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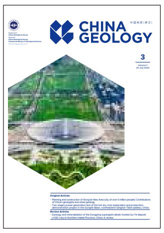

Risk assessment of coastal flooding disaster by storm surge based on Elevation-Area method and hydrodynamic models: Taking Bohai Bay as an example

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ABSTRACT

The future inundation by storm surge on coastal areas are currently ill-defined. With increasing global sea-level due to climate change, the coastal flooding by storm surge is more and more frequently, especially in coastal lowland with land subsidence. Therefore, the risk assessment of such inundation for these areas is of great significance for the sustainable socio-economic development. In this paper, the authors use Elevation-Area method and Regional Ocean Model System (ROMS) model to assess the risk of the inundation of Bohai Bay by storm surge. The simulation results of Elevation-Area method show that either a 50-year or 100-year storm surge can inundate coastal areas exceeding 8000 km^2; the numerical simulation results based on hydrodynamics, considering ground friction and duration of the storm surge high water, show that a 50-year or 100-year storm surge can only inundate an area of over 2000 km^2, which is far less than 8000 km^2; while, when taking into account the land subsidence and sea level rise, the very inundation range will rapidly increase by 2050 and 2100. The storm surge will greatly impact the coastal area within about 10–30 km of the Bohai Bay, in where almost all major coastal projects are located. The prompt response to flood disaster due to storm surge is urgently needed, for which five suggestions have been proposed based on the geological background of Bohai Bay. This study may offer insight into the development of the response and adaptive plans for flooding disasters caused by storm surge.

1. Introduction

Storm surge is a destructive natural disaster in coastal areas, which is generally due to serious atmospheric disturbances like high winds and dramatic changes in atmospheric pressure, resulting in irregular changes in sea level. It is a type of gravitational long wave that occurs in the near shore ocean, with a period of several hours to several days (Feng SZ, 1982). The rate of sea-level rise shows an accelerated trend since 2000 for both China's coast (MNR, 2001, 2023) and global coast (IPCC, 2021). Considering that the impact of storm surge flooding induced by rising sea levels will increase, the research on the risks due to climate change in future is of great significance for sustainable social economic development. In China, coastal zones hold 46.3% of the population and 59.1% of GDP (Gross Domestic Product) (Li C et al., 2024). Therefore, the coastal disasters in these areas cause massive economic losses, and which are dominated by the disasters due to storm surges. For instance, in just 2022, China experienced five storm surges, which resulted in a direct economic loss of 2.38×10^9 CNY (Chinese yuan), accounting for 99% of the total losses (MNR, 2023). Therefore, how to deal with the challenge brought by storm surges, so as to reduce losses, is a key question for coastal areas regarding property damage and loss of life.

The study on storm surges began in the 1920s, initially

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with a preliminary analysis and exploration of the causes and processes of storm surge phenomena. Since the 1950s, with the advancement of computer technology, research on numerical simulation of storm surges has emerged. After the 1990s, various numerical models have been developed and applied extensively, especially in this century (Song CC et al., 2014; Li X et al., 2016; Chen J et al., 2016; Li Y et al., 2016). The complexity of the models has been continuously increasing with the deepening of human understanding on storm surges and the development of computer computing capabilities, so as to more accurately reflect the changing processes and internal mechanisms of the formation, development, and disappearance of storm surges.

Bohai Bay experienced 14 storm surges from 1949 to 1994, four of which are catastrophic, with an average of once every 11 years (You JY, 1995). Furthermore, another eight catastrophic storm surges occurred since 1995, indicating an increased occurrence, which may due to accelerating climate change. Storm surges in this region often occur along the coasts of Cangzhou and Tianjin, Tianjin Binhai New Area and Hebei Cangzhou Bohai New Area, where most of the land elevation are lower than +5 m, and very easy been flooded by storm surge. Therefore, strengthened and in-depth study on the disasters due to storm surges is in urgent need for Bohai Bay. In Bohai Sea, the storm surges are mainly caused by the weather type of cold front (Wang JH et al., 2014), and the catastrophic storm surges are mainly concentrated in the summer and autumn seasons with an average occurrence of once every four years in recent years, generally causing significant losses to personnel and property. While, for small storm surge, it occur 1–2 times per year in the average without seasonality (Feng RX, 2012; Wang C, 2013). Most previous researches regarding the Bohai Bay are focus on what have happened storm surge, and less efforts have been made to research on the risks related to climate change in future.

In this article, the authors use various model tools along with the sea-level data, tidal monitoring data, and land subsidence data, to predict the effects of storm surge, with the ultimate purposes of (1) constructing the models for storm surge study; (2) simulating the potential flooding area by storm surge taking into account the sea level rise and land subsidence in 2020, 2050 and 2100; and (3) discussing the effect and adaptive strategy of the storm surge in the Bohai Bay.

2. Study area

The study area of the Bohai Bay is subject to a mid-latitude, continental monsoon climate and lies in temperate climate zone with distinct four seasons (Fig. 1a) on the west coast of the Bohai Sea. The Bohai Bay is a semi-enclosed marine environment, and connected to the Pacific Ocean crossing the Bohai Strait and the Yellow Sea (Fig. 1b). The

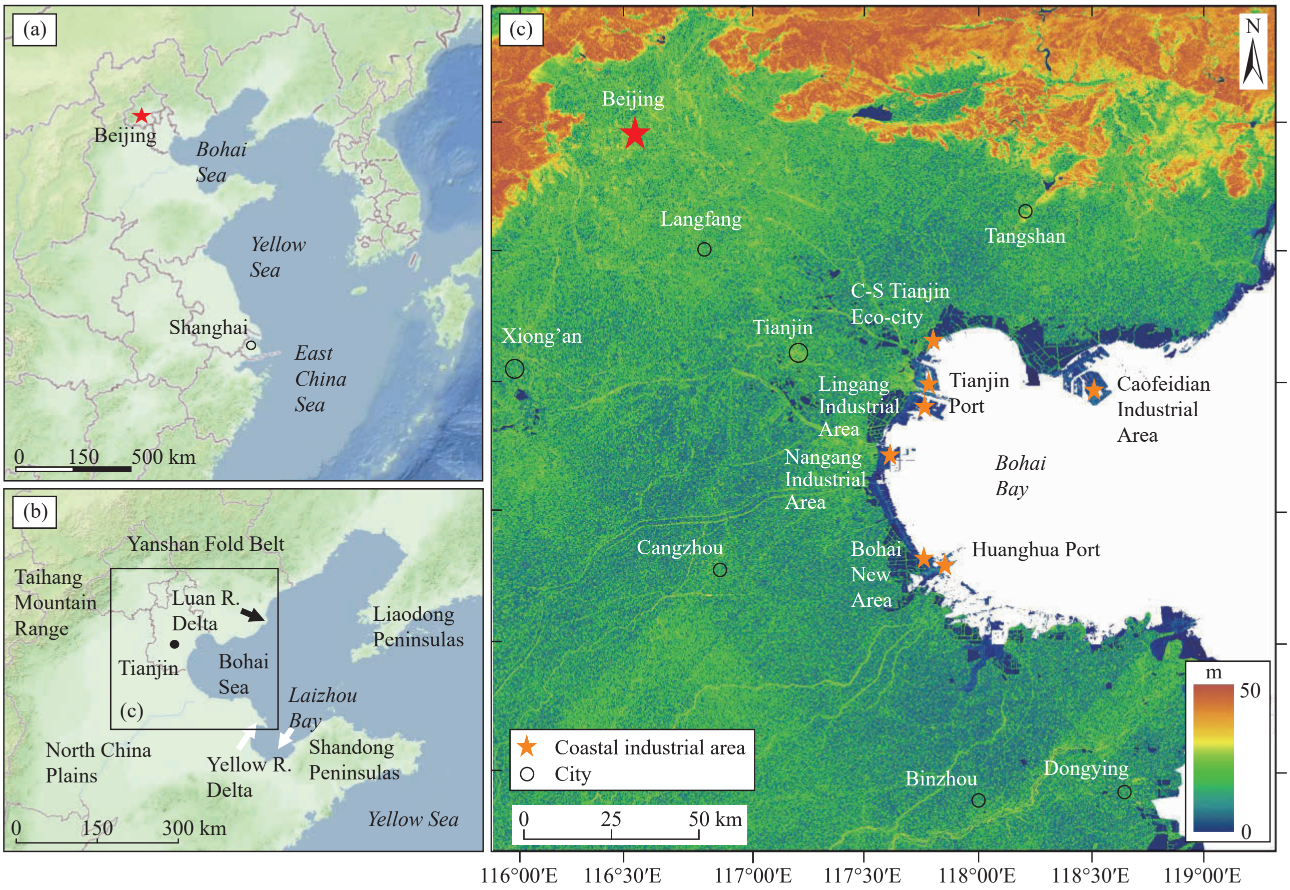

Fig. 1. Sketch map of the Bohai Bay and study area. Basemap cited from: https://map.tianditu.gov.cn/.

seabed terrain gradually deepens from the shore to the bay, with an average depth of 12.5 m (SOA, 2011). The overall terrain of the coastal zone is high and low in the west and east, respectively, and slightly inclined towards the sea from north to south and west to east, and characterized by its low-lying nature (less than +5 m of elevation) (Fig. 1c). As estimated, the long-term tectonic subsidence in Tianjin is approximate 1.3–2.0 mm per year (Wang RB et al., 2003). From the monitoring of land subsidence in the Tianjin Plain area, the subsidence rate has significantly decreased from a few centimeters per year to approximate 10 mm per year (Yi CR, 2017; Li JQ et al., 2023). However, over the past two decades, the average rate of sea-level rise along the coastline of China has surged from 2.4–4.0 mm per year (MNR, 2001, 2023), indicating a discernible acceleration in seal level rise. Comparing with Holocene rising rate of relative sea-level (Wang F et al., 2015, 2020, 2024; Wang H et al., 2022), the relative sea-level rise rate has reached its peak in Holocene. Local reference tidal levels are 1.14 m and 2.30 m for the Mean High Waters (MHW) and the Highest High Waters (HHW), respectively.

In Tianjin and Cangzhou cities, most blocks in the original intertidal zone (at an elevation of +0.5 – +1 m) have been developed and utilized through artificial reclamation (at an elevation of +2 – +4 m). The terrain in Hangu and Tanggu area of Tianjin is relatively low, with a surface elevation of just about +1.5 – +0.5 m and locally negative values (between 0 m and −1 m). The terrain in the southern Tianjin is relatively high, with a surface elevation of about +1.0 – +4 m and a local embankment elevation of about +7 m. Overall, the land area is relatively flat. The terrain of the sea area is characterized by a tilt from west to east with an elevation of 0 – −10 m and local waterways of lower than −20 m, and the bottom mainly composed of muddy-sandy sediment.

3. Methodology

3.1. data sources

The elevation data are download from open DEM (Digital Elevation Model) data of Advanced Land Observing Satellite (ALOS), and the horizontal and vertical accuracy of this data can reach 12.5 m (https://search.asf.alaska.edu/#/).

The sea-level change data are collected from Sea level bulletins published annually by Ministry of Natural Resources of the People’s Republic of China at www.mnr.gov.cn.

The land subsidence data are collected from available papers, news and monitoring data (Yi CR, 2017; Li JQ et al., 2023).

3.2. Flooding models

At present, the methods for the determination of coastal flood extent can be generally classified into two types: One is the Geographic Information System (GIS)-based Elevation-Area method, and another is the hydrodynamic evolution-based numerical models.

Nowadays, the GIS-based Evaluation-Area method is generally used, particularly for researches with respect to large-scale coastal flood (Rowley RJ et al, 2007; Fang J et al, 2014). The method is in possession of the advantages that it provides rapid delineation of high-risk areas, specially and information on macro disaster risk prevention in coastal zones for decision making, but is restricted by neglecting the duration of extreme water levels, the surface roughness, and the fact that not all areas are influenced by a certain water level, leading to overestimated risks.

Hydrodynamic evolution-based numerical models like FVCOM (Finite Volume Coastal Ocean Model), ADCIRC (ADvanced CIRCulation model), and other numerical models for large-scale storm surge, can effectively simulate the processes such as water level of storm surge and flooding. However, practical application of these models for risk assessment on large-scale coastal flood is very limited for difficulties primarily composed of: 1) The demand of large and complex data; 2) the complicated and time-consuming solving process; 3) a good simulation of the disaster-causing factors in regard of intensity, but inadequately considering other factors like the vulnerability of the disaster-bearing body. Since more accurate terrain data is available, for instance 5-m LiDAR elevation data or more accurate data, the use of GIS raster data-based two dimensional (2D) flood models like Lisflood (Bates PD et al, 2000), JFLOW (Bradbrook K, 2006) has become more widespread. By simplifying the physical processes, thereby improving the efficiency in solving process to a great extent, these models show excellent performance in researches at small scale (Yin J et al, 2016). For the purpose of improving the simulation of extreme water levels, improving the efficiency in solving process by simplifying the solving process, some researches have adopted the storm surge-related products by others, which are in general based on numerical models for storm surges at large scale and specific products for certain areas, for instance, extreme water level heights under multiple return periods, as the inputs for land flood processes. Then, a GIS raster data-based 2D flood model is employed for the evolution of flooding processes. However, the very method is currently impractical for the risk assessment of coastal floods at large scale, and the reason for this is largely because of necessity of massive extremely accurate basic data, however, the acquisition of which remains a huge challenge in the case of large scale.

As commented earlier, many recent researches are generally carried out on the basis of FVCOM, ADCIRC and other models taking into account the circumstance of land inundation by seawater in the course of storm surges (Kowaleski AM et al., 2020; Wang F et al., 2019; Chen C et al., 2022). Actually, using the Regional Ocean Model System (ROMS) model, various physical and ecological parameters can be integrated, including marine biology, geochemistry, sedimentation, and ocean surface waves, so as to simulate more practically a variety of oceanic and coastal environments (Qin GR et al., 2023). With its versatility and scalability, the ROMS model has been recognized as a distinguished method for research on inundation by storm surge. In the very study, the ROMS wet/dry method is used to study the inundation process under storm surge.

3.3. ROMS model

The ROMS model is a free surface, sigma-coordinate, primitive equations ocean model, principally proposed by the researchers from the University of California, Los Angeles (UCLA), Rutgers University, and the French National Research Institute for Sustainable Development (IRD), with the aim of seeking solution for the Reynolds-Averaged Navier-Stokes (RANS) equations on the ground of the hydrostatic and Boussinesq assumptions (Haidvogel DB et al., 2008). The version 4.0 is used in the present study.

The governing equations in Cartesian coordinates are shown as follows. The Reynolds-averaged formulation of the momentum equations in horizontal direction (*x*) and vertical direction (*y*) are (Equ. 1, 2):

$$\frac{\partial u}{\partial t}+\vec{v}\cdot\nabla u-fv=-\frac{\partial\phi}{\partial x}-\frac{\partial}{\partial z}\left(\overline{u'w'}-\nu\frac{\partial u}{\partial z}\right)+F_u+D_u \tag{1}$$

$$\frac{\partial v}{\partial t}+\vec{v}\cdot\nabla v+fu=-\frac{\partial\phi}{\partial y}-\frac{\partial}{\partial z}\left(\overline{v'w'}-\nu\frac{\partial v}{\partial z}\right)+F_v+D_v \tag{2}$$

The equation of state is expressed as (Equ. 3):

$$\rho=\rho(T,S,P) \tag{3}$$

The hydrostatic assumption gives as a force balance in the vertical dimension (Equ. 4):

$$\frac{\partial\phi}{\partial z}=-\frac{\rho g}{\rho_0} \tag{4}$$

The continuity equation for an incompressible fluid is (Equ. 5):

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{5}$$

All the above equations are closed through parameterization of the Reynolds stresses and turbulent tracer fluxes, as shown below (Equ. 6, 7):

$$\overline{u'w'}=-K_m\frac{\partial u}{\partial z} \tag{6}$$

$$\overline{v'w'}=-K_m\frac{\partial v}{\partial z} \tag{7}$$

where *u*, *v* and *w* denote the components of velocity vector $\vec{v}$ in the *x*, *y* and *z* directions, respectively, *t denotes* the time, ϕ denotes the dynamic pressure, f denotes the Coriolis parameter, *D* is the diffusive term, *F* denotes the forcing term, including surface wind stress and wave radiation stress, *T* denotes the temperature, *S* denotes the salinity and *P* denotes the pressure, *g* denotes the gravitational acceleration, ρ denotes the density of water, and K_m denotes the eddy viscosity for momentum.

The ROMS domain covers the western Bohai Bay as shown in Fig. 1 (117.11°E–118.21°E, 38.45°N–39.46°N), which has the same spatial resolution of 200 m in both latitude and longitude, resulting in a total grid points of 497×897. In addition, five sigma levels are applied in the *z* direction. For the domain of the model, there is an open boundary on the eastern side, on which the 2D momentum condition and 3D (three dimensional) momentum radiation condition are given, and a close boundary on each of the other three sides. Furthermore, the time-dependent water elevations and depth-averaged velocities are composed of eight main astronomical tides (Li Y et al., 2019).

For storm surge simulation, the wind stress, which is calculated based on the wind field at a 10 m distance using the following Equ. 8, is used as the external forcing boundary condition in the study. The wind field data at a 10 m depth on the ocean surface is obtained using a mixture of NCEP/QSCAT (National Center for Environmental Prediction/Quick Scatter Meter) wind direction data. For the database, the spatial resolution is 0.5° x 0.5° and the time resolution is 6 h (Schneider DP et al., 2013).

$$\vec{\tau}_s=C_d\rho_a\vec{W}\left|\vec{W}\right| \tag{8}$$

where C_d denotes the wind drag coefficient, which is 0.0026 in this paper, ρ_a denotes the density of air, $\vec{W}$ denotes the wind speed vector.

The calculation of seabed friction force adopts the law of quadratic friction (Equ. 9):

$$\vec{\tau}_b=C_f\rho\vec{V}\left|\vec{V}\right| \tag{9}$$

where C_f denotes the friction coefficient, which is 0.012 in this paper, ρdenotes the density of air, $\vec{V}$ denotes the velocity of bottom sea water.

The wetting and drying method of ROMS is used to simulate the flooding process of ocean water under storm surge (Qin GR et al., 2023). By performing the method at each time step of the barotropic engine, the sum of the local bathymetry and the free-surface displacement at the grid center is calculated and defined as the total depth of the water, between which and the critical parameter, i.e. the minimum depth specified by the user, a comparison is then made. If the total depth of the water is found to be less than the critical parameter, the cell is identified as “dry”, implying flux of ocean water from the cell is not allowed for the time step. Otherwise the cell is considered as ‘wet’, i.e. flux of ocean water is allowed.

Given the spatially invariant nature of the ROMS land/sea mask, the mask requires adjustments in performing simulation of inundation by storm surge. In this study, a maximum inundation elevation of +10 m is used, which indicates that a land with a height of +10 m at maximum can be submerged by seawater. On basis of the maximum inundation elevation, modification to the bathymetry of grid for numerical examples is made, and then an initial mask with a certain submerged space is obtained. It is worth noting that the movement of initial free surface to the real level surface should be carried out before calculating.

4. Results and discussion

4.1. Model validation

This article verifies the ROMS model with wind field effects in terms of the adaptability and accuracy in simulating storm surges in the Bohai Bay by simulating a cold wave-induced storm surge in October 2003. During the storm surge occurred in mid-October 2003, strong cold air from Siberia moved towards the southeast, causing a strong northeast wind to blow over the Bohai Sea (Li Y et al., 2019). Besides an average wind speed of 9–10 levels with an instantaneous maximum wind speed of 12 levels and a long duration of the strong wind, which pushed seawater towards the windward shore, October 11th is also the 16th day of the 9th lunar month, which is an astronomical high tide period, the combined effect caused an large increase in water level, and resulted in the strongest storm surge of cold wave type since 1992 along the southwestern coast of the Bohai Bay. Specifically, the water level in the western coast of the Bohai Bay sharply increased, and seawater has come ashore with a maximum tide level of +5.2 m, causing a direct economic loss of 244×10^6 CNY.

Fig. 2 shows the comparison between the calculated tide levels of Huanghua Port, Cangzhou and the predicted tide levels. The starting time is 00:00 on October 10th. The average simulation error is less than 10 cm and the relative error is within 4% for both high and low tide levels. The overall fit between the simulation results and the actual measurements is good. Fig. 3 shows the comparison between the calculated and the measured tidal levels of Huanghua Port. From the calculation results, the model can essentially reflect the increasing trend of the storm surge, but for simulation of high and low tide levels, it shows, more or less, error between the simulated and the predicted values. Wind drag coefficient in Equ. 8 was modified to achieve the external forcing boundary conditions required for simulation of the storm surges with 50-year and 100-year return periods.

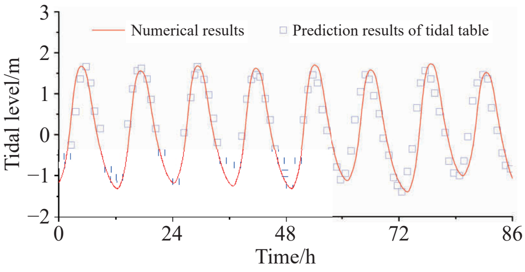

Fig. 2. Comparison of simulated and predicted tide levels during the storm surge in Huanghua Port.

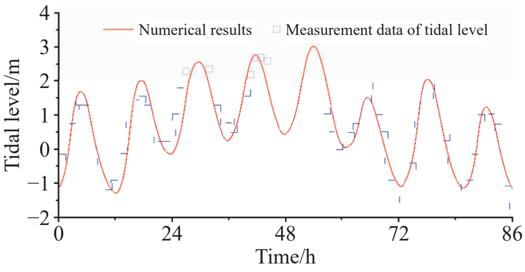

Fig. 3. Comparison of simulated and measured tidal levels during the storm surge in Huanghua Port.

4.2. Flooding area based on Elevation-Area Method

The water level in the Bohai Bay is +3.092 m for 50-year storm surge, and +3.262 m for 100-year (Wu SH et al., 2002). In accordance with the GIS-based Elevation-Area method mentioned above, the modeling results show that a 50-year storm surge can inundate 8126 km^2 of land (Fig. 4a; Table 1), and after taking into account the land subsidence and sea level rise due to climate change, the figure will increase to 8838 km^2 in 2050 (Fig. 4b; Table 1), and 9739 km^2 in 2100 (Fig. 4c; Table 1). Hangu, Tanggu, and Dagang along the coast of Tianjin City, as well as eastern area of Huanghua and northern area of Cangzhou City in Hebei Province, will be inundated. Moreover, major coastal engineering areas, except for parts of Tianjin New Port and Huanghua Port, will also be inundated. With respect to a 100-year storm surge, the area of land to be inundated is 8432 km^2 (Fig. 4d; Table 1), and after considering the land subsidence and sea level rise due to climate change, it will increase to 9085 km^2 in 2050 (Fig. 4e; Table 1), and 9907 km^2 in 2100 (Fig. 4f; Table 1). However, in reality, the floods during the process of flooding from the ocean to land is also negatively affected by many other factors, which are not included in the simulation, such as the friction between floods and the ground, and the duration of high water levels, leading to reduced energy capacity. Therefore, the actual flooded area will be, in all probability, much smaller than the above-mentioned ones.

4.3. Flooding area based on numerical model

In recent years, the land subsidence rate in the Tianjin Plain area has shown a trend of decreasing from a few centimeters per year to approximate 10 mm per year, and then to approximate 7 mm per year (Yi CR, 2017), which is also demonstrated by the data from Tianjin Municipal Bureau of Planning and Natural Resources. However, although according to our monitoring data of three coastal stations over the past 10 years has shown a decreasing trend, the average land subsidence rate is still up to approximate 10 mm per year. Moreover, the land subsidence rate of Huanghua, next to Tianjin, is ca.10–20 mm per year (Tian XW et al., 2018). Regarding the sea level rise in China, the monitoring data shows an accelerating trend since 2000 from 2.4 mm per year in 2000 (MNR, 2001) to 4 mm per year in 2022 (MNR, 2023). This article uses a land subsidence rate of 10 mm per year and an average sea level rise of 4 mm per year as the basic data for model prediction. That is to say, the relative sea level in the Bohai Bay area will rise at a rate of 14 mm per

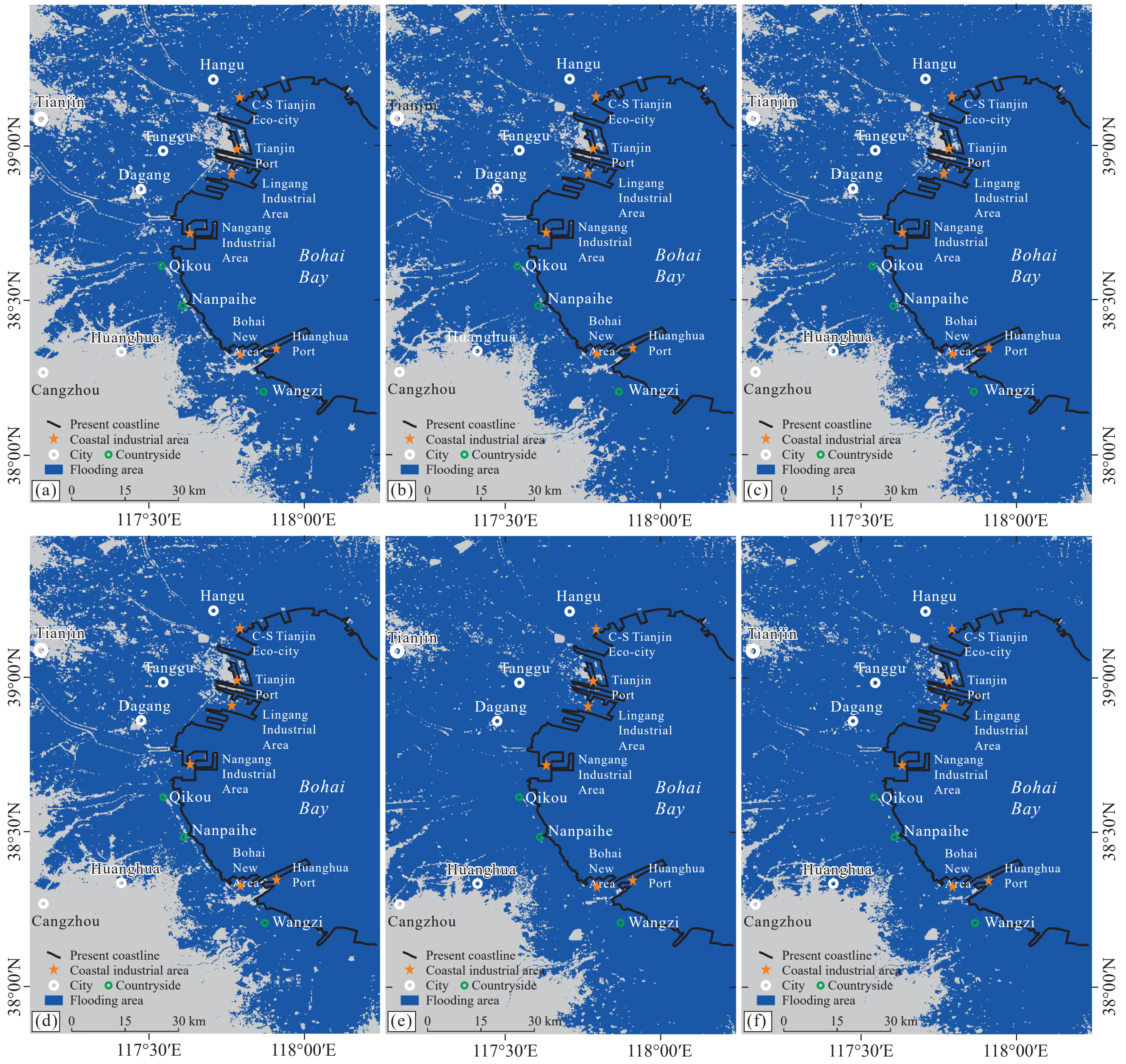

Fig. 4. Flooding area based on Elevation Area Method. a–c–inundated area by once in 50-year storm surge during 2020, 2050, 2100; d–f–inundated area by once in 100-year storm surge during 2020, 2050, 2100.

Table 1. Flooding area calculated based on Elevation-Area Method and hydrodynamic model.

Year	Based on elevation-area method/km^2		Based on hydrodynamic model/km^2	
	50-year storm surge	100-year storm surge	50-year storm surge	100-year storm surge
2020	8126	8432	2356	2437
2050	8838	9739	3067	3562
2100	9085	9907	5221	5854

year in future, with an accumulated rise of 0.42 m by 2050 and 1.12 m by 2100.

Based on a numerical model of hydrodynamic evolution, taking into account both the land subsidence and sea-level rise, simulations were conducted concerning the inundation range of 50-year and 100-year storm surges in 2020, 2050, and 2100, starting from 2020. The results show that:

(i) 2020. In 2020, numerical model simulations based on hydrodynamic evolution showed that the inundation area was 2356 km^2 for a 50-year storm surge (Fig. 5a; Table 1), and 2437 km^2 (Fig. 5b; Table 1) for a 100-year storm surge. Fig. 3 shows that except for the C-S Tianjin Ecological City and some urban areas of Hangu, some areas along the Haihe River in Tanggu, the original salt fields, shrimp ponds, and other water surfaces in the southern part of the Haihe River would be inundated, while the rest of the areas would be hardly affected. The flood inundation area predicted by the dynamic evolution model was much smaller than that by the Elevation-Area method, mainly due to the fact that the numerical model considered the resistance of ground friction to storm surge and

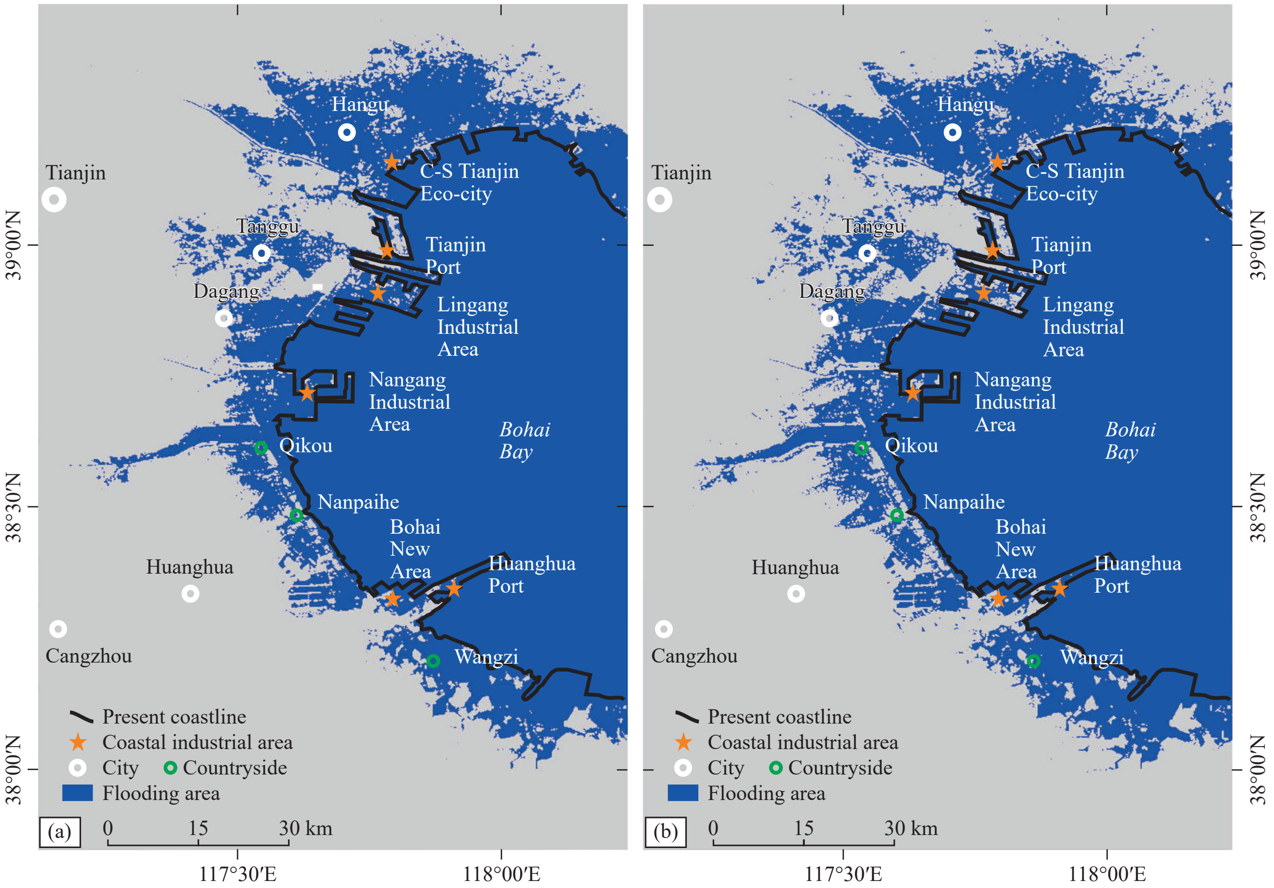

Fig. 5. Flooding area by hydrodynamic models in 2020.

land inundation, as well as the actual duration of high water level during storm surge.

(ii) 2050. Considering both the land subsidence and sea level rise, the inundated area would increase to 3067 km^2 by a 50-year storm surge (Fig. 6a), and to 3562 km^2 by a 100-year one, in 2050 (Fig. 6b; Table 1).

(iii) 2100. Likewise, the inundated area would increase to 5221 km^2 by a 50-year storm surge (Fig. 7a), and to 5854 km^2 by a 100-year one, in 2100 (Fig. 7b; Table 1).

As shown in Fig. 8, the dynamic processes of the high tide level floodplain under the condition of a 100-year return period in 2100 indicate that a strong easterly wind will quickly cause seawater to accumulate towards the west coast of the Bohai Sea, causing huge rise in water level in Bohai Bay area. The area along Haihe River of Tanggu and eastern area of Hangu will be inundated in the first day (Fig. 8a), and near coastal area of Dagang and Huanghua will be inundated in the second day (Fig. 8b), then the seawater will inundate the area along local rivers in the third day (Fig. 8c), and the inundated area will continue to increase in the fourth day (Fig. 8d).

4.4. Impact and adaptation to storm surge disasters

Storm surges are mainly formed by natural processes under the combined action of meteorological and astronomical tides, and currently they are beyond human control. Moreover, with changes in climate like sea-level rise induced by global warming, the extreme weather events are and continue to be more frequent and/or more intense, including heat waves, cold waves, storm surges etc. Therefore, more attention needs to be paid on this. According to statistics from the 2022 Bulletin of China Marine Disaster, storm surges account for 99% of all marine disaster losses in China (MNR, 2023). Fortunately, the disasters caused by storm surges are closely related to human activities, thus the loss of which can be markedly reduced by developing scientific response and adaptation plans through technologies such as accurate storm surge forecasting, storm surge disaster simulation, and zoning of storm surge disaster levels.

The simulation results show that the coastal area within about 10–30 km is a key area for risk and loss reduction of disaster due to storm surges, particularly given that a lot of major coastal engineering projects are located in this area, such as, for just the Bohai Bay, there are Central Fishing Port-Beijiang Power Plant, China-Singapore Tianjin Ecological City, Tianjin New Harbor-Lingang Economic Zone, Nangang Industrial Zone, Bohai New Area-Huanghua Harbor, etc.. The coastal areas of China can be mainly divided into two categories: one is the muddy subsidence coast, and the other one is the bedrock uplift coast (Wang F et al., 2023). The Bohai Bay is a typical muddy subsidence coast, which is highly susceptible to the sea level rise. Although it is protected by coastal embankments, the surface elevation of its coastal areas is relatively low, with large areas even below 0 m. Thus, once a storm surge floods, the seawater is extremely difficult to retreat.

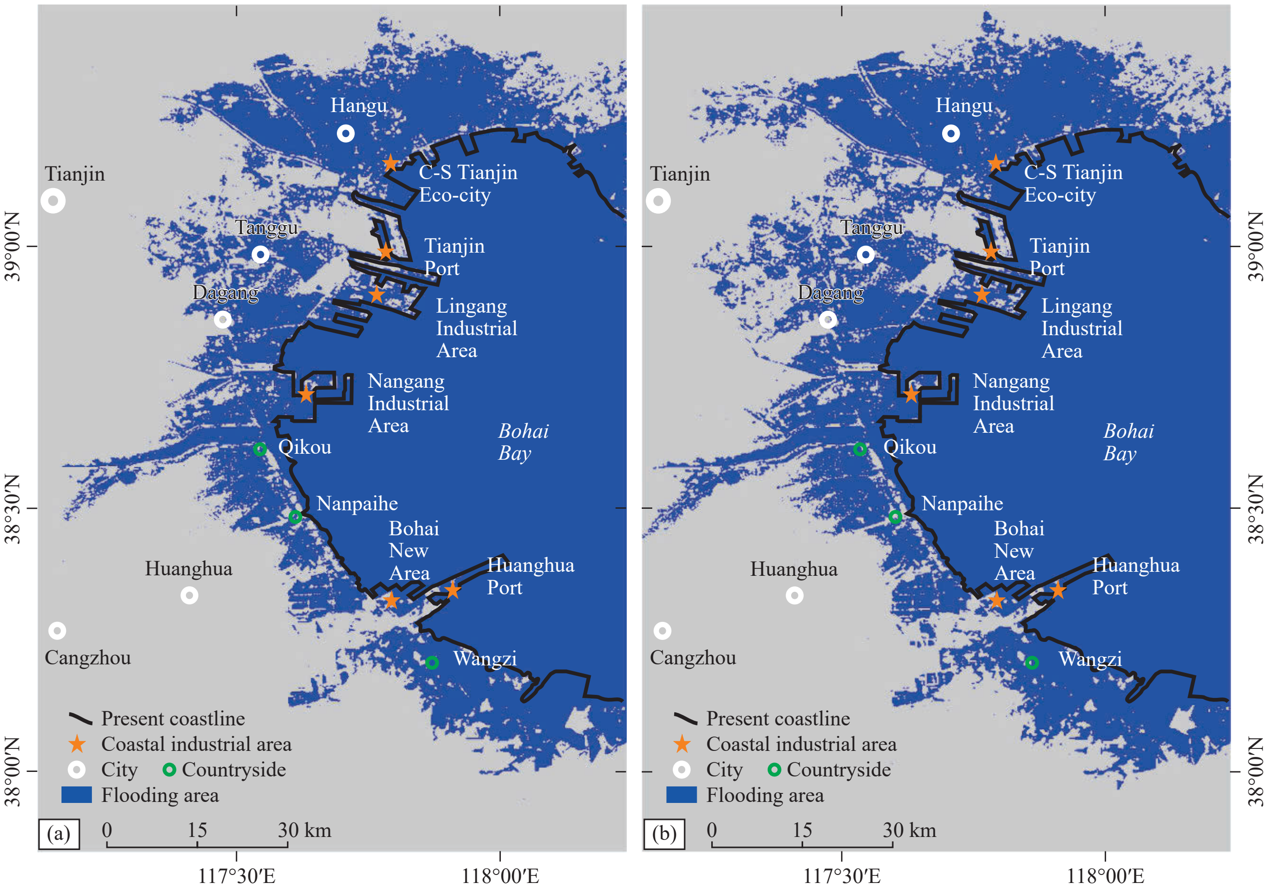

Fig. 6. Flooding area by hydrodynamic models in 2050.

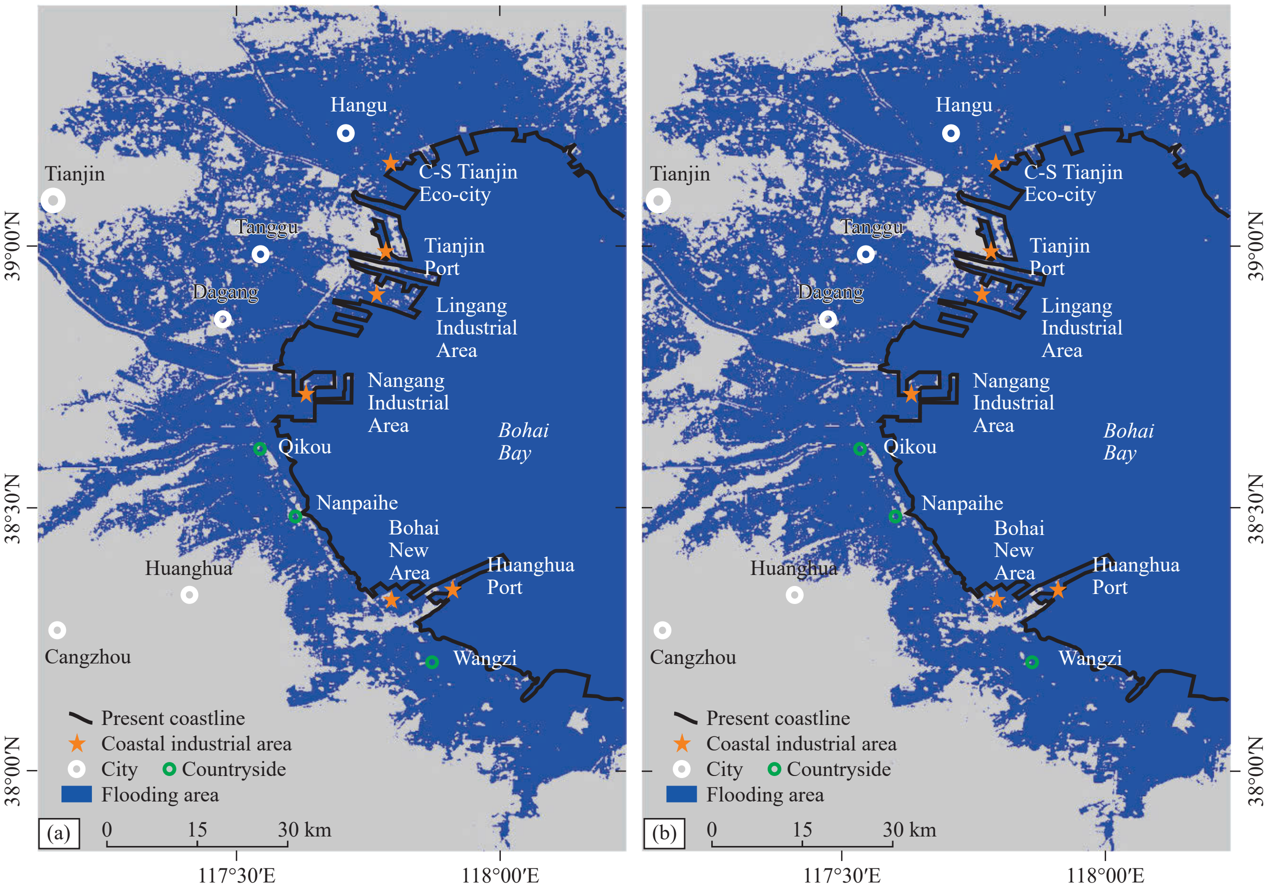

Fig. 7. Flooding area by hydrodynamic models in 2100.

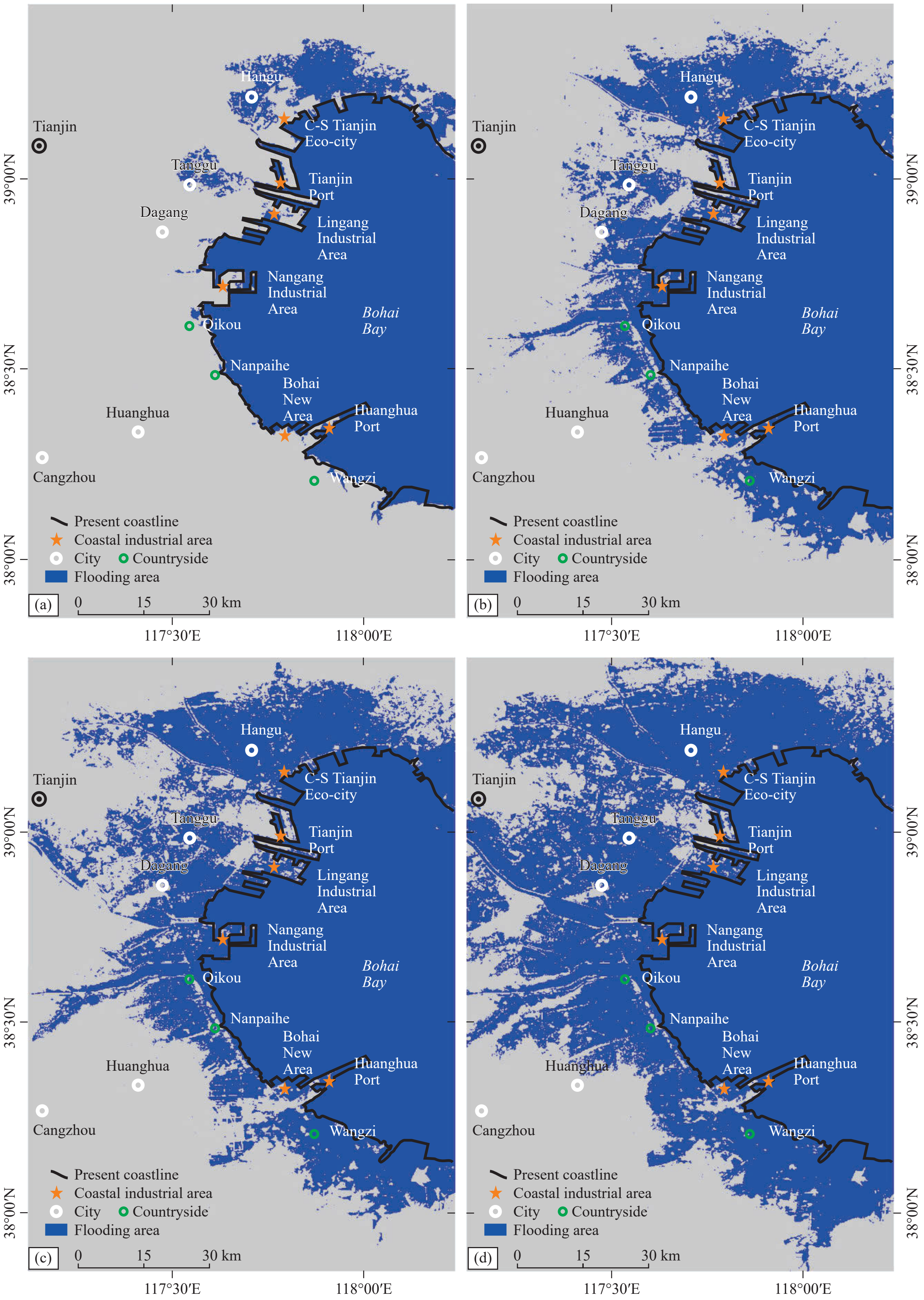

Fig. 8. Areas affected by storm surge for a return period of 100-year in 2100. a–d denote the first, second, third, and fourth days of the storm surge, respectively.

In the light of this, the recommendations are proposed as follows to cope with and adapt to the storm surge disaster in the Bohai Bay:

(i) Firstly, it is recommended to strengthen the construction of coastal embankments and then to build an oyster reef ecological corridor, and/or preferably a *Spartina alterniflora* corridor, on the seaward side of the coastal embankments, so as to enhance their protection capabilities.

(ii) Secondly, to strictly control land subsidence continuously. In recent years, the prevention and control of land subsidence have made notable achievements; which should be well maintained. Furthermore, more efforts are to be made to the areas with severe subsidence using targeted measures, in order to achieve comprehensive control of land subsidence.

(iii) Thirdly, to establish safety islands based on the current surface elevation, to plan and construct emergency evacuation routes for large communities or densely populated areas, to establish normalized emergency channels for sparsely populated areas, and to promptly notify personnel to transfer and if applicable, to provide assistance for personnel transfer, under the circumstance of storm surge;

(iv) Fourthly, to strengthen publicity and education, and training if applicable, on storm surge disaster and prevention through means of television, radio, Internet, community, etc., thereby improving people's awareness of and ability to disaster prevention.

(v) Finally, to strengthen the monitoring and early warning of storm surges.

5. Conclusions

This article simulates and predicts the impact of storm surges on the Bohai Bay, and draws the following main conclusions:

(i) In the current situation, without the protection of coastal embankments, the simulation results by Elevation-Area method show that the inundated area is 8126 km^2 of land for a 50-year storm surge and 8432 km^2 for a 100-year one, and taking into account the land subsidence and sea level rise, the figures will increase to 8838 km^2 and 9739 km^2 in 2050, 9085 km^2 and 9907 km^2 in 2100, respectively.

(ii) The numerical simulation results by hydrodynamic-based model show that the submerged area is 2356 km^2 of land for a 50-year storm surge and 2437 km^2 for a 100-year one, and considering land subsidence and sea level rise, the figures will increase to 3067 km^2 and 5221 km^2 in 2050, 3562 km^2 and 5854 km^2 in 2100, respectively.

(iii) The storm surge disaster will impose massive adverse effects on the coastal area within about 10–30 km of the Bohai Bay, in where almost all major coastal projects are located. The response to storm surge disasters is urgent, and five suggestions have been proposed in this regard.

CRediT authorship contribution statement

Fu Wang and Yong Li conceived of the presented idea and wrote the manuscript in consultation. Xue-zheng Liu, Yong Li and Heng Yu developed the numerical models. Fu Wang, Yong Li and Xue-zheng Liu provided figures and tables in the manuscript. Heng Yu, Ming-zheng Wen and Yun-zhuang Hu 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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