics in different periods. Between 1985 to 2003, the reclaimed types were mainly enclosing reclamation (e.g., pond and salt pan), and the ecological impact of reclamation was concentrated as low and moderate impact. After 2003, as the proportion of harbor and seawall increased, the area designated as high and medium impact grew at the cost of low impact (Figure 8).

The RCEI model may have some limitations that need to be improved in future studies. First, because of the hydrodynamic environment of the sea, the sediment environment, noise, pollution, biological habitat, and diversity were focused on, and the ecological impact on other aspects, such as storm surges and floods, ecosystem services, and values, was not considered. Due to a lack of pertinent data, it is challenging to accurately gauge the spatial-temporal distribution and frequency of ecological disasters. Second, the attenuation of RCEI is affected not only by the distance, but also is related to the hydrodynamic conditions of the sea area. The authors used a two-dimensional tidal model to calculate the amplitude, phase lag, and tidal current in M_2 spatial simulations in the Bohai Sea [22]. However, the simulated object was a single hydrodynamic factor, and little attention was paid to the spatial simulation of the ecologically integrated condition. Taking all these factors into consideration, this study used a fixed value of the ecological impact intensity parameter for every reclamation type to evaluate the RCEI in coastal waters. The ecological impact assessment based on the six indexes has a close relationship with the reclamation type in the study areas.

4.1.2. Model Sensitivity

In the simulation of the RCEI spatial distribution (Figure 9), it was found that RCEI was highly sensitive to marine constructions. For example, if a port with a width of 1 km and a length of 3 km was built in a sea area with a good ecological environment, which was perpendicular to the MWBB, the surrounding sea area with 9.6 km^2 could become significantly affected because the ocean has good ecological connectivity [31]. Therefore, the impact of marine constructions on ecological connectivity could be reduced through minimizing the length of buildings and reducing their distances from land. Additionally, even though remote sensing data have produced a high-precision image of the RCEI and marine structures on the spatio-temporal scales, long-term studies are still necessary to determine the precise effects of artificial structures on ocean connection.

4.1.3. Sources of Model Uncertainty

The uncertainty of ecological cumulative impact assessment comes mainly from the assessment system and data [40]. On the one hand, the establishment of this evaluation system was based on widely reported results, which were described in the Sections 1 and 2.4.1. On the other hand, the data uncertainty refers to errors caused by observation and processing: first, remote sensing images cannot capture the benthic structure of the optical deep water area, and the area covered by the structures submerged by the sea cannot be tracked in the observation of the coastal reclamation and its marine constructions; and second, the application of the attenuation function to the numerical simulation will inevitably cause differences from the actual ecological cumulative impact. For example, the half attenuation coefficient may be different in different sea areas, and the use of a unified coefficient in this article will inevitably cause errors.

4.2. Economy and Urbanization Drivers

Up to present, most of the studies were based on descriptive work simply to infer the driving factors of reclamation and compare the relationships among humanistic and social factors and reclamation activities [41], whereby further experiments were needed to quantify the relative importance of different driving factors and reveal their quantitative response relationships [42]. In a survey on the area of reclamation, it was found that only indicators related to the marine industry were positively correlated with the area of reclamation, such as marine industry employees, marine industry GDP, the added value of marine oil and gas, the added value of marine chemicals, etc. [38]. Wang et al. [13] showed that reclamation expansion is strongly associated with socioeconomic variables, such as GDP, population, and urbanization level. As a result, a variety of socioeconomic factors influence coastal reclamation. The path analysis is capable of exploring the driving forces of reclamation projects using varying regression equations, and the findings showed that cargo throughput and mariculture production in the Bohai Sea is also driving coastal expansion.

4.3. Management Implications

4.3.1. Industrial Development

The Circum-Bohai-Sea is not only one of the most important economic zones in China, but also an early developed area. However, its limited land supply has led to insufficient space for its urban expansion, especially in the Bohai Bay and Laizhou Bay with silty, sandy shoals and low-level terrain. In order to obtain expanded space for further urban and industry development, intensive reclamation projects have taken place there (Figure 7). Since 1985, two large-scale reclamation activities have also occurred and led to the industrial development of cities around the Bohai Sea. In the 1980s–1990s, the reclamation area was focused on the development of agriculture and fishing. After the 21st century, the reclamation activities were shifted to aquaculture, urbanization, and industrialization, and various port terminals and coastal industries were continually settled in the coastal water of the Bohai Sea. According to statistics, from 1998 to 2018, the cargo throughput of the main ports of the Bohai Sea was increased by 11.6 times, and the aquaculture production was increased by 3.3 times. Although the high-intensity development and utilization of coastal resources has promoted the development of industrial economy significantly, the coastal cities of the Bohai Sea are facing serious homogeneity problems in the current development stage, as ports and docks, port industries, ponds, and salt fields have been settled and dispersed in 13 coastal cities; the development and utilization methods of Bohai Bay and Laizhou Bay are very similar (Figure 11). In order to avoid the vicious competition in regional industries, idle resources, and resource waste, a mechanism for efficient and intensive use of reclaimed land resources should be established because only scientific and reasonable reclamation activities could meet the efficient development of regional port terminals and port industries, while providing enough space for agriculture breeding and salt production.

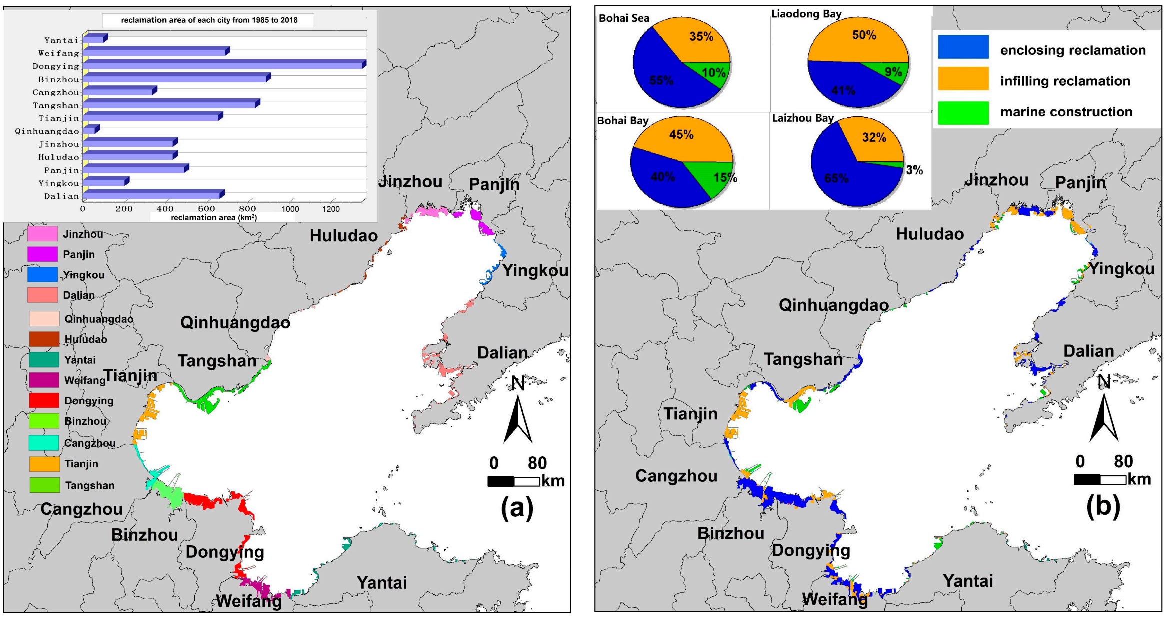

Figure 11. Reclamation area (**a**) and its utilization types (**b**) of 13 coastal cities from 1985 to 2018.

Currently, the economy of coastal waters of the Bohai Sea is developing rapidly with continual gathering of population, finance, and logistics to the sea, and the coastal ecosystem is facing severe challenges (Figure 9). Therefore, we suggest focusing on economizing the sea utilization, scientifically planning the layout of marine industries and the use of marine space, learning from the development experience of other coastal areas in China, giving full play to late-comer advantages, and promoting leaping development.

4.3.2. Ecological Protection Suggestions

Since the 21st century, the RCEI in the Bohai Sea has risen from low to moderate. In fact, the ecological impact of reclamation was concentrated generally in the main bays of the Bohai Sea. The RCEI varied greatly depending on the stage of reclamation and was exacerbated by the cumulative effect of the four stages of reclamation (Figure 9). In particular, in Bohai Bay and Laizhou Bay, with severely damaged biological communities, comprehensive measures should be used for both the restoration and protection of coastal wetland and marine biodiversity [15]. In addition, the implementation of the most stringent management of coastal reclamation, the implementation of the Bohai Sea environmental protection project with land and sea coordination, river and sea considerations, and the restoration of damaged habitats, should be carried out to gradually restore and improve the resource and environmental carrying capacity of Bohai Sea.

In order to mitigate the threat of storms and sea level rise caused by global climate change [43,44], humans have implemented synthetic engineering structures, such as sea dikes, breakwaters, and spur dams, leading to an increase in the proportion of the boundary length of the protective dams in the Bohai Sea of 7.8% from 2003 to 2018. However, in the process of constructing these marine constructions, the natural ecosystems, including grasses, trees and biological communities of the ocean and land, were destroyed, and the potential loss of ecological benefits was difficult to estimate. In order to reduce this conflict, engineering measures based on marine ecology could be used. For example, the planting and restoration of salt marshes, shellfish or coral reefs can be considered as an adaptation strategy to cope with sea level rise and storm surges and to support the restoration of multiple ecological functions, including carbon sequestration, provision of habitat, and maintenance of clean air and water [45].

5. Conclusions

Reclamation activities could directly change the hydrodynamic conditions and seawater exchange capacity of the coastal waters, resulting in natural movement of the water body instead of simple changes in the coastline. We proposed a method for identifying the extent of existing coastal reclamation, and the RCEI were established on the basis of the ecological influence characteristics of different reclamation types and their attenuation effect on adjacent areas. Results showed that reclamation had taken place in approximately 5800 km^2 of natural sea areas from 1985 to 2018. The RCEI score of the Bohai Sea in 2018 was 2.2 out of 6.0, indicating a moderate impact. The expansion of coastal projects, such as ports and wharves, was the main contributor to the increase in the RCEI. Additionally, the spatial distribution characteristics revealed that the RCEI in the offshore areas was much higher, with denser and more highly impacted areas than that in the open seas, and the intensity of the impact decreased from the offshore area to the open sea. Moreover, some local areas were significantly affected by the RCEI, especially in major bays such as the Laizhou Bay and the Bohai Bay.

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Data Availability Statement: The satellite altimeter data used in our study can be downloaded from the Radar Altimeter Database System (http://rads.tudelft.nl/rads/rads.shtml (last accessed on: 1 May 2021)).

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