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Changes of coastline and tidal flat and its implication for ecological protection under human activities: Take China's Bohai Bay as an example

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A B S T R A C T

The change processes and trends of shoreline and tidal flat forced by human activities are essential issues for the sustainability of coastal area, which is also of great significance for understanding coastal ecological environment changes and even global changes. Based on field measurements, combined with Linear Regression (LR) model and Inverse Distance Weighing (IDW) method, this paper presents detailed analysis on the change history and trend of the shoreline and tidal flat in Bohai Bay. The shoreline faces a high erosion chance under the action of natural factors, while the tidal flat faces a different erosion and deposition patterns in Bohai Bay due to the impact of human activities. The implication of change rule for ecological protection and recovery is also discussed. Measures should be taken to protect the coastal ecological environment. The models used in this paper show a high correlation coefficient between observed and modeling data, which means that this method can be used to predict the changing trend of shoreline and tidal flat. The research results of present study can provide scientific supports for future coastal protection and management.

1. Introduction

Coastal zone has become the most intense area of human activities, more than half of the world's population lives within about 60 km of the coast, and two-thirds of cities with a population of 2.5 million or more are located near the tidal estuary. However, as the land-sea interaction zone, the geological environment of this area is extremely vulnerable, and also is a sensitive alternating ecosystem (Yanes A et al., 2019), sensitizing to sea level, sedimentation, land subsidence etc. Especially, the sea level is predicted accelerated rising during this century (IPCC, 2013, 2021), with a background of the reduced dramatically riverine sediment load to the estuaries, and the coastal erosions happened in most of the big river deltas (Blum MD and Roberts HH, 2009; Ericson JP et al., 2006).

Tianjin-Hebei coast is in the coordinated development of Beijing-Tianjin-Hebei, which is one of the most developed coasts in China, prized for their high commercial and ecological value (Fig. 1). During the last fifty years, due to the human activities, such as reclamation, seawall construction and aquaculture, the percent of natural shoreline has decreased from 50.8% in 1970s to 10% in 2015, more than 600 km^2 new land were formed from initial shoreline to 3–5 m water depth (Yan HK et al., 2013; Lai S et al., 2015; Shi PX et al., 2016; Wang F et al., 2020; Wang FC et al., 2021), which will influence the coastal changes in the near future.

In addition, all coastlines of China are facing continuing sea level rising. From 1980 to 2020, the average absolute sea level rise rate along the coast of China was 3.4 mm/yr. The rate of Bohai Sea, where Tianjin and Hebei province located, was slightly higher by 3.8 mm/yr (MLR, 2021). The developed Bohai Bay coastal area is subject to ongoing rising sea level, and a reduced supply of river sediments (Xue Z et

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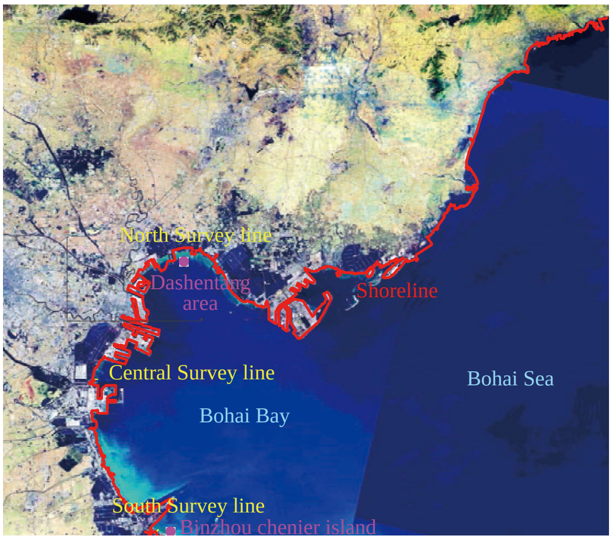

Fig. 1. Geographical location of the shoreline and survey line.

al., 2009; Wang F et al., 2018). The presence of shoreline and tidal flat can be a natural buffer to alleviate possible damage from extreme storm events and coastal flooding resulting from climate change and sea-level rise (Sardá R et al., 2005; IPCC, 2013; Li Y et al., 2016, 2017, 2019).

Therefore, study the historical shoreline and tidal flat changes and predict their trends under natural and human factors are essential issues for the sustainability of this area. Moreover, studying change trends of coastline and tidal flat under human factors is of great significance for protecting and restoring coastal ecological environment (Liu H and Jezek KC, 2004). Previous studies in this study area mainly focus on the history change of the modern shoreline and the tidal flats by processing remote sensing images, unmanned aerial vehicle survey, monitoring profiles, carrying capacity analysis and so on (Wang Y and Zhu DK, 1990; Wang F et al., 2010, 2020; Li YN et al., 2015; Hou XY et al., 2016; Ding XS et al., 2019; Zhang TH and Niu XJ, 2020; Li Y et al., 2021).

As the natural changes of the coast have been hidden by the human activities, it's important to know the coast natural changing tend under a global sea-level rise for coast management and ecological recovery. The area considered in present study is the coastal region along Tianjin and Hebei Province, which is showed in Fig. 1. The overall goal of the research is to develop regional assessment models for shoreline and tidal flat changes, which can also be applied for other coastal regions. Based on collected data, conventional surveys and numerical prediction models, the research content includes analyses of actual measurements, future development trends and implication for ecological protection and recovery.

2. Methodology

2.1. Shoreline

The first assessment procedure used for shoreline location research is the study site selection. The shoreline of Tianjin and Hebei is selected as the research subject. The next essential step is to obtain the location information of the shoreline. Based on collected data, the spatial and statistical analyses are processed. At last, the changing trends of the shoreline location are predicted and analyzed by using the LR model.

In order to fulfill the study, the crucial data about the shoreline location must be gained after site selection. Two age-old maps of China published in 1900 and 1950 and two satellite images photographed in 2000 and 2020 are used in this study (Figs. 2, 3). The map of North Eastern China published in 1900 was prepared by the Military Information Division of USA and the other map of China coast and Korea was compiled and drawn in the Cartographic Section of the National Geographic Society, USA. In addition, the satellite images are all extracted from Landsat OLI (Operational Land Imager) remote sensing data set.

The four periods of shoreline location are shown in Fig. 4. The first two period locations are extracted from maps of China published in 1900 and 1950 (Fig. 2). The next two period locations are extracted from satellite images photographed in 2000 and 2020 (Fig. 3). With the rapid development of economy in Beijing-Tianjin-Hebei region, there has been great demand for land. From Fig. 4, in Binhai New Area of Tianjin and Caofeidian of Hebei Province, it can be seen that large scale reclamation of land has been taking place. The coastline of these areas is mainly artificial coastline now. By comparing the shoreline locations of the four periods, we can see that the change range in large section of coastal region is not too exquisite, except the region in Binhai New Area of Tianjin and Caofeidian of Hebei Province. In addition, several key locations in four period shorelines are coincident. It confirms the validity and the accuracy of the two maps (Fig. 2) on the other hand. The location of the coastline has a great impact on the coast hydrodynamic conditions, which will affect the coastal ecosystem. There is a further discussion in later chapters.

2.2. Tidal flat

As for the tidal flat change, the first study procedure is also the site selection. As pointed out by black lines in Fig. 1, three typical survey lines in Bohai Bay are selected, which are located respectively in north, central and south of the Bohai Bay. Then, the elevation measurements of the tidal flat at specific point are extracted and analyzed. Based on these survey data, the change trends are predicted by using the LR model and the numerical results are discussed.

iRTK5 was used to determine the elevation of the observation sites on the tidal flat (Fig. 5a). iRTK5 is the new high-quality scalable GNSS (Global Navigation Satellite System) receiver of Hi-Target, which benefit from the next-generation GNSS engine, unlimited communication technology and innovative designs. Fig. 5b shows our surveyors in field survey when measuring site elevations of the tidal flat.

2.3. Numerical methods

In present study, the Inverse Distance Weighted (IDW) interpolation method is applied to create tidal flat maps of gathered data and obtain the elevation values of expected

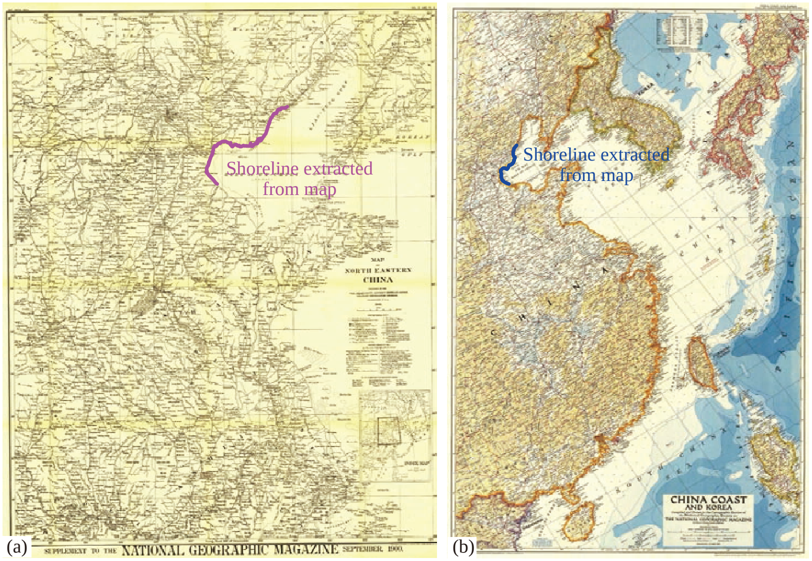

Fig. 2. Maps of China published in 1900 and 1950, coupled with extracted shoreline locations; a–map of North Eastern China published in 1900 by the Military Information Division of USA; b–map of China coast and Korea compiled in 1950 by the National Geographic Society, USA.

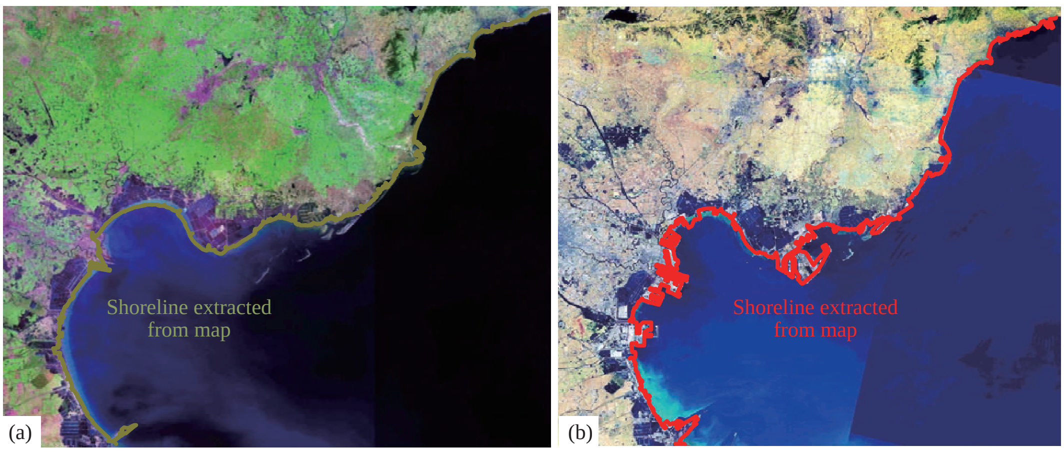

Fig. 3. Satellite maps, extracted from Landsat OLI remote sensing data set and coupled with extracted shoreline locations; a–map photographed in 2000; b–map photographed in 2020.

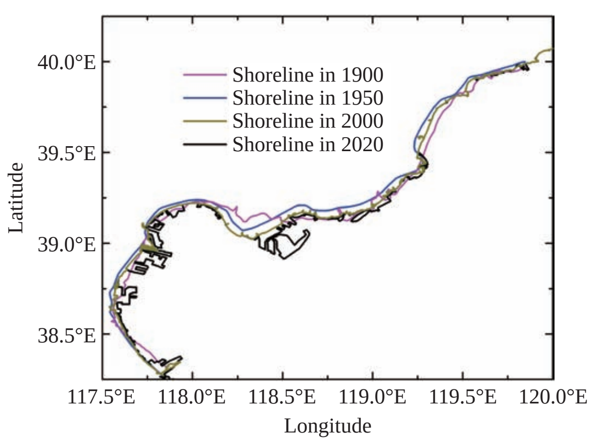

Fig. 4. Four periods of shoreline location extracted from collected maps.

sites. This method is widely used in the study of erosion and deposition in other coastal regions in the world (Jaffe BE et al., 2007; Luan HL et al., 2016; Jiang C et al., 2017). The IDW interpolation explicitly depends on the assumption that observations further away should have their contributions diminished according to how far away they are. The interpolating formula used in this study can be expressed as follows:

$$Z_j = k_j \sum_{i=1}^{n} \frac{1}{d_{ij}} Z_i \tag{1}$$

$$k_j = 1 / \sum_{i=1}^{n} \frac{1}{d_{ij}} \tag{2}$$

where Z_j and Z_i denote the value of an interpolated unknown point and known point, respectively. d_{ij} is a given distance from the known point to the unknown point. n is the total number of known points used in interpolation.

The Pearson Correlation Coefficient (PCC) is used to

Fig. 5. Field measurement for elevation of the tidal flat; a–measuring instrument (iRTK5); b–field measurement.

determine how strong that the relationship is between two period measurements. In statistics, the PCC is a measure of linear correlation between two sets of data, which can be calculated by (Abushandi E and Abualkishik A, 2020):

$$r_{xy} = \frac{N\sum x_i y_i - \sum x_i \sum y_i}{\sqrt{N\sum x_i^2 - \left(\sum x_i\right)^2}\sqrt{N\sum y_i^2 - \left(\sum y_i\right)^2}} \tag{3}$$

where r_{xy} is the Pearson coefficient and N is sample size. x_i and y_i are the individual sample points indexed with i.

In addition, the LR is conducted to predict the future changes of shoreline and tidal flat. The LR is the approximation of a linear model used to describe the relationship between two or more variables. It can be used to carry out shoreline and tidal flat change analysis (Qiao G et al., 2018; Liu YF et al., 2020). In simple linear regression, there are two variables, a dependent variable and an independent variable. The formula of LR is:

$$f_i = \beta_0 + \beta_1 \times x_{i1} + \beta_2 \times x_{i2} + \cdots + \beta_p \times x_{ip} + \epsilon \tag{4}$$

where f_i is the dependent variable. x_{ip} is the independent variable and p is the number of independent variable. β_0 denotes the constant term and β_p denotes the slope coefficients for each independent variable. ϵ is the model's error term, which also known as the residual.

If the value of PCC is closer to −1.00 or +1.00, then it means that extraordinary linearity is achieved between two different period measurements. Consequently, the LR can be conducted in order to find the future changes. However, if the value is closer to 0, then it indicates that the variation between two variables is great and the linear model cannot be used to predict future changes.

3. Results and Discussion

3.1. Shoreline

The change of shoreline location is considered in two directions, including longitude direction and latitude direction. Table 1 shows the calculation results of the Pearson correlation for shoreline locations between the 1900's and 1950's. Generally speaking, a correlation value of 0.7 between two variables would indicate that a significant and positive linear relationship exists between the two variables. The values of PCC are all greater than 0.99, and it shows a very obvious linear correlation in two directions between the two periods of the shoreline location.

Table 2 shows the LR model coefficients for shoreline change. The coefficient of determination (R^2) is a statistical metric which is used to measure how much of the variation in outcome can be explained by the variation in the independent variables. Because the R^2 values of 0.999 and 0.995 are very close to 1, and the p-value of 0.000 is less than the default significance level of 0.05, a significant linear regression relationship exists between the shoreline locations in 1950 and those in 1900.

According to the numerical results of Table 2, The resulting linear equations to estimate shoreline location change for two directions can be expressed as:

$$f_{n+1}(lon) = 0.999 \times f_n(lon) + 0.107 \tag{5}$$

$$f_{n+1}(lat) = 1.025 \times f_n(lat) - 0.965 \tag{6}$$

Table 1. Pearson correlation for shoreline locations between the 1900's and 1950's.

Coordinate	PCC	N
Longitude (lon)	0.999	243
Latitude (lat)	0.998	243

Table 2. LR model coefficients for shoreline change.

Coordinate	Constant	1st (Slope)	R^2 statistic	p-value
Longitude (lon)	0.107	0.999	0.999	0.000
Latitude (lat)	−0.965	1.025	0.995	0.000

where f_{n+1} is the modeled shoreline locations in degrees for the next 50 years' period and f_n is the previous shoreline locations in degrees.

Based on Eq. 5 and Eq. 6, the shoreline locations in 2000 and 2050 are predicted. Fig. 6 shows the comparison of past, present and expected future shoreline locations. In 1900, the shoreline is mainly on the most seaward than others on Bohai Bay from Huanghua Harbor to Dashentang, on the most landward in Nanpu-Caofeidian, nearly the same with present shoreline from the Eastern Caofeidian to Luanhe Delta, and on most seaward from Northeast Luanghe Delta to the north boundary of Hebei Province. In 1950, comparing with that of 1900, the shoreline in Bohai Bay are moved landward by natural erosion. The shoreline of Nanpu-Caofeidian, moved seaward by silting. The shorelines of Eastern Caofeidian to the boundary of Hebei Province are moved landwards by natural erosion. In general, the shoreline is eroded from 1900 to 1950. Moreover, two predicted shorelines are given in Fig. 6 based on the changing trend from 1900 to 1950. The prediction results show that the erosion of coastline will be going on for 100 years with minimal human intervention.

The aquaculture has become a growth since the 1970's and human activity plays a more important role in shoreline change. Especially since 2000, great changes have happened to coastal area from Huanghua Harbor to Caofeidian because of the reclamation, and the natural changing trend is completely covered by human activities. Comparing predicted 2000 and 2050 shoreline with real 2020 shoreline given by remote sensing, great differences are shown, which is because that the huge reclamation have greatly changed the sites of shorelines. Although the predicted shoreline are different from the real shoreline, those discrepancies can remind us where have to facing a more pressure from marine. For example, the real shoreline of Caofeidian and Lingang Industrial Area have huge discrepancy with predicted shoreline, those areas are facing more pressure from marine than the area of Nandagang, Nanpu and Luanhe Delta. Decision makers should pay more attention to those coast regions with higher disaster risks.

3.2. Tidal flat

In general, the change trends of the tidal flat mainly depend on coastal dynamic conditions, which are affected by many factors (Pethick J, 2001; Günaydin K and Kabdasli S, 2003; Fan YS et al., 2018; Zhang TH and Niu XJ, 2020). The impact of some factors is long-term and gradual, including sea level change, ocean dynamics, land subsidence, groundwater over exploitation and so on. However, the impact of storm surge and coastal engineering construction is short-term and rapid. Under the influence of various coastal dynamic factors, the coastal sediment is transported away from the shore and moved to other places under the action of coastal current. The sediment in the lower part of the tidal flat can also be transported to the upper part through the action of waves, resulting in erosion or deposition.

The measurements along three survey lines were conducted twice, one was during period 26–27 July 2018 and the other was during 5–7 August 2019. Fig. 7 show the two elevation measurements for tidal flats of north line, central line and south line, respectively. The maximum value of the elevation is 1.29 m and the minimum value of the elevation is

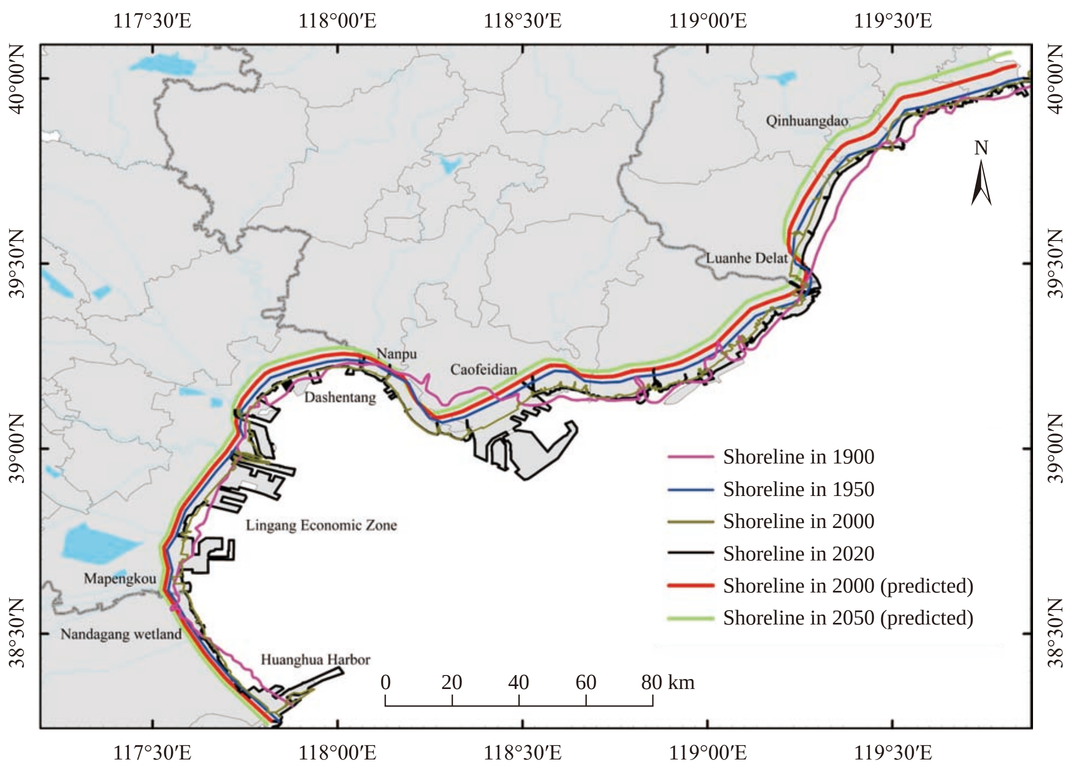

Fig. 6. Comparison of past, present and expected future shoreline locations.

−1.28 m. Table 3 shows the average horizontal distance between two adjacent sites. The horizontal distances used in field survey of 2019 are much smaller than those of 2018. In order to compare the data of the two periods at the corresponding sites, an interpolation method must be adopted to process the measurements.

First, the three-dimensional contour maps for the second elevation of tidal flat obtained in 2019 are created. This step is performed by using the MATLAB procedure to deal with the survey data. Fig. 8 shows the contour maps for north line, central line and south line, respectively. The high elevation area signed with yellow color indicates the shoreline direction and the area colored by blue presents the offshore direction.

For the better comparison, the IDW method has been applied on the second field measurements to obtain the elevation values at the survey sites of the first field measurements. Fig. 9a shows the comparison of the two elevation measurements for north line of tidal flat. The mean values of tidal flat elevations for the first and the second field measurements are 0.17 m and 0.28 m respectively. The north line of tidal flat in Bohai Bay is generally characterized by deposition. The average deposition depth is 0.11 m and the sedimentation rate is 0.11 m/yr. The sedimentation rate tends to increase along with the offshore direction. The shoreline changes caused by large-scale reclamation projects in coastal region of Tianjin and Hebei which weaken the residual current of the Boahai Bay and the velocity decreases generally in the nearshore area between 0 m and 5 m isobaths (Jia H et al., 2018; Bai YC et al., 2021). The sediments are more easily deposited in the region of tidal flat. From the perspective of coastal ecological environment, the accretion tidal flat can provide more living space for nearshore and coastal life.

Fig. 9b shows the comparison of the two elevation measurements for central line. The mean values of tidal flat elevations for the first and the second field measurements are −0.23 m and −0.18 m, respectively. The mean deposition

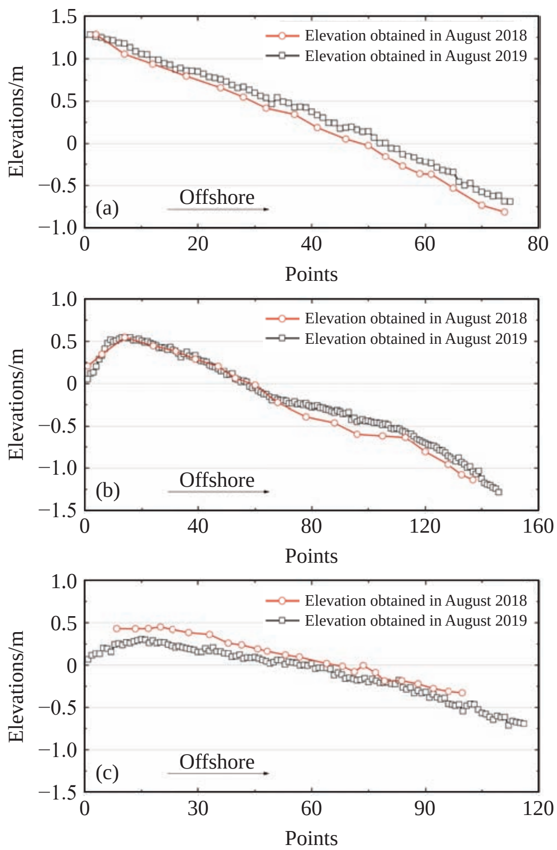

Fig. 7. Elevation measurements of tidal flat for three survey lines; a–north line located in Bohai Bay; b–central line located in west of Bohai Bay; c–south line located in Bohai Bay.

Table 3. Average horizontal distance between two adjacent sites.

Survey line	2018	2019
North line	99.1 m	23.7 m
Central line	94.6 m	13.4 m
South line	51.0 m	12.1 m

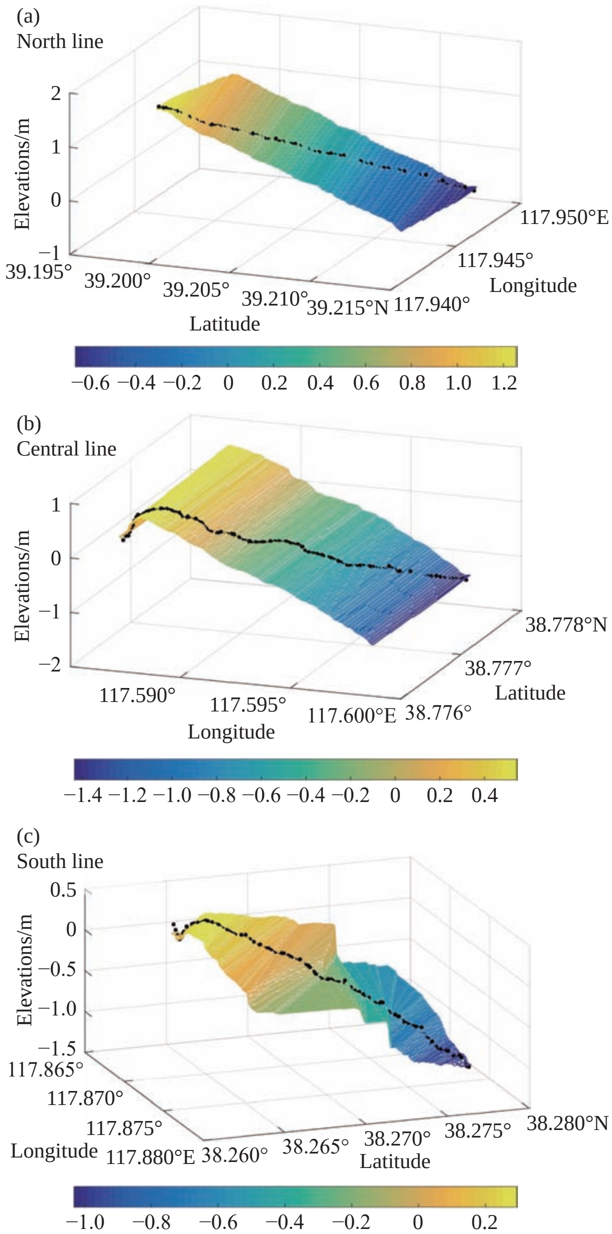

Fig. 8. Contour map using IDW method for the second elevation of tidal flat.

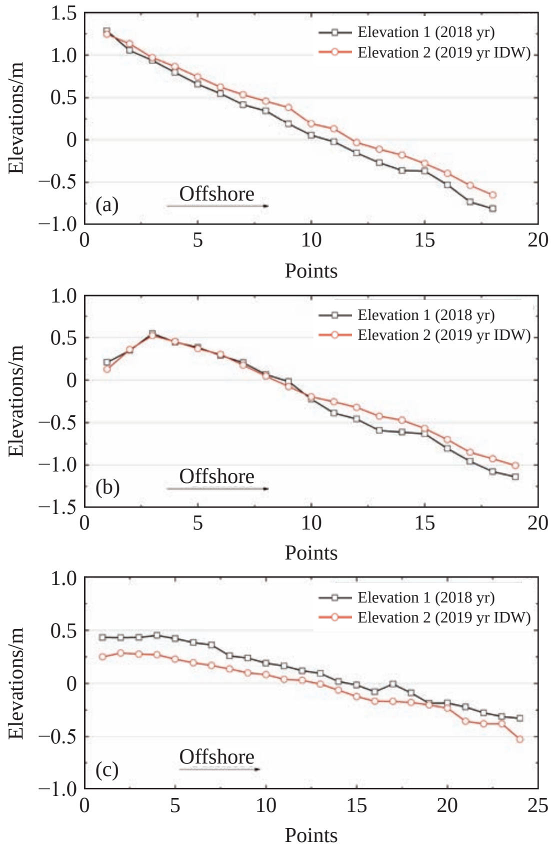

Fig. 9. Comparison of the two elevation measurements for tidal flat; a–north line located in Bohai Bay; b–central line located in west of Bohai Bay; c–south line located in Bohai Bay.

height is 0.05 m. The elevations with relatively high altitude have no obvious change. There is an erosion tendency in the nearshore site (Number 1 point) of the central survey line, but the lower part of the line has evidently deposition trend.

Fig. 9c shows the comparison of the two elevation measurements for south line. The mean values of tidal flat elevations for the first and the second field measurements are 0.10 m and −0.03 m respectively. Unlike the varying trend of the north line and central line, the south line is totally characterized by erosion and the average erosion depth is 0.13 m. It is noteworthy that the erosion condition of the nearshore tidal flat is relatively more severe. The south line locates in the south of Huanghua Port. Simulation results show that the implementation of reclamation projects may causes the tidal current movement more intense near the Huanghua Port (Bai YC et al., 2021). Generally speaking, the eroded hydrodynamic environment is not conducive to ecological protection and restoration.

Table 4 illustrates the values of Pearson correlation coefficient between the first and the second field measurements. The results show a strong relationship between the first and the second field measurements with all the PCC coefficients greater than 0.98.

The coefficients of regression variables are calculated by Matlab software, which are shown in Table 5. The input data for regression analysis are two variables. The independent values of first variable are the first field measurements obtained in 2018 and the dependent values of second variable are the second field measurements obtained in 2019. It can be concluded from linear regression analysis that the dynamic change of tidal flat is linear.

According to Table 5, linear equations which can be used to predict tidal flat change are as following:

$$f_{n+1}(\text{north}) = 0.923 \times f_n(\text{north}) + 0.128 \tag{7}$$

$$f_{n+1}(\text{center}) = 0.88 \times f_n(\text{center}) + 0.023 \tag{8}$$

$$f_{n+1}(\text{south}) = 0.89 \times f_n(\text{south}) - 0.115 \tag{9}$$

where f_{n+1} is the modeled elevations of tidal flat in meters for the next one year's period and f_n is the previous elevations in meters.

Using Eqs. 7–9, the changes of tidal flat elevation have been predicted for the next 10 years at the same locations in addition to the second field measurements. The field measurements and numerical elevations for the next 10 years based on the linear regression model are shown in Fig. 10, for north line, central and south line respectively. For the north line in Bohai Bay (Fig. 10a), the slope of tidal flat becomes more and more gentle. The maximum deposition position locates at the site of number 18 point which is the end of the survey line. The maximum deposition height is 1.27 m. In the west central area of the Bohai Bay, the variation trend of tidal flat is relatively complex (Fig. 10b). The elevation of site of number 7 point has nearly no change for the next 10 years. The sites above this site keep eroded and the maximum erosion height is 0.24 m. However, the sites below this site appear siltation and the intensity increases gradually with the distance to the site of number 7 point. The maximum deposition depth is 0.86 m. Continuous deposition may weaken the residual current and result in weak water exchange capacity and low pollutant-diffusing capacity (Jia H et al., 2018). This situation is unfavorable for the diffusion of pollutants, and therefore lead to increased water pollution in the Bohai Bay.

As for the south survey line (Fig. 10c), the total evolution trend is keeping eroded and the maximum erosion height is 0.89 m. Through the above analysis, it can be seen that only the south line is undergoing erosion. This survey line is close

Table 4. Pearson correlation between the first and the second field measurements.

Survey line	PCC	*N*
North line	0.998	18
Central line	0.996	19
South line	0.986	24

Table 5. LR model coefficients for tidal flat change.

Survey line	Constant	1st (Slope)	R^2 statistic	*p*-value
North line	0.128	0.923	0.996	0.000
Central line	0.023	0.880	0.991	0.000
South line	−0.115	0.890	0.972	0.000

to Huanghua Harbor and the erosion of tidal flat is disadvantageous to the stability of coastal projects.

Present research offers a methodology that can be used to investigate other coastal regions combining field measurement and numerical modeling. It will enable the administrators and decision makers to identify the coast regions with a higher disaster risk. Moreover, it will help them to find suitable solutions to existing problems.

4. Implication for ecological protection and recovery

Ecosystem protection and recovery must follow the rule of the trend of natural evolution (NDRC, 2020). The changing trend of coastline and tidal flat is surely an essential issue which influences the coastal ecosystem protection and recovery. As showed in Fig. 1, the coastal area of Dashentang is close to the north survey line. The results in this area show that high sedimentation rates happened to the tidal flat and will maintain this trend because of human activity (Figs. 9a, 10a). Previous studies show that the mean high water are higher than the height of nature tidal flat connected with Dike, which means the sea water can influence the Dike directly (Wang F et al., 2010; Fig. 11). With the sea level rise (IPCC, 2021), the dike will face more pressure from ocean in the near future.

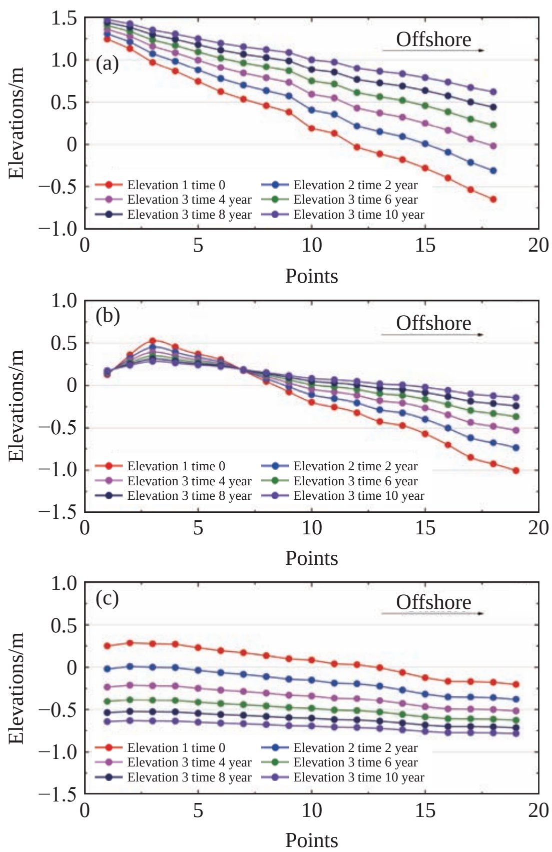

Fig. 10. Present and expected future elevations for the next 10 years based on the linear regression model; a–north line located in Bohai Bay; b–central line located in west of Bohai Bay; c–south line located in Boahi Bay.

The shoreline changes caused by large-scale reclamation projects in Caofeidian of Hebei Province weaken the ocean current in north coast of Bohai Bay. The sediments are more easily deposited and the water depth shows a shallow trend. Our findings show a good phenomenon for coastal area of Dashentang, more sediments accreting in tidal flat can protect the dike, and which is of great benefit to ecological dike construction. The accretion tidal flat above mean sea level can provide growth space for plant and sea birds. Therefore, we suggest that ecological dike construction can be taken in this area.

The results of coastline and tidal flat in southern Bohai Bay, Binzhou chenier Island and Wetland National Natural Reserve, Shandong Province, show that strong erosion happened to the chenier coastline and tidal flat. The Binzhou chenier island locates closely to the south survey line (Fig. 1). The Huanghua Port and Binzhou Port changed the offshore current conditions, which lead to the lack of adequate supply of shell and their debris to the chenier. In addition, human activities such as salt field construction, shell mining, and excavation of aquaculture ponds have also gradually change the morphology behind chenier (Xu YM and Wang YH, 2015).

The Binzhou chenier island is the only natural chenier coast of China now (Fig. 12) and it is of great significance for coastal ecological recovering of the reserve. Although nature and human activity have changed morphology of this area, the original chenier-lagoon system is still preserved. Therefore, in

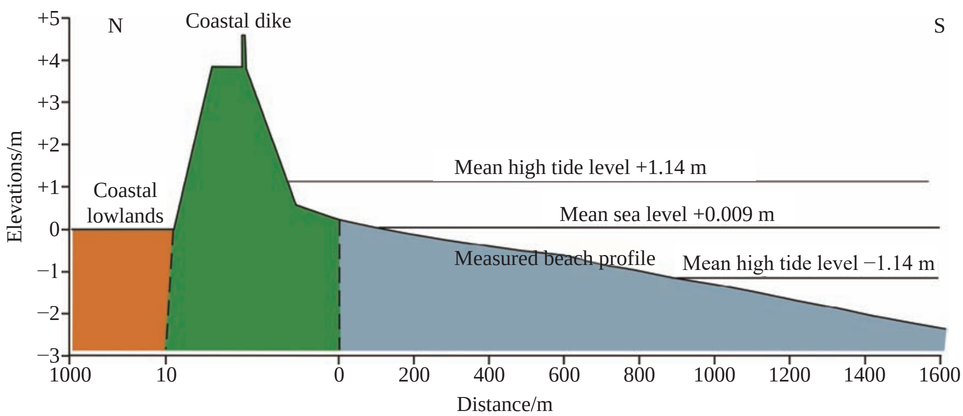

Fig. 11. Tidal flat in coastal area of Dashentang.

Fig. 12. Aerial photograph of shell chenier in Binzhou Shell Dike Islands.

order to protect this ecosystem, the following proposals are given based on our research results: (1) strengthen monitoring on the chenier, tidal flat and shallow sea; (2) strengthen study on the evolution history, trend, driving mechanism of this ecosystem; (3) provide comprehensive suggestions on chenier-lagoon recovery.

5. Conclusions

This study has investigated the changes of coastline and tidal flat and its implication for ecological protection, taking Bohai Bay as the example. The following conclusions could be drawn by present research:

(i) The research results show strong linear relationship between the two different period measurements for shoreline location and tidal flat elevation. Pearson correlation coefficients between two variables are all greater than 0.98 and the values of p-value are less than the default significance level of 0.05. Linear regression analysis also concludes that the change trends of shoreline position and tidal flat elevation are linear and can be predicted by LR models.

(ii) The coastal regions of Caofeidian and Lingang Industrial Area in Bohai Bay, especially the artificial shorelines, will face a huge pressure of change from the ocean. Comparing predicted 2000 and 2050 shorelines with real 2000 and 2020 shorelines given by remote sensing, great differences are shown. These discrepancies can remind us where have to facing a more pressure in the future under natural factors.

(iii) The variation law of tidal flat in Bohai Bay is complicated under the influence of human activities. The north line of tidal flat in Bohai Bay is generally characterized by deposition and the average sedimentation rate is 0.11 m/yr. As for the central survey line, the lower part (offshore direction) has evidently deposition trend and the mean deposition rates of the line is 0.05 m/yr. The south line is totally characterized by erosion and the average erosion rate is 0.13 m/yr.

(iv) As regards the implication for ecological protection and recovery, high sedimentation rates happened to the tidal flat in north of Bohai Bay, which is of great benefit to ecological dike construction in this area. Instead, strong erosion happened to the chenier coastline and tidal flat in south of Bohai Bay and appropriate measures should be taken to protect the Binzhou chenier island.

CRediT authorship contribution statement

Fu Wang and Yong Li conceived of the presented idea. Yong Li and Fu Wang wrote the manuscript in consultation. Yong Li and Fu Wang developed the numerical models. Yong Li, Heng Yu, Fu Wang and Fei-cui Wang provided figures and tables in the manuscript. Ming-zheng Wen and Peng Yang contributed to field measurements and helped supervise the project. All authors discussed the results and contributed to the final manuscript.

Declaration of competing interest

The authors declare no conflicts of interest.

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References

Abushandi E, Abualkishik A. 2020. Shoreline erosion assessment modelling for sohar region: measurements, analysis, and scenario. Scientific Reports, 10, 4048. doi: 10.1038/s41598-020-61033-y.

Bai YC, Shi FS, Xu HY, Huang Z. 2021. Coastline and tidal current changes responses due to large-scale reclamation in Bohai Sea. Marine Science Bulletin, 40(6), 621–635 (in Chinese with English abstract).

Blum MD, Roberts HH. 2009. Drowning of the Mississippi Delta due to insufficient sediment supply and global sea-level rise. Nature Geoscience, 2(7), 488–491. doi: 10.1038/ngeo553.

Ding XS, Shan XJ, Chen YL, Jin XS, Muhammed FR. 2019. Dynamics of shoreline and land reclamation from 1985 to 2015 in the Bohai Sea. Journal of Geographical Sciences, 29(12), 2031–2046 . doi: 10.1007/s11442-019-1703-1.

Ericson JP, Vorosmarty CJ, Dingman SL, Ward LG, Meybeck M. 2006. Effective sea-level rise and deltas: Causes of change and human dimension implications. Global and Planetary Change, 50(1–2), 63–82. doi: 10.1016/j.gloplacha.2005.07.004.

Fan YS, Chen SL, Zhao B, Ji HY, Jiang C. 2018. Monitoring tidal flat dynamics affected by human activities along an eroded coast in the Yellow River Delta. Environmental Monitoring and Assessment, 190(7), 396. doi: 10.1007/s10661-018-6747-7.

Günaydin K, Kabdasli S. 2003. Characteristics of coastal erosion geometry under regular and irregular waves. Ocean Engineering, 30(13), 1579–1593. doi: 10.1016/S0029-8018(03)00011-8.

Hou XY, Wu T, Hou W, Chen Q, Wang YD, Yu LJ. 2016. Characteristics of coastline changes in mainland China since the early 1940s. Science China Earth Sciences, 59, 1791–1802. doi: 10.1007/s11430-016-5317-5.

IPCC. 2013. Fifth Report-Climate Change, the Physical Science Basis. Web site: https://www.ipcc.ch/report/ar5/wg1/.

IPCC. 2021. Sixth Report-Climate Change, the Physical Science Basis. Web site: https://www.ipcc.ch/report/ar6/wg1/.

Jaffe BE, Smith RE, Foxgrover AC. 2007. Anthropogenic influence on sedimentation and intertidal mudflat change in San Pablo Bay, California: 1856–1983. Estuarine Coastal and Shelf Science, 73(1–2), 175–187. doi: 10.1016/j.ecss.2007.02.017.

Jia H, Shen YM, Su MR, Yu CX. 2018. Numerical simulation of hydrodynamic and water quality effects of shoreline changes in Bohai Bay. Frontiers of Earth Science, 12(3), 625–639. doi: 10.1007/s11707-018-0688-x.

Jiang C, Pan S, Chen SL. 2017. Recent morphological changes of the Yellow River (Huanghe) submerged delta: causes and environmental implications. Geomorphology, 293(Part A), 93–107. doi: 10.1016/j.geomorph.2017.04.036.

Lai S, Loke LHL, Hilton MJ, Bouma TJ, Todd PA. 2015. The effects of urbanization on coastal habitats and the potential for ecological engineering: A Singapore case study. Ocean and Coastal Management, 103, 78–85. doi: 10.1016/j.ocecoaman.2014.11.006.

Li Y, Tian LZ, Pei YD, Wang F, Wang H. 2016. Numerical simulation of storm surge inundation in the west zone of Bohai Bay. Geological Bulletin of China, 35(10), 1638–1645 (in Chinese with English abstract).

Li Y, Chen X, Tian LZ, Li JF. 2017. Numerical simulation of the storm surge in Bohai Bay based on a coupled ocean-atmosphere model. Journal of Shanghai Jiaotong University, 51(12), 1512–1519. doi: 10.16183/j.cnki.jsjtu.2017.12.015.

Li Y, Chen X, Jiang XY, Li JF, Tian LZ. 2019. Numerical simulations and comparative analysis for two types of storm surges in the Bohai Sea using a coupled atmosphere-ocean model. Acta Oceanologica Sinica, 38(9), 39–51. doi: 10.1007/s13131-019-1383-9.

Li Y, Wen MZ, Yang P, Tian LZ, Hu YZ, Wang H. 2021. Construction of "atmosphere-land-sea" comprehensive geological survey and observation system in Tianjin and Hebei coastal zone. North China Geology, 44(4), 40–46 (in Chinese with English abstract).

Li YN, Wang Q, Guo PF, Zhang SY, Hu H. 2015. Shoreline succession during recent 20 years in the Bohai Sea and the strategies for the development and utilization. Transactions of Oceanology and Limnology, (3), 32–38 (in Chinese with English abstract).

Liu H, Jezek KC. 2004. Automated extraction of coastline from satellite imagery by integrating Canny edge detection and local adaptive thresholding method. International Journal of Remote Sensing, 25(5), 937–958. doi: 10.1080/0143116031000139890.

Liu YF, Ma J, Wang XX, Zhong QY, Zong JM, Wu WB, Wang Q, Zhao B. 2020. Joint effect of spartina alterniflora invasion and reclamation on the spatial and temporal dynamics of tidal flats in Yangtze River estuary. Remote Sensing, 12(11), 1725. doi: 10.3390/rs12111725.

Luan HL, Ding PX, Wang ZB, Ge JZ Yang SL. 2016. Decadal morphological evolution of the Yangtze Estuary in response to river input changes and estuarine engineering projects. Geomorphology, 265(4), 12–23. doi: 10.1016/j.geomorph.2016.04.022.

MLR. 2021. Sea level bulletins 2020. Ministry of land resources, People's Republic of China. Web site: http://www.nmdis.org.cn/hygb/zghpmgb/ (in Chinese).

NDRC. 2020. Master plan for major national ecosystem protection and restoration projects (2021–2035). Web site: http://www.ndrc.gov.cn/xxgk/zcfb/tz/202006/t20200611_1231112_ext.html (in Chinese).

Pethick J. 2001. Coastal management and sea-level rise. Catena, 42(2–4), 307–322. doi: 0.1016/S0341-8162(00)00143-0.

Qiao G, Mi H, Wang WA, Tong XH, Li ZB, Li T, Liu SJ, Hong Y. 2018. 55-year (1960–2015) spatiotemporal shoreline change analysis using historical DISP and Landsat time series data in Shanghai. International Journal of Applied Earth Observation and Geoinformation, 68, 238–251. doi: 10.1016/j.jag.2018.02.009.

Sardá R, Avila C, Mora J. 2005. A methodological approach to be used in integrated coastal zone management processes: The case of the Catalan Coast (Catalonia, Spain). Estuarine, Coastal and Shelf Science, 62(3), 427–439. doi: 10.1016/j.ecss.2004.09.028.

Shi PX, Wang F, Shang ZW, Kang H, Xiao GQ, Yang JL, Li JF, Jiang XY, Chen YS, Tian LZ, Li Y. 2016. The present situation and changing characteristics of the shoreline along Tianjin-Hebei coastal areas and proposal for protection. Geological Bulletin of China, 35(10), 1630–1637 (in Chinese with English abstract).

Wang F, Pei YD, Li JF, Shang ZW, Fan CF, Tian LZ, Song MY, Geng Y, Wang H. 2010. Current elevation of Tianjin tidal zone and the urban safety of Binhai New Area, China. Geological Bulletin of China, 29(5), 682–687 (in Chinese with English abstract).

Wang F, Shang ZW, Li JF, Jiang XY, Wen MZ, Shi PX, Tian LZ, Chen YS, Yang P, Hu YZ, Li Y, Yuan HF, Wang H. 2020. Research status and protection suggestions of chenier on Bohai Bay. Geological Survey and Research, 43(4), 293–316 (in Chinese with English abstract).

Wang F, Tian LZ, Jiang XY, Marshall W, Wang H. 2018. Human-induced changes in recent sedimentation rates in Bohai Bay, China: implications for coastal development. Science China:Earth Sciences, 61(10), 1510–1522. doi: 10.1007/s11430-017-9237-4.

Wang FC, Yang P, Shi PX, Shang ZW, Xiao GQ, Wang F. 2021. Research on the status of Hebei Province's coastline in 2019 based on Landsat OLI images. North China Geology, 44(4), 35–40 (in Chinese with English abstract).

Wang Y, Zhu DK. 1990. Tidal flats of China. Quaternary Sciences, 10(4), 291–300 (in Chinese with English abstract).

Xu YM, Wang YH. 2015. Hydrodynamic response of chenier coast to storm surges on the abandoned Yellow River Delta plain. Marine Geology and Quaternary Geology, 35(6), 25–32 (in Chinese with English abstract).

Xue Z, Feng A, Yin P, Xia D. 2009. Coastal erosion induced by human activities: A northwest Bohai Sea case study. Journal of Coastal Research, 25(3), 723–733. doi: 10.2112/07-0959.1.

Yan HK, Wang N, Yu TL, Fu Q, Liang C. 2013. Comparing effects of land reclamation techniques on water pollution and fishery loss for a large-scale offshore airport island in Jinzhou Bay, Bohai Sea, China. Marine Pollution Bulletin, 71(1–2), 29–40. doi: 10.1016/j.marpolbul.2013.03.040.

Yanes A, Botero CM, Arrizabalaga M, Vasquez JG. 2019. Methodological proposal for ecological risk assessment of the coastal zone of Antioquia, Colombia. Ecological Engineering, 130, 242–251. doi: 10.1016/j.ecoleng.2017.12.010.

Zhang TH, Niu XJ. 2020. Analysis on the utilization and carrying capacity of coastal tidal flat in bays around the Bohai Sea. Ocean and Coastal Management, 203, 105449. doi: 10.1016/j.ocecoaman.2020.105449.