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ARTICLE

Quantitative Risk Assessment of Tropical Cyclone-Induced Extreme Waves on Marine Aquaculture Based on Physical Vulnerability

Jiayi Fang[1,2] · Siying Zhu[1,2] · Wanchao Bian[1,2] · Shuiqing Li[3] · Wankang Yang[4] · Zhihui Mo[1,2] · Siru Yang[1,2] · Peng Yun[5] · Yuhan Yan[5] · Xianwu Shi[6] · Junfeng Xu[1,2] · Tangao Hu[1,2]

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Abstract

Marine aquaculture plays a significant role in China's economic development, accounting for nearly one-third of the aquaculture industry. Tropical Cyclone (TC)-induced extreme waves are one of the primary factors that destabilize the structures of aquaculture net cages, resulting in substantial economic losses. However, current research on quantitative risk assessment in marine aquaculture is limited. To fill this gap, we took Northern East China Sea (NECS) as the study area to examine the potential impact of tropical cyclone-induced extreme waves on marine aquaculture. First, we simulated TC-induced extreme waves between 1979 and 2018 by a tightly coupled ADvanced CIRCulation (ADCIRC) model and Simulating Waves Nearshore numerical model, and calculated the probability of occurrence and return period of the hazard. Subsequently, by constructing the failure probability of net cage structures under different significant wave heights, we established a physical vulnerability function relating wave height to failure probability. Using the developed physical vulnerability curves, we assessed the risk faced by offshore marine surface aquaculture under extreme typhoon waves with different return periods, and calculated the expected loss for marine aquaculture. The research results reveal that the hazard of extreme typhoon waves exhibited a spatial pattern of higher occurrences in the vicinity of Qinhuangdao, the Shandong Peninsula, and the northern Jiangsu region compared to other coastal regions, and the risk of marine aquaculture is high in the southern part of Liaoning Province, the eastern part of Shandong Province, and the northeastern part of Jiangsu Province. It is crucial to enhance the capacity for disaster response, reduce potential losses, and improve the ability of marine aquaculture to withstand TC-induced extreme waves in these areas.

Keywords China · Failure probability · Marine aquaculture · Numerical simulation · Risk assessment · Tropical cyclone-induced extreme waves

✉ Jiayi Fang
jyfang@hznu.edu.cn

1 Institute of Remote Sensing and Earth Sciences, Hangzhou Normal University, Hangzhou 311121, China

2 Zhejiang Provincial Key Laboratory of Wetland Intelligent Monitoring and Ecological Restoration, Hangzhou 311121, China

3 Key Laboratory of Ocean Observation and Forecasting, Key Laboratory of Ocean Circulation and Waves, Institute of Oceanology, Chinese Academy of Sciences, Qingdao 266071, China

4 Ministry of Natural Resources, Second Institute of Oceanography, Hangzhou 310012, China

5 Zhejiang Institute of Hydraulics and Estuary, Hangzhou 310020, China

6 Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China

1 Introduction

The aquaculture industry is one of the fastest-growing sectors in China's agricultural production and is considered a vital strategic industry. China is the world's largest producer of aquatic products and holds the highest aquaculture production globally, with approximately 40% of global aquaculture products originating from China (State Council Information Office of the People's Republic of China 2023). The development of China's marine aquaculture industry has made significant contributions to meeting domestic and global seafood demands, reducing reliance on natural marine fishery resources, and promoting the scientific conservation and sustainable utilization of global fishery resources.

Aquaculture can be divided into freshwater aquaculture and marine aquaculture. According to the statistics, in 2022, the marine aquaculture area in China reached 2.074 million hectares, with a total production of 22.76 million tons, accounting for approximately 40.9% of the national aquaculture production. The value of marine aquaculture products amounted to CNY 463.88 billion yuan (about USD 68.97 billion for the 2022 exchange rate), with a production value ratio of 46.7:53.3 between marine and freshwater products (The People's Republic of China Ministry of Agriculture, Fisheries Bureau 2023). Therefore, marine aquaculture is a crucial pillar of China's agricultural industry.

Marine aquaculture industry faces various challenges and vulnerabilities, including water pollution, oxygen depletion, high temperatures, diseases, and extreme weather events (Klinger and Naylor 2012; Ottinger et al. 2016; Barange et al. 2018; Reid et al. 2019; Naylor et al. 2021). Among these, tropical cyclones (TCs) and flooding pose the greatest threat to the industry. According to the China Fishery Statistical Yearbook 2023, in 2022, the total losses in the national aquatic products sector amounted to USD 1,369.21 million, with losses caused by typhoons and flooding reaching USD 360.09 million (the 2022 USD value), accounting for 26.3% of the total losses. Marine aquaculture facilities are often located in nearshore and offshore areas, making them highly vulnerable to oceanic hazards such as TCs. They are susceptible to various forms of physical damage, and powerful cyclone-induced waves (also known as typhoon waves) caused by the passage of TCs are one of the primary factors that destabilize the structures of aquaculture net cages. Strong storms and waves can result in the fragmentation or displacement of cage nets, buoys, platforms, and other facilities, leading to the escape or death of farmed species.

China is one of the countries most affected by TCs and TC-induced waves (Fang et al. 2017). In recent years, TC-induced extreme wave heights in the Northern East China Sea (NECS) have been increasing (Feng et al. 2018; Li et al. 2018). With global climate change, TC-induced extreme waves may exhibit more uncertain changes, posing greater impacts on offshore activities, including marine production and aquaculture operations (Emanuel 2005; Guan et al. 2018). For example, there is evidence of a poleward shift in the location of maximum intensity for TCs (Kossin et al. 2014). This shift has resulted in an unfavorable situation for aquaculture in the NECS.

Research on the quantitative risk assessment of TC-induced waves on marine aquaculture is currently limited. Scholars have employed methods such as physical model experiment (Huang et al. 2006; Xu et al. 2013; Zhao et al. 2013; Bai et al. 2016) and numerical simulation (Zhang et al. 2021; Shi et al. 2022) to assess the structural safety of aquaculture facilities. Some studies have examined specific components of net cages, such as the failure life span of floating pipes (Bai et al. 2016), the failure probability of cables, and the mechanical performance of cage barriers (Liu et al. 2017). These investigations analyzed the probability of component failure in net cages during TC events and explored the relationships between typhoon waves and component failure probability, aiming to optimize cage structures. These studies were carried out at a local scale from a coastal or ocean engineering perspective, with a focus on net cage dynamic response and deformation. Although these studies have made progress in experimental research, there is still a need for large-scale spatial quantitative risk assessments of TC-induced extreme wave impact on marine aquaculture, with a focus on the physical vulnerability. Therefore, further exploration is necessary to understand the physical vulnerability and risk of marine aquaculture in relation to TC-induced extreme waves.

This study primarily focused on the physical vulnerability of marine aquaculture facilities. By utilizing ocean hydrodynamic simulations and physical vulnerability experiments of aquaculture facilities, a quantitative risk assessment method based on physical vulnerability curves for marine aquaculture facilities was developed to achieve large-scale spatial quantitative evaluations. First, the ADvanced CIRCulation and Simulating Waves Nearshore (ADCIRC+SWAN) coupled model was employed to simulate historical typhoon events between 1979–2018 in the NECS, obtaining the characteristic distribution of significant wave heights during typhoon passages in the eastern waters of China and analyzing the risk levels of extreme typhoon waves in this region. Second, the failure probabilities of key components of net cages (floating rings, nets, mooring ropes) were analyzed, and physical vulnerability curves for their response to extreme typhoon waves were constructed. Based on the spatial characteristics of extreme typhoon waves and the physical vulnerability curves of net cage failures, a quantitative risk assessment model for offshore marine surface aquaculture was developed to evaluate the extent of damage in aquaculture areas and calculate the expected losses, providing a reference for the prevention of typhoon wave disasters in the aquaculture sector.

The structure of this article is as follows: In the second part, we introduce the research methodology, including the simulation of typhoon processes and typhoon waves using the ADCIRC+SWAN coupled model, the calculation of significant wave heights under different return periods based on extreme value theory models, the prediction of the failure probability of net cage key components under the action of extreme typhoon waves, and the construction of a quantitative risk assessment model. The third part presents the main results of this study. The fourth part is dedicated to discussions and prospects. Finally, the fifth part provides a summary of the study.

2 Data and Method

This section presents a detailed description of the study area, data sources, and methods employed. By integrating numerical simulation results with physical vulnerability curves, a large-scale risk assessment framework was developed. This framework enables the quantitative assessment of TC-induced wave impacts on offshore marine surface aquaculture.

2.1 The Study Area

We selected the NECS as the study area (Fig. 1), covering the coordinates 117°E–128°E and 31°N–41.1°N. The NECS is characterized by a wide continental shelf with water depths generally shallower than 200 m, consisting of an inner gulf—the Bohai Sea, and an outer gulf—the Yellow Sea (Li et al. 2020). There are five provincial-level administrative regions—Liaoning Province, Hebei Province, Tianjin Municipality, Shandong Province, and Jiangsu Province (from north to south). This region is a marginal sea located in the western North Pacific Ocean, which is one of the areas that most severely affected by TCs. It was reported that 41 TCs passed through the NECS from 1979 to 2018. It consists of 17 fishing grounds. This area accounts for 70.9% of the total aquaculture area in China and exhibited a rapid growth from 2000 to 2020 (Liu et al. 2023). Notably, Shandong Province emerged as the leading province with the largest aquaculture area, encompassing approximately 39% of the total nationally (Liu et al. 2020).

2.2 Data

The simulation of TC-induced extreme waves for the NECS was achieved by a tightly coupled ADCIRC model and SWAN numerical model. The datasets that support the coupled model including geographic data and meteorological

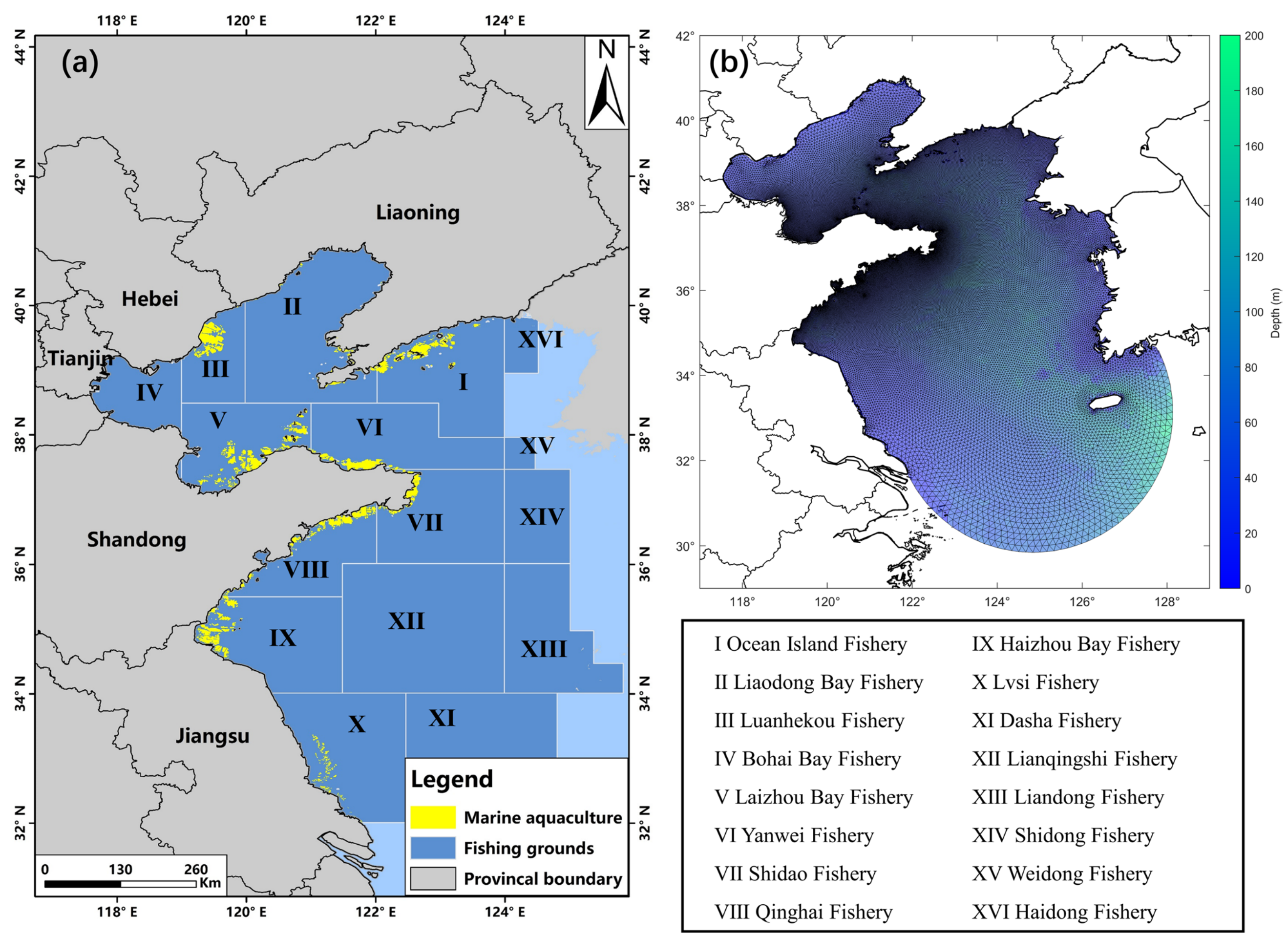

Fig. 1 The study area—the Northern East China Sea (NECS). **a** Distribution of marine aquaculture and fishing grounds in the NECS (data for fishing grounds were from the North Sea Forecasting and Disaster Reduction Center of the Ministry of Natural Resources); **b** bathymetry and unstructured grid of the computational domain

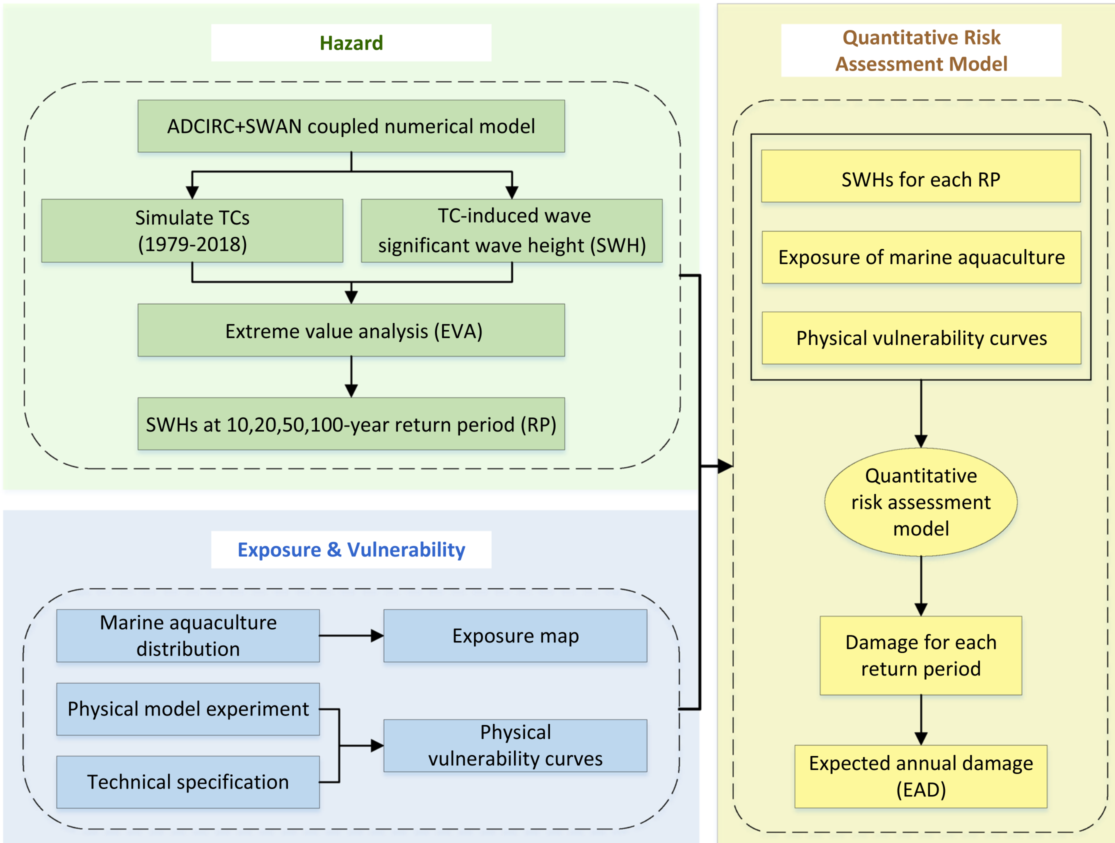

Fig. 2 Flowchart showing the general methodological approach of the research where the three components of risk—hazard, exposure, and vulnerability—are combined in a quantitative risk assessment model

data are as follows: the bathymetry data are the General Bathymetric Chart of the Oceans (GEBCO)[1] with a resolution of 15′; wind and air pressure data are provided by ERA5 (Hersbach et al. 2018); TC best-track data with information of time, location, air pressure, and intensity were extracted from the Best Track Dataset for Tropical Cyclones in the Western North Pacific, which was provided by the Shanghai Typhoon Institute of the China Meteorological Administration (Ying et al. 2014).[2]

In this study, we focused on offshore marine surface aquaculture. Offshore marine surface aquaculture refers to the practice of cultivating aquatic organisms, such as fish, shellfish, and algae, in the surface waters of the ocean, typically in controlled or semi-controlled environments (Liu et al. 2022). This form of aquaculture is distinguished from other types, such as bottom net-cage aquaculture and land-based marine aquaculture, by its location and method of cultivation. The offshore marine surface aquaculture dataset is from the National Earth System Science Data Center.[3] This dataset covers visible marine aquaculture on the water surface, including cage, raft, and hanging net farming (without specific distinction of types). Using Sentinel-2 and Sentinel-1 dense time-series imagery, this dataset employed object-oriented and visual interpretation methods to provide the spatial distribution of offshore aquaculture along the Chinese coasts (Wang et al. 2018; Liu et al. 2020).

To analyze aquaculture losses, official government statistics data of historical damages and aquatic products were collected from the China Fishery Statistical Yearbooks, covering the period from 2000 to 2023.

[1] GEBCO is available at https://www.gebco.net/data_and_products/gridded_bathymetry_data/.

[2] www.typhoon.org.cn

[3] Offshore marine aquaculture data are available from the National Earth System Science Data Center, National Science & Technology Infrastructure of China at http://www.geodata.cn, with DOI of 10.12041/geodata.122606915581534.ver1.db.

2.3 Methods

This study proposed a framework (Fig. 2) for quantitative risk assessment of marine aquaculture. First, TC waves were simulated by a tightly coupled ADCIRC+SWAN model for the NECS covering the four decades from 1979 to 2018, with 41 TC events. Extreme waves of different return periods were calculated by extreme value analysis. Second, physical vulnerability curves for marine aquaculture were built by representing failure probabilities for given extreme wave heights. Finally, a quantitative risk assessment was conducted by combing the three components of risk—hazard, exposure, and vulnerability, to compute the expected annual damages (EAD).

2.3.1 Assessment of the Hazard—Tropical Cyclone-Induced Extreme Waves

The ADCIRC model has been widely used to predict tides and storm surges (Luettich et al. 1992). It is built in an unstructured triangular mesh to solve fluid equations using the finite element method. The SWAN model is the third-generation wave model developed by Delft University of Technology (Booij et al. 1999). The ADCIRC+SWAN model couples the ADCIRC and SWAN models by swapping data in the same grid (Dietrich et al. 2011; Santiago-Collazo et al. 2019). The computational algorithms can be found in the model user manual by Luettich and Westerink (2004). This model is widely applied to simulate extreme waves and storm surges for coastal areas (Feng et al. 2018; Shih et al. 2018; Vijayan et al. 2023).

The ADCIRC+SWAN coupled model was forced by a constructed wind field from the Holland parametric TC wind model and satellite-observed TC best tracks. The unstructured triangular mesh includes 49,094 nodes and 95,682 triangular elements (Fig. 1b). The grid resolution of the model ranges from 500 m on the coastline for the NECS to 10 km along the abyssal open boundary. Time intervals of the ADCIRC and SWAN model are respectively 1 second and 30 minutes. The SWAN and ADCIRC exchange data every 10 min. The model outputs simulated results every 6 hours. The coupling of the physical mechanism and validation were described in detail in Wang et al. (2019) and Li et al. (2020). The coupled model had been fully validated using the nearshore wave observations, with relative errors (the ratio between the bias and mean) generally within a magnitude of ~5% (Wang et al. 2019), which indicates that it can effectively reproduce TC wave heights from offshore deep waters to nearshore shallow water regions.

The analysis focused on extreme significant wave height (SWH) in terms of return periods. To calculate different return periods of TC-induced extreme waves in local nearshore areas, extreme value analysis was employed

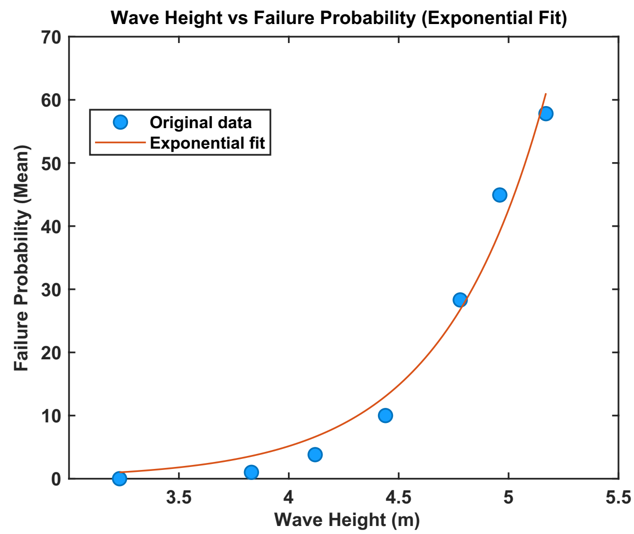

Fig. 3 Physical vulnerability curve for marine aquaculture

(Shi et al. 2021). The maximum SWHs in each calculation grid was extracted to construct the 1979–2018 extremum sequence for each calculation grid in the study area.

The Gumbel model was used to calculate the probability distribution of SWHs at each grid with a return period of 2, 5, 10, 20, 50, and 100 years to form a spatial distribution field of wave heights in the study area corresponding to different return periods to assess the risk of TC-induced extreme waves in this area. Based on the extreme samples of the wave height, the Gumbel model was used as a frequency analysis method to evaluate the return period value of typhoon wave height at each grid. The Gumbel distribution model is expressed as follows (Coles et al. 2001; Fang et al. 2021).

$$F(x) = e^{-e^{\frac{x-\mu}{\beta}}} \quad (1)$$

In Eq. 1, x refers to the extreme samples, μ is the location parameter, and β is the scale parameter. Based on the simulated storm surges during 40 years, the TC-induced SWHs were calculated at each grid along the coastline.

2.3.2 Physical Vulnerability Curves for Marine Aquaculture

In our case, the physical vulnerability of marine aquaculture is represented by a wave height-damage function (or vulnerability curve) that estimates the damage for a given extreme wave height. Using physical model experiment and numerical simulation, Shi et al. (2022) developed physical vulnerability curves of the cage components (floating collar, nets, and mooring lines) under TC-induced extreme waves at different return periods using the lumped-mass and finite element methods. The failure probability of the cage components was analyzed based on the Monte Carlo method. To convert these components into one curve for marine aquaculture, we took the average based on experiment results for marine aquaculture facilities—see Fig. 3 and Eq. 2.

$$P(H) = 0.001101 \exp\left(2.11 SWHs_{2,5,10,20,50,100}\right) \quad (2)$$

To verify the reliability of the physical vulnerability curves for marine aquaculture, we also refer to the "Technical Specifications for the Investigation and Assessment of Key Hazards in Marine Disasters – Aquaculture," provided by the Ministry of Natural Resources of the People's Republic of China. It is one of the 109 assessment and zoning technical specifications that were formulated, revised, and carried out during the first National Comprehensive Survey on Natural Disaster Risks in China. These technical specifications solve the long-standing problem of inconsistent technical specifications and standards, and support specifications and zoning under a unified technical system. In this Technical Specifications, damage level is divided into three grades. Grade I: TC-induced SWHs of 10-year return period is higher than 5.5 m, and aquaculture facilities have sustained significant damage, resulting in a complete loss of aquaculture function; Grade II: SWHs of 10-year return period is higher than 4 m and less than 5.5 m, some components of the aquaculture facilities have been damaged, leading to a partial impact on aquaculture function; Grade III: SWHs of 10-year return period is higher than 3 m and less than 4 m, aquaculture facilities remain undamaged or have incurred only minor damage, with no significant impact on aquaculture function. This qualitative description of damage level aligns well with the experiment results shown in Fig. 3.

2.3.3 Quantitative Risk Assessment

A quantitative risk assessment model integrates the three key components of risk, that is, hazard, exposure, and vulnerability, to quantify the expected annual damages (EAD). Expected annual damages represent the projected impact of potential adverse events or risks in terms of economic losses. The calculation involves considering the probabilities of various damage scenarios and their corresponding monetary values. The formula for calculating EAD, as expressed in Eq. 3, involves integrating the product of the loss of marine aquaculture areas $D_\theta(p)$ considering the vulnerability curve (θ) specific to the marine aquaculture sector and its associated probability of occurrence (p) for extreme events.

$$EAD = \int_{p=0}^{1} D_\theta(p)dp \quad (3)$$

In this study, EAD is expressed in two ways: expected loss ratio per year, and expected economic losses per year for marine aquaculture. Due to the lack of monetary values of marine aquaculture for each province, we used an approximated number to assess expected economic losses. According to the China Fishery Statistical Yearbook 2023, the output value of marine aquaculture in 2022 amounted to CNY 463.9 billion yuan, while the current marine aquaculture area in China spans 20,740 km^2. Consequently, an approximate value of CNY 22.4 million yuan per km^2 has been used as a proxy for output value per km^2, facilitating subsequent estimations of expected economic losses. Furthermore, the EAD values are aggregated at the provincial level, allowing for a comprehensive assessment of the potential economic impacts on marine aquaculture across different regions. $P(H)$ refers to the probability of loss for each return period. $F(A)$ refers to areas of marine aquaculture. The average economic output of marine aquaculture per km^2 is $A(E)$, and the expected economic loss is $E(L)$.

$$D\left(L_{2,5,10,20,50,100}\right) = F(A) \times P\left(H_{2,5,10,20,50,100}\right) \quad (4)$$

$$\begin{aligned} E(L) = {} & \mathrm{D}\left(\mathrm{L}_2\right) \times \mathrm{A(E)} \times 50\% + \mathrm{D}\left(\mathrm{L}_5\right) \times \mathrm{A(E)} \times 20\% \\ & + \mathrm{D}\left(\mathrm{L}_{10}\right) \times \mathrm{A(E)} \times 10\% + \mathrm{D}\left(\mathrm{L}_{20}\right) \times \mathrm{A(E)} \times 5\% \\ & + \mathrm{D}\left(\mathrm{L}_{50}\right) \times \mathrm{A(E)} \times 2\% + \mathrm{D}\left(\mathrm{L}_{100}\right) \times \mathrm{A(E)} \times 1\% \end{aligned} \quad (5)$$

3 Results

This section elaborates on the main findings of the study. It encompasses the hazard assessment of TC-induced extreme waves for various return periods, as well as the estimation of expected economic losses.

3.1 Assessment of the Hazard—Tropical Cyclone-Induced Extreme Waves

Figures 4 and 5 and Supplementary Fig. 1[4] illustrate the SWHs derived from the ADCIRC+SWAN model for different return periods, at the provincial level (30 km buffer zone), fishing ground level, and mesh grid level, respectively.

According to Fig. 4, the SWHs due to TCs are generally below 4 m in the 10-year and 20-year return periods. During the 50-year return period, the SWHs increased significantly

[4] https://doi.org/10.5281/zenodo.15165339

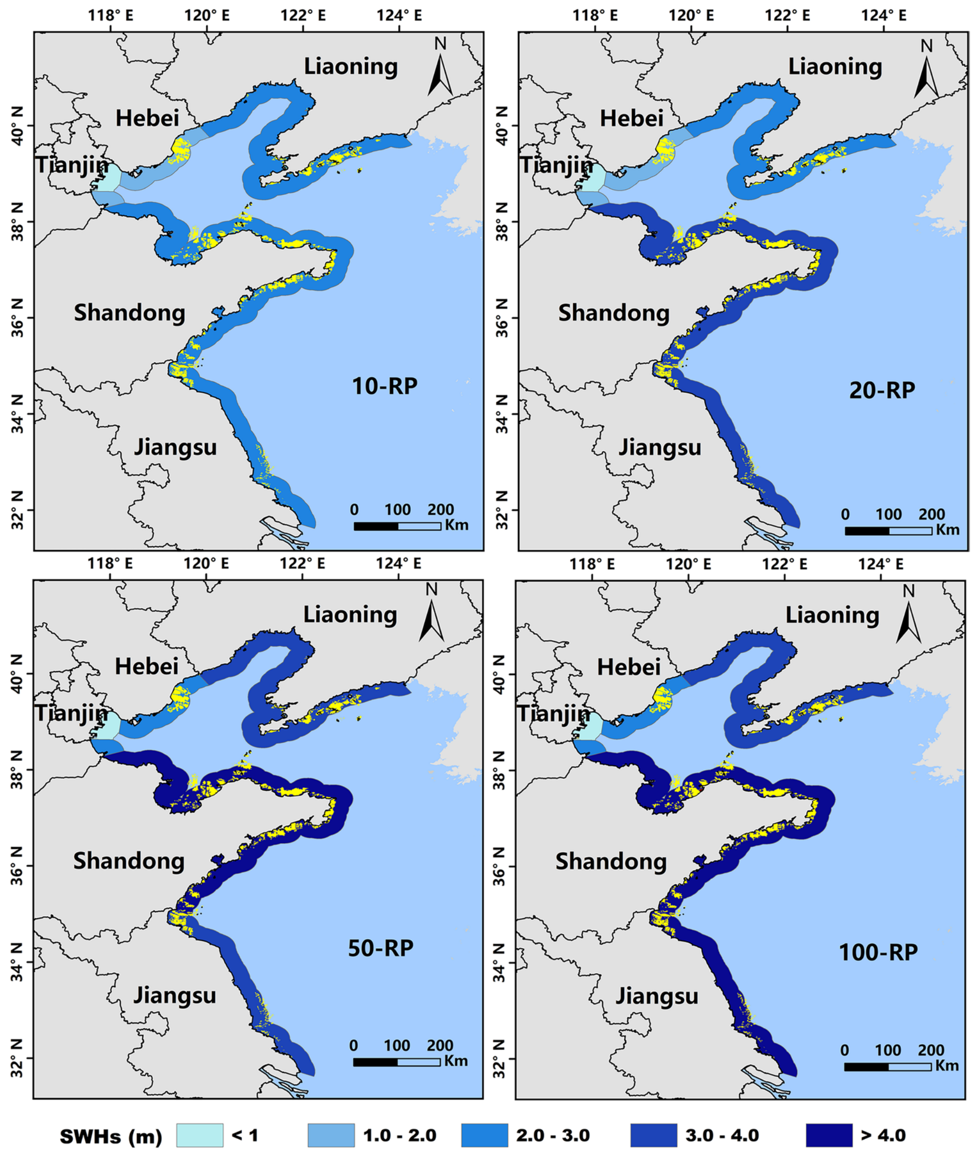

Fig. 4 Significant wave heights (SWHs) for each province under 10, 20, 50, and 100-year return periods (RP). Distribution of marine aquaculture is represented in yellow. The buffer zone is 30 km

in various locations, most notably on the buffer zone off the coast of the Shandong Peninsula, where the wave heights exceed 4 m. The wave heights continued to increase during the 100-year recurrence period, and the SWHs along the coast of the Shandong Peninsula and the coast of Jiangsu Province exceed 4 m (also shown in Supplementary Table 1)[4] (VIII).

Figure 5 shows that extreme waves in the open sea (more than 100 km away from the coastline) are much higher compared to extreme waves along the coasts. The average SWHs in the Bohai Sea basin are lower compared to the average SWHs in the Yellow Sea basin. Therefore, aquaculture activities in the Bohai Sea basin are relatively less affected by TC-induced waves, and aquaculture in the Yellow Sea area is more affected by TC-induced waves together with the fisheries that are more seriously affected by typhoon waves. The corresponding average SWHs for each fishing ground under different recurrence periods are analyzed (Supplementary Table 2)[4]. The SWHs caused by TCs are generally below 5 m for the 10-year and 20-year return periods. However, for the 50-year return period, there is a notable increase in SWHs, with the majority of wave heights falling within the range of 5 to 10 m. The results show that Ocean Island Fishery (I), Laizhou Bay Fishery (V), Yanwei Fishery (VI), Shidao Fishery (VII), Qinghai Fishery (VIII) and Haizhou Bay Fishery (IX) experience more severe wave intensities in comparison to other fishing grounds. Among them, a large number of fishing grounds are distributed in the sea area near Shandong due to its rich fishery resources and geographical advantages, but at the same time, the open sea area of the region also creates a situation where it is extremely vulnerable to typhoon waves. In the Tianjin coastal area, due to its natural topographical advantages, the height of

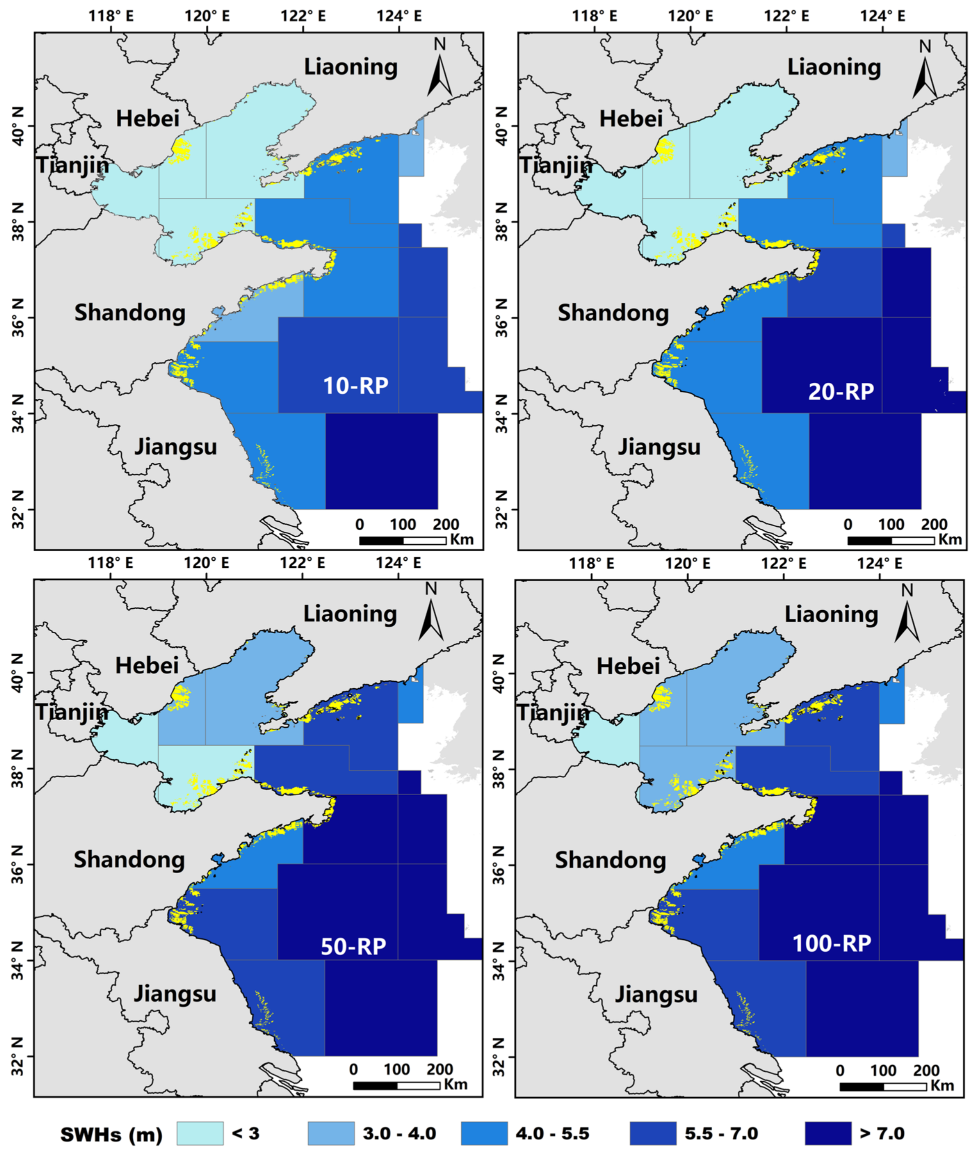

Fig. 5 Significant wave heights (SWHs) for 17 fishing grounds (Fig. 1) under 10, 20, 50, and 100 return periods (RP). Distribution of marine aquaculture is represented in yellow

the typhoon wave is relatively low, so the impact on the aquaculture by typhoon waves is also less. Although the majority of offshore aquaculture facilities are situated in nearshore areas (less than 50 km away from the coastline), extreme waves in the open sea, despite the absence of such facilities, can still pose a significant threat to the operational safety of offshore fishing vessels and any potential future aquaculture endeavors in those areas. Therefore, the influence of wave intensity should be considered not only for nearshore aquaculture but also for offshore fishing endeavors.

3.2 Expected Loss for Marine Aquaculture

Figure 6 illustrates the probability distributions of damage extent. Within the 10-year RP and 20-year RP intervals, the likelihood of damage to most fisheries remains relatively low, rarely exceeding 2%, except for a minority of fisheries in Liaoning and Shandong Provinces, where the probabilities approach 10%. For the 50-year RP and 100-year RP, a marked increase in the probability of damage is observed for individual fisheries. Specifically, the majority of fisheries in Liaoning and the northern regions of Shandong experience damage probabilities ranging from 10% to 50%. Some fisheries incur a damage probability of 50%–100%, posing a risk of total destruction, which constitutes a severe threat to aquaculture activities. Conversely, fisheries in Hebei and southeastern Jiangsu Provinces exhibit a slightly lower damage probability, remaining below 2%. At the 100-year RP, fishing grounds in Liaoning and Shandong are virtually facing total destruction, with damage probabilities spanning 50%–100%, incurring substantial economic losses. Even in Hebei, the damage probability has escalated to 10%. From the perspective of expected loss ratio, most aquaculture

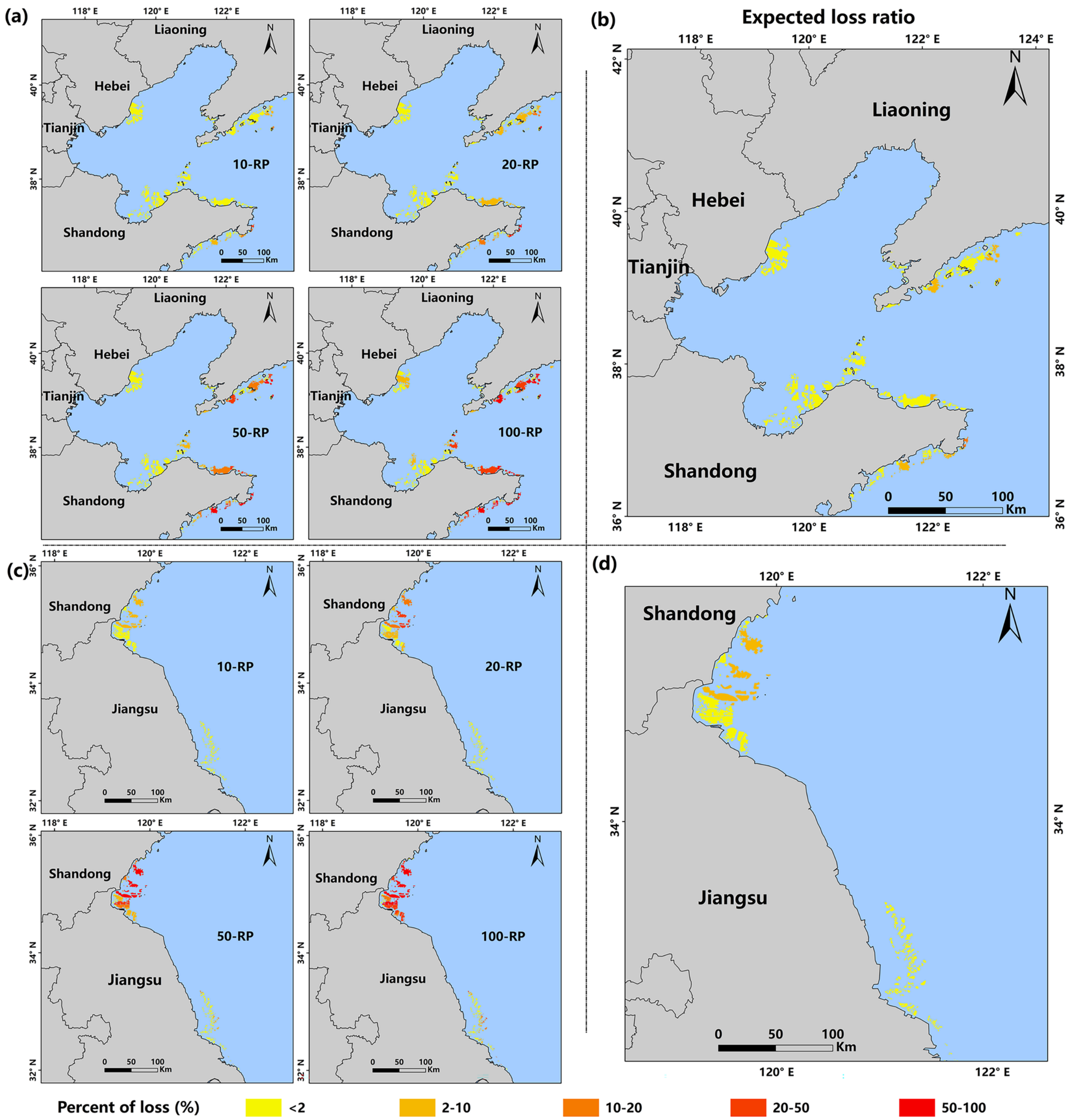

Fig. 6 Expected loss rate distribution for fisheries in each province due to tropical cyclone (TC)-induced waves at 10, 20, 50, and 100-year return periods. **a** Regions including Liaoning, Hebei, Tianjin, and the northern part of Shandong Province at 10, 20, 50, and 100-year return periods; **c** Regions including the southern part of Shandong and Jiangsu Province at 10, 20, 50, and 100-year return periods; **b** and **d** Expected loss ratio per year

areas experience less than 2% damage per year. Some parts in Liaoning and Shandong exhibit damage from 2%–10% per year. However, a small fraction of fisheries in Shandong Province faces a damage probability exceeding 10% per year, indicating a relatively low resilience against TC-induced waves.

Based on the calculation results presented in Fig. 7, several hotspot fisheries have been identified as exhibiting pronounced physical vulnerability to extreme typhoon waves across varying return periods. These include Ocean Island Fishery (I) in southern Liaoning Province, Yanwei Fishery (VI) and Shidao Fishery (VII) in eastern Shandong Province, Qinghai Fishery

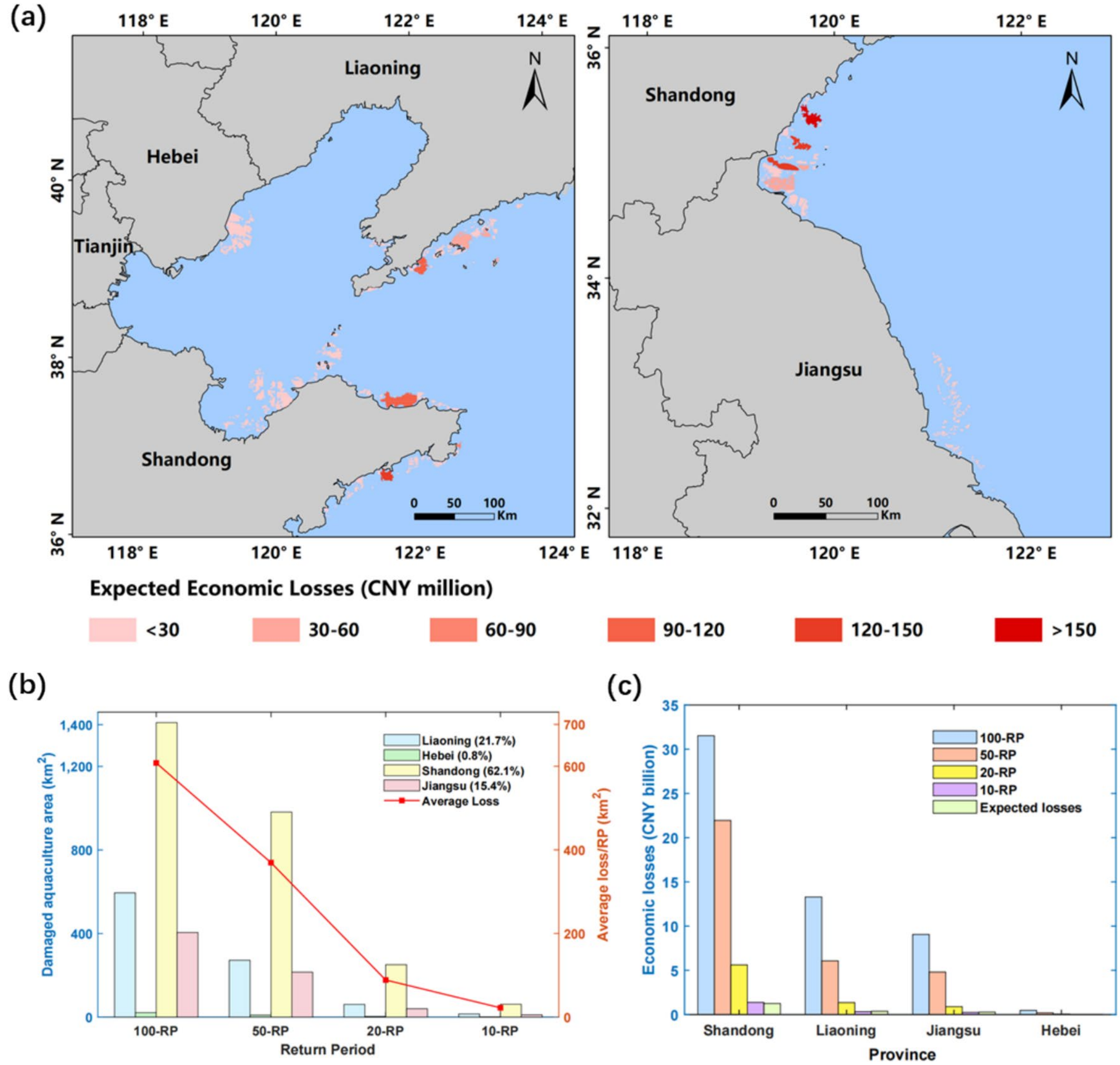

Fig. 7 **a** Expected economic losses of marine aquaculture per year due to tropical cyclone (TC)-induced waves. **b** Damaged aquaculture areas and average loss for each province at 10, 20, 50, and 100-year return periods. **c** Economic losses at 10, 20, 50, and 100-year return periods, and expected economic losses for each province

(VIII) in southeastern Shandong Province, and Haizhou Bay Fishery (IX) in northeastern Jiangsu Province. Some regions in Liaoning and Shandong are projected to incur annual economic losses exceeding CNY 90 million yuan, aligning with the distribution of loss probabilities. These fisheries exhibit significant vulnerability, marked by high expected loss values in the face of extreme typhoon waves. Shandong suffers the most extensive damage to aquaculture areas, with over 1,400 km^2 affected, corresponding to expected economic losses of approximately CNY 31 billion under a 100-year return period. Liaoning follows, with approximately 600 km^2 of damaged aquaculture areas under a 100-year RP, incurring losses of nearly CNY 6 billion. From the perspective of expected annual economic losses, Shandong experiences CNY 1.25 billion loss, Liaoning incurs CNY 378 million loss, and Jiangsu suffers CNY 275 million loss. In total, the NECS region experiences an expected annual loss of CNY 1.92 billion due to TC-induced extreme waves, posing a major setback to fishery production activities, the livelihoods of fishermen, and other related sectors.

4 Discussions

In this section, historical data on aquaculture losses from the China Fishery Statistical Yearbooks and a comparison of these historical losses with the expected economic losses due to TC-induced waves are discussed. Then, a discussion of the implications of our study for the field of fishery insurance follows.

4.1 Implication from Historical Damages

To understand historical changes of damages due to TC-induced waves, we collected economic losses data and used the Consumer Price Index to adjust economic losses to the 2023 values, so that it could be directly compared across different years. Figure 8a clearly shows that in most years, losses in aquatic products and damage to fishery facilities caused by TC-induced waves accounted for over half of the total direct economic losses in aquaculture activities, and in some years, such as 2017 and 2021, these losses even reached up to 80% of the total economic losses. Aquatic product losses and fishing facilities losses due to TCs accounted for 37.6% and 18.7%, respectively. Losses attributed to other factors, including disease and pollution, accounted for less than 50% of the total. Furthermore, the magnitude of economic losses incurred in aquaculture due to typhoon waves was substantial, with 2014 being a notable example where typhoon waves caused economic losses of up to CNY 30 billion yuan. This underscores the fact that typhoon waves were a primary contributor to economic losses in aquaculture. Typically, the direct economic losses stemming from the loss of aquatic products due to TC waves exceeded those caused by damage to fishery facilities. With advancements in science and technology, as well as emergency management, and the continuous improvement of aquaculture practices, the overall direct economic losses from aquaculture activities have exhibited a fluctuating downward trend in recent years. Nevertheless, the proportion of losses in aquatic products and damage to fishery facilities

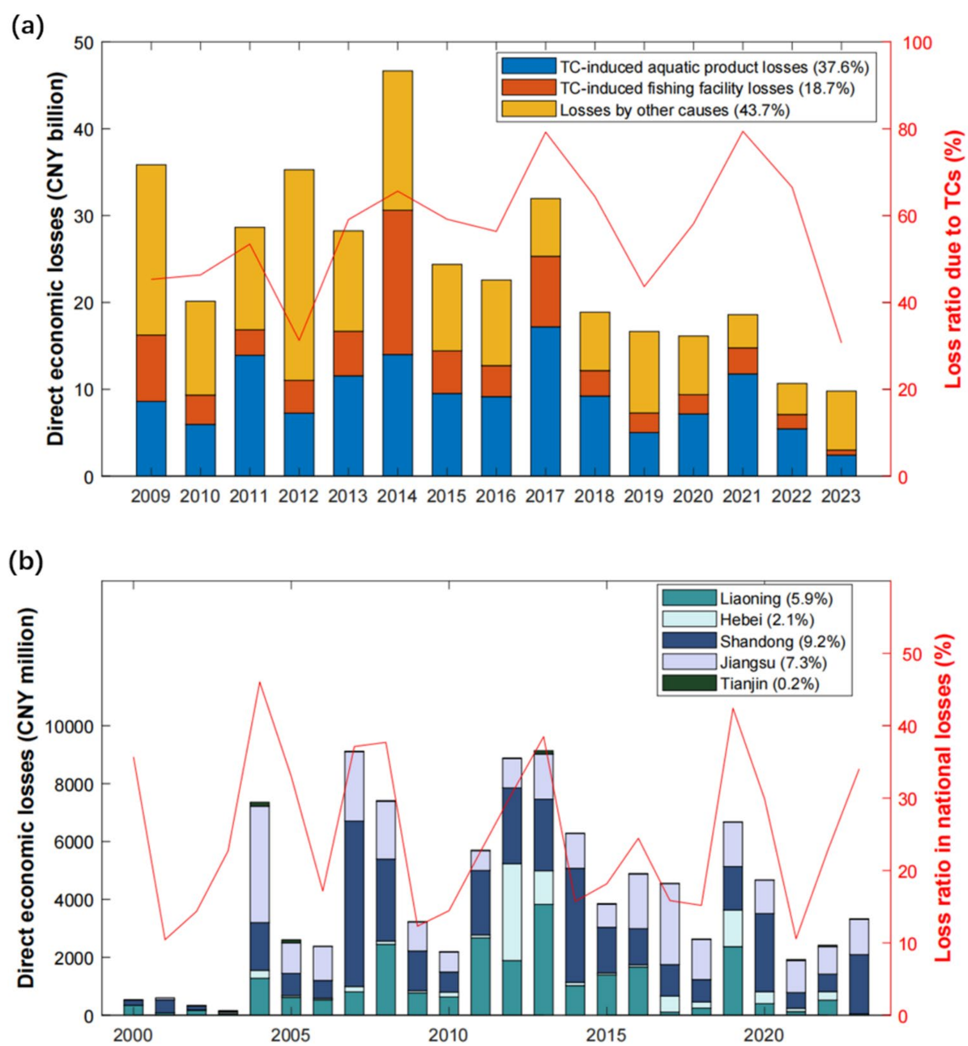

Fig. 8 **a** Direct economic losses between 2009 and 2023 due to tropical cyclones (TCs) including losses of aquatic products and losses of fishing facilities, and economic losses caused by other factors. The red line refers to the ratio of losses caused by TCs (encompassing both aquatic product losses and fishery facility losses) and the total losses incurred during this period. **b** Direct economic losses incurred in aquaculture in Liaoning, Hebei, Shandong, Jiangsu, and Tianjin from 2000 to 2023. The red line represents the percentage of the aggregated provincial losses in the national aquaculture losses during this period

attributed to typhoons and waves has not decreased proportionally with the reduction in total losses. This indicates a pronounced vulnerability of aquaculture in addressing threats posed by typhoons and waves.

Figure 8b depicts the direct economic losses incurred in aquaculture activities in the five provinces of Liaoning, Hebei, Shandong, Jiangsu, and Tianjin over a 23-year period, spanning from 2000 to 2023, as well as their respective shares in the national economic losses stemming from aquaculture. Generally, due to the unpredictable nature of tropical cyclone disasters, the economic losses suffered by these five provinces varied annually. However, in comparison, Shandong Province consistently experienced a substantial amount of economic losses, averaging a 9.2% share in the national loss rate over the 23-year period, peaking at nearly CNY 6,000 million yuan in 2007. Jiangsu Province followed closely, with an average national share of 7.3%, and its aquaculture activities experienced the highest direct economic losses, amounting to approximately CNY 4,000 million yuan, in 2004. Liaoning Province, contributing 5.9% on average, also experienced significant losses, reaching nearly CNY 4,000 million yuan in 2013. Hebei Province, averaging a 2.1% share in the national loss rate, suffered its highest losses in 2012, totaling approximately CNY 2,500 million yuan over the 23-year period. One reason for Tianjin's relatively small share lies in the fact that Tianjin has a smaller aquaculture area. Another reason is that Tianjin is less affected by typhoon waves than the other four provinces. This pattern also aligns with the expected loss for marine aquaculture shown in Sect. 3.2. Given the limitation of historical economic damages, we encourage policymakers and regulators to take action to improve data collection and sharing mechanisms, thereby refining the validation processes of simulation models.

4.2 Implication for Fisheries Insurance

The significance of risk assessment in marine aquaculture is paramount to the advancement of fishery insurance. China's marine aquaculture sector, characterized by a predominantly small-scale, individual farmer-driven landscape, lacks the scale and sophistication seen in other industries. Furthermore, the intricate and unpredictable nature of the marine environment, coupled with the frequent occurrence of severe weather and disasters, underscores the vulnerability of this sector to natural hazards and risks. Consequently, the development of a comprehensive fishery insurance is not only a necessity but also a global trend (James et al. 2023; Xue et al. 2023). Large-scale risk assessment models could be a useful tool for fishery insurance. Large-scale risk assessment models and local engineering models should be mutually complementary. Local engineering models provide relatively precise experimental results and empirical formula, which can be integrated into large-scale risk assessment models. Large-scale risk assessments can facilitate a more comprehensive understanding of the distribution of disaster risks at multiple scales and identification of high-risk and vulnerable spots, providing support for coastal stakeholders. The results can guide the layout and optimization of aquaculture facilities, enhance farming efficiency and productivity, and thereby promote the sustainable development of marine aquaculture.

In 2022, China's agricultural insurance premium surpassed the CNY 100 billion yuan mark for the first time, reaching a total of 119.2 billion yuan. Within this figure, fishery insurance premiums amounted to only 3.824 billion yuan (accounting for 3.2%), despite the fact that the fishery sector contributes nearly 10% to the overall output value of agriculture, forestry, animal husbandry, and fishery. This disparity suggests that fishery insurance, particularly marine aquaculture insurance, lags behind the sector's actual scale of development, with limited coverage. Moreover, within the realm of fishery insurance, freshwater aquaculture insurance dominates, accounting for over 80% of the total fishery insurance business, highlighting the pressing need for marine aquaculture insurance to catch up.

A pivotal challenge hindering the full development of marine aquaculture insurance lies in the difficulties associated with obtaining accurate data for underwriting and claims processing, as well as managing and controlling risks effectively, mainly relying on the self-discipline of aquaculture farmers (Yu et al. 2020). To address this gap, this study proposed a framework to assess expected losses of aquaculture based on physical vulnerability. First, it facilitates the development of insurance products that cater specifically to the needs of marine aquaculture. It provides references for insurance companies, assisting them in more accurately quantifying the risk of losses to aquaculture facilities (for example, fish cages) under extreme conditions. Based on these risk assessment results, insurance companies can optimize the pricing strategies of their insurance products, ensuring that premiums can cover potential losses while not imposing undue financial burdens on aquaculture farmers. Second, by understanding the unique vulnerabilities of different types of aquaculture net cages and their varying degrees of resilience to typhoon waves, insurers can design insurance policies that offer targeted coverage, such as including specific exclusions or enhancements based on the location and characteristics of the aquaculture operation. Furthermore, the study's findings inform risk management strategies for both insurers and aquaculture farmers. By identifying patterns and trends in typhoon wave heights and their impact on aquaculture facilities, farmers can implement proactive measures to mitigate risks, such as reinforcing their net cages or relocating to safer areas. Insurers, on the other hand, can leverage this information to provide risk mitigation advice and support to their clients, fostering a stronger partnership and enhancing the overall resilience of the aquaculture sector.

5 Conclusion

In this study, we proposed a novel framework of a quantitative risk assessment of TC-induced extreme waves on marine aquaculture, employing a physical vulnerability function relating wave height to failure probability. By integrating hazard assessment using the maximum SWHs simulated by the ADCIRC+SWAN coupled model over a 40-year period, we have provided a comprehensive evaluation of the risks confronting coastal aquaculture, coupled with an assessment of physical vulnerability of net cage structures.

In contrast to traditional research that frequently relies on qualitative analysis methods, this study adopted a quantitative approach grounded in physical vulnerability at a large scale. This shift from qualitative to quantitative assessment significantly mitigates subjectivity and presents more precise and intuitive results. Traditional quantitative risk assessments commonly categorize the risks of aquaculture facilities into three or five levels, ranging from low to high. However, under such a grading system, it becomes challenging to make meaningful comparisons across different cases and lacks the capability to provide specific estimated loss values. Conversely, quantitative analysis offers outcomes that are more straightforward, concise, and accurate, making it a more potent tool for practical applications, beneficial for stakeholders and the insurance industry alike. This framework not only advances the field of marine aquaculture risk assessment but also paves the way for the development of tailored insurance policies that can effectively bolster the resilience of the aquaculture industry against typhoons and extreme waves, strengthen the protection of fisheries and livelihoods, and contribute to improving the overall well-being of those reliant on this vital industry.

There are several directions for further research. While this study focused on the NECS as the primary study area, future endeavors could expand the scope to encompass wider geographical regions, including a national or even global perspective. Moreover, the current absence of detailed economic value data for individual aquaculture farms necessitates the utilization of national-level aquaculture values as a proxy for estimating expected economic losses. As more specific and detailed economic data become available, these estimates can be refined and updated. Access to more granular data would not only enable a more precise quantification of potential losses but also strengthen the reliability and practical implications of the research findings.

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