Risk characteristics of China's marine disasters and trends since 2000

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Understanding the risk characteristics of marine disasters is of great importance for disaster prevention and mitigation. In this study, we considered four types of marine disasters typical in China, including storm surges, rough seas, harmful algal blooms, and oil spills to identify risk characteristics. Disaster risk was analyzed based on the theory that the marine disaster risk consists of hazard, exposure, and vulnerability. These three factors have been analyzed based on statistical data from a collection of historical documents and official records. The following characteristics were identified. First, the occurrence frequency of storm surges and rough waves has remained stable over the past few decades, but the occurrence frequency of red tides and oil spills has shown a downward trend. Second, storm surges were found to be the main cause of economic losses, while rough seas were the main cause of death. Economic losses and fatalities have shown a downward trend against the backdrop of a growing economy and population. Third, there are clear regional differences in the spatial distribution of all disasters, so it is necessary to formulate disaster prevention and mitigation plans according to the spatial differentiation of risks. Based on the various disaster prevention and mitigation measures taken by the government, this study makes some recommendations for future actions that the government should take from the perspective of risk composition. The risk analysis paradigm for marine disasters provided in this study is expected to be used for future marine disaster prevention and mitigation.

KEYWORDS

risk characteristics, marine disaster, coastal China, hazard, exposure, vulnerability

1 Introduction

Disasters pose a significant challenge to economic development and social security all over the world. Disaster management is considered to be an important part of responding effectively to disasters (Baker and Refsgaard, 2007; Vanderhorst et al., 2021). Some disasters, such as storm surges, have become more frequent and severe, especially in the context of climate change (Leal et al., 2022); hence, effective disaster management has become increasingly important (Mall et al., 2019).

Disaster management consists of four distinct phases, which are mitigation, preparedness, response, and recovery (Yu et al., 2018). Disaster risk analysis and assessment are the foundation for disaster management and provide important information for each of the four phases, especially for disaster decision-making (Gong and Forrest, 2014).

Coastal zones are five times more vulnerable to disasters than inland areas (Haran, 2020). Therefore, marine disasters are of greater concern than land disasters. China has more than 18,000 kilometers of continental coastline, 7372 islands over 500 square meters in area, and nearly 3 million square kilometers of sea areas. Historically, these areas have suffered from frequent marine disasters (Wang, 2020). For this reason, marine disasters have received substantial attention in China (Zhao et al., 2020).

A number of scholars have focused on disaster risks analysis, risk reduction, and risk management framework (Chen et al., 2020; Ekstrom et al., 2020; Trotta et al., 2021; Liu, 2022). An accurate understanding of disaster risk characteristics is necessary for building an effective risk management framework. Since the State Oceanic Administration (SOA) started issuing Marine Disaster Bulletins (MDB) in April 1990, first-hand information on mainland China's marine disasters have been officially and systematically recorded. These data, combined with other statistical data, provide an opportunity to study marine disaster risk characteristics in China.

Analyzing the risk characteristics of these disasters is important for systematic analysis of the characteristics of China's marine disaster risk. Generally, disasters can be categorized based on temporal scales into rapid-onset hazards and slow-onset hazards (Gill and Malamud, 2014). Rapid-onset disasters includes storm surges, rough seas, red tides, green tides, and oil spills, which have temporal scales of hours, days, and months. Slow-onset disasters include coastal erosion, seawater intrusion, coastal soil salinization, and sea level rise, which have temporal scales of more than three months (Fang et al., 2017). All of these disasters have had adverse effects on economic and social development. However, for slow-onset disasters, there is a lack of detailed information or records about their effects, possibly because they do not result in immediate visible economic losses and fatalities and thus fail to attract the attention of government entities.

Worldwide, a great deal of research has been conducted on marine risk management (Ouyang, 2020; Rangel-Buitrago et al., 2020). Most of these studies select a specific disaster for in-depth analysis, but seldom examine their risks from the perspective of three independent determinants: hazard, exposure, and vulnerability. Hence, in order to fully understand the risk characteristics of China's marine disasters, this study focused on the storm surges, rough seas, harmful algal blooms (including red tides and *Ulva prolifera* (*U. Prolifera*) green tides), and oil spills by considering the hazard, exposure, and vulnerability of marine disasters in China. These disasters are considered to be the most typical disasters in China and have the most detailed records. The objectives of this study were to analyze the risk characteristics of marine disasters in China, discuss the status quo regarding China's marine disaster risk, and provide useful information for improving China's marine disaster management. The rest of this paper is structured as follows. Section 2 provides the detailed data sources and describes the data processing. Section 3 analyzes the risk characteristics from the perspective of hazard, exposure, and vulnerability, as well as the disaster temporal and spatial characteristics. Section 4 reviews China's management of marine disasters, as well as China's marine disaster-related legal system, system of organization, operating mechanism, and emergency response plans. Section 5 discusses the future opportunities of China's marine disaster management.

2 Data and methods

2.1 Risk analysis method

This study analyzed the risk composition of China's marine disasters from the perspective of hazard, exposure, and vulnerability, as shown in formula (1). In addition, understanding disaster risk requires us to not only consider hazard, exposure, and vulnerability, but also to consider the society's capacity to protect itself from disasters. Therefore, disaster coping capability (resilience) is also an important part of disaster risk analysis.

$$\text{Risk} = \text{Hazard} \times \text{Exposure} \times \text{Vulnerability} \qquad (1)$$

2.2 Study area

This study focused on the coastal zone and offshore areas of mainland China. A total of 52 coastal cities contributed data on economy and population values for the risk analysis. For ease of description, all locations used in this study have been marked on a map (Figure 1), and the distribution of offshore waters is as follows: China's offshore waters from north to south are the Bohai Sea, the Yellow Sea, the East China Sea, and the South China Sea.

2.3 Data sources and processing

To analyze the risk characteristics of marine disasters in China, official government statistical data were collected from the sources listed below.

- Marine Disaster Bulletin (MDB)
- Bulletin of Marine Ecological Environment Status in China (BMEES)
- Marine Environment Quality Bulletin (MEQB)
- Statistical Bulletin of China's Marine Economy (SBCME)
- China Urban Statistical Yearbook (CUSY)
- China Statistical Yearbook (CSY)

We focused on hazard, exposure, and vulnerability and used data from a series of records that were issued to the public annually to provide the official statistical information (Table 1).
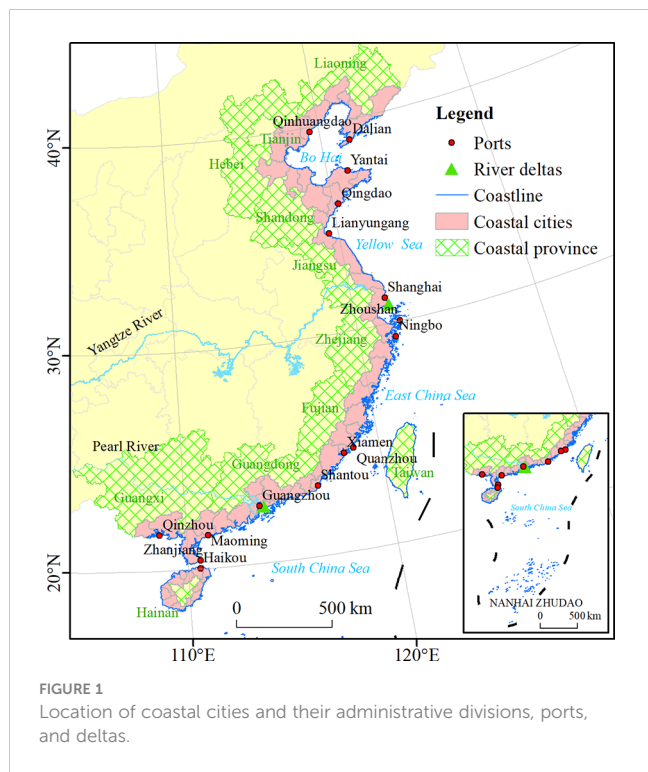
FIGURE 1
Location of coastal cities and their administrative divisions, ports, and deltas.

(1) Hazard: The hazard associated with disasters is usually expressed in terms of the disaster's intensity, occurrence frequency, and duration (Zhang, 2004). MDBs do not contain much detail on the intensity and duration of storm surges, rough seas, harmful algal blooms (red tides and *U. Prolifera* green tides), and oil spills, but do contain a detail about their frequencies.

(2) Exposure: Exposure changes over time and from place to place and is different for different disasters. Despite this, all disasters will eventually affect human society. In this paper, exposure is represented by the marine-related gross domestic product, marine-related value added by industry, GDP of coastal cities, and resident population of coastal cities.

(3) Vulnerability: The vulnerability of the environment reflects the susceptibility of society to marine disasters. Therefore, economic and infrastructure losses caused by various disasters were used to measure vulnerability.

(4) Resilience: The ability to prevent disasters reflects the ability of emergency departments and the masses to prepare for disasters beforehand and respond during disasters. Not all marine disaster prevention and mitigation capabilities are clearly documented, so this study obtained relevant data from published studies.

To eliminate the differences in economic statistical data caused by inflation and facilitate the comparison of economic data in different years, since 2000, the consumer price index (CPI) is used to convert the economic data to the recalculated values as follows:

$$GDP_{i-2021} = GDP_i * \frac{CPI_{2021}}{CPI_i} \qquad (2)$$

where GDP_{i-2021} represents the recalculated GDP values for year i based on 2021, GDP_i represents the published GDP value of year i by CSY, CPI_{2021} represents the CPI index based on 2021, and CPI_i represents the published CPI value of year i by CSY.

3 Risk characteristic analysis

3.1 Hazard

MDBs lack frequency data for rough seas for 2000 and 2001, so its statistics begin in 2002. It can be seen from Figure 2A that since the beginning of the 21st century, the frequency of storm surges and rough seas has been relatively stable.

The data show that 1,425 red tides occurred in China's coastal areas from 2000 to 2021. The frequency and cumulative area of red tides shows an initial increase followed by a decrease (Figure 2B). The frequency of red tides peaked at 119 in 2003 and the cumulative area peaked at 27,070 km² in 2005. Except for 2021, the frequency and cumulative area showed a downward trend.

Compared with other disasters, *U. Prolifera* occurred relatively late. It first occurred in 2007 and has re-occurred frequently in the Yellow Sea waters of China since then. Over the years, its maximum coverage area has been relatively stable (annual average of 679 km²), but the maximum distribution area fluctuates substantially compared with annual average of 3724 km² (Figure 2C).

The data on oil spills are missing statistics for 2000 and 2001. Based on available records, the number of oil spills and the amount of oil spilled both show an overall downward trend (Figure 2D). Oil

TABLE 1 Data sources.

	Hazard	Exposure	Vulnerability	Resilience
Storm surge	MDB (2000-2021)	MDB (2000-2021)	SBCME (2000-2021); CUSY (2000-2021)	Liu et al., 2019
Rough seas	Ditto	Ditto	Ditto	Liu et al., 2019
Red tide	Ditto	Ditto	Ditto	Not accessible
U. Prolifera	MDB (2008–2021)	Ditto	Ditto	Not accessible
Oil spill	MDB (2000–2021); MEQB (2000); BMEES (2006)	Ditto	Ditto	Xiong et al., 2015

spills peaked at 3,817 tons in 2004 and the number of oil spills peaked at 136 in 2008.

3.2 Exposure

Figure 3 shows that, since 2000, the resident population and GDP of China's coastal cities have shown a trend of continuous growth. The resident population has increased from 0.23 billion in 2000 to more than 0.3 billion in 2020, and the GDP increased from 5434 billion Chinese yuan (CNY) in 2000 to 36101 billion CNY in 2021. Of particular concern is the economic data related to the marine industry. Marine-related gross domestic product has grown from 661 billion CNY in 2000 to 9,039 billion CNY in 2021, and the marine-related value added of industry has grown from 367 billion CNY in 2000 to 5949 billion CNY in 2021.

3.3 Vulnerability

Disaster vulnerability can be represented by the degree of loss after a disaster. The greater the disaster-associated losses, the higher the vulnerability. A low degree of loss means low vulnerability (Huang et al., 2019). From 2000 to 2021, marine disasters caused a total loss of 321.2 billion CNY in mainland China, and caused up to 2,805 deaths. Most economic losses were caused by storm surges (295.4 billion CNY). Economic losses caused by rough seas and red tide were 5.91 and 5.03 billion CNY respectively, and losses caused by

U. Prolifera and oil spills are only sporadically recorded in individual years, so they are not shown in Figure 4. The vast majority of fatalities (including disappearances) were caused by storm surges (1,908 fatalities) and rough seas (888 fatalities). Very few deaths or disappearances were caused by other disasters. Swells killed eight people in 2011 and oil spills killed one person in 2000. Red tides and *U. Prolifera* did not cause deaths or disappearances, so Figure 4A does not show a death toll curve for red tide, *U. Prolifera*, and oil spills. Both economic losses and deaths showed an overall downward trend during the study period. Economic losses during 2011 and 2021 (102.5 billion CNY) were less than that during 2000 and 2010 (218.8 billion CNY), a 53% reduction. The decline in the number of deaths is more pronounced than the decline in economic losses. Fatalities from 2011 to 2021 (total 525 people) were less than that from 2000 to 2010 (total 2280 people), a 77% reduction.

3.4 Disaster temporal characteristics

Over the past 22 years, the occurrence frequency of storm surge and rough seas has remained stable. In contrast, economic losses and fatalities have shown a downward trend against a backdrop of a continuously growing economy and population. This phenomenon is consistent with previous research (Liu et al., 2019), which determined that coastal engineering is considered an effective way to reduce losses. In other words, the decline in economic losses and fatalities is a result of the engineered disaster prevention and mitigation measures in coastal zones, which have achieved remarkable results.
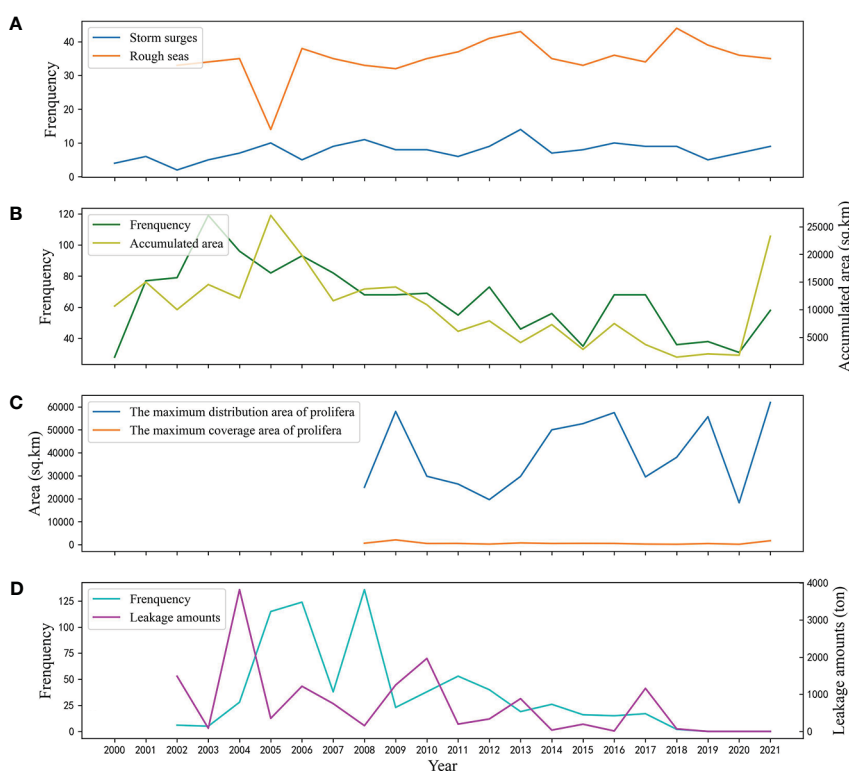

FIGURE 2
(A) Frequency of storm surges and rough seas (B) Frequency and accumulative area of red tides (C) The maximum distribution area and maximum coverage area of U. Prolifera (D) Frequency and leakage amounts of oil spills.
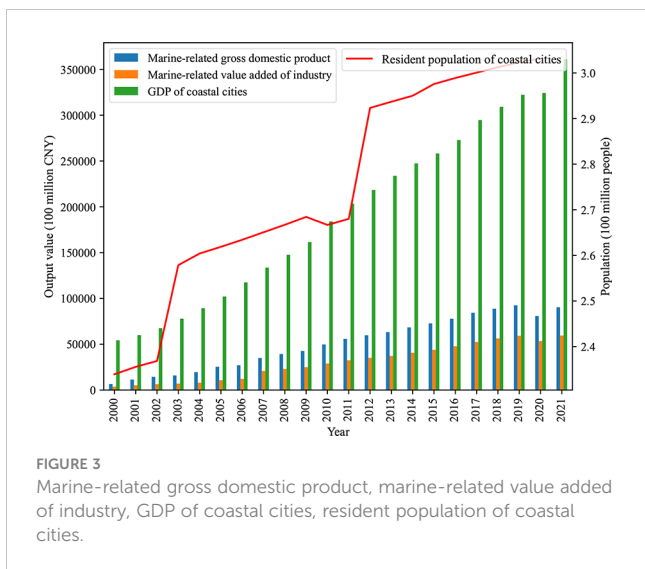
FIGURE 3
Marine-related gross domestic product, marine-related value added of industry, GDP of coastal cities, resident population of coastal cities.

The frequency of red tides and oil spills showed a downward trend over the study period. The cumulative area of red tides and leakage amounts of oil spills also showed a downward trend.

The maximum coverage area of *U. Prolifera* remained stable, although the maximum distribution area fluctuated greatly from year to year. Despite extensive research, the mechanisms behind *U. Prolifera* outbreaks are not well understood (Zhang et al., 2019). Therefore, it is difficult to explain the reasons for tits area fluctuations.

Storm surges caused the heaviest direct economic losses, accounting for 92% of the total direct economic losses. Wave disasters caused the greatest number of deaths and disappearances, accounting for 68% of the total.

3.5 Disaster spatial characteristics

The coastal zones along the Bohai Sea and the northern Yellow Sea are under the threat of extra-tropical induced storm surges

(ETSSs), while the coastal zones along the southern Yellow Sea, the East China Sea, and the South China Sea are under the threat of typhoon-induced storm surges (TSSs) (Wang et al., 2021). Figure 5 shows how typhoons travel from the sea to the land, affecting mainly coastal areas in southeast China. In contrast, rough seas occur in all sea areas, so there are no obvious spatial characteristics.

MDBs records include only a general description of the location of red tides and *U. Prolifera* outbreaks. There are no exact coordinates recorded, so it is difficult to visually represent them on the map. We can describe their distribution only qualitatively. *U. Prolifera* is a serious environmental problem attracting worldwide attention (Zhang et al., 2019). It has occurred annually for the past 16 years (2007–2022) in the Yellow Sea off the coasts of Jiangsu and Shandong Province. Qingdao City is one of the cities most seriously affected by *U. Prolifera*, requiring a substantial amount of manpower and material resources to salvage if every year. Red tides occur in all sea areas, but are especially concentrated in the seas near economically developed and densely populated areas, such as Bohai Bay, Yangtze River Delta, and the Pearl River Delta. They are extremely common in Zhejiang Province and the Yangtze River estuary (He et al., 2021).

It can be seen from Figure 5 that oil spill disasters occur in all sea areas, although they are particularly concentrated in the Bohai Sea, the northern waters of the Yellow Sea, the waters near Shanghai Port, the waters near Fujian Province, and the waters near Guangzhou Port. This is basically consistent with previous predictions of oil spill risk areas (Zhu et al., 2022).

4 Discussions

4.1 Analytical method

Many models have been proposed worldwide for disaster risk analysis. Disaster risk is most often described as consisting of hazard, exposure, and vulnerability (Kron, 2002; Carrão et al.,
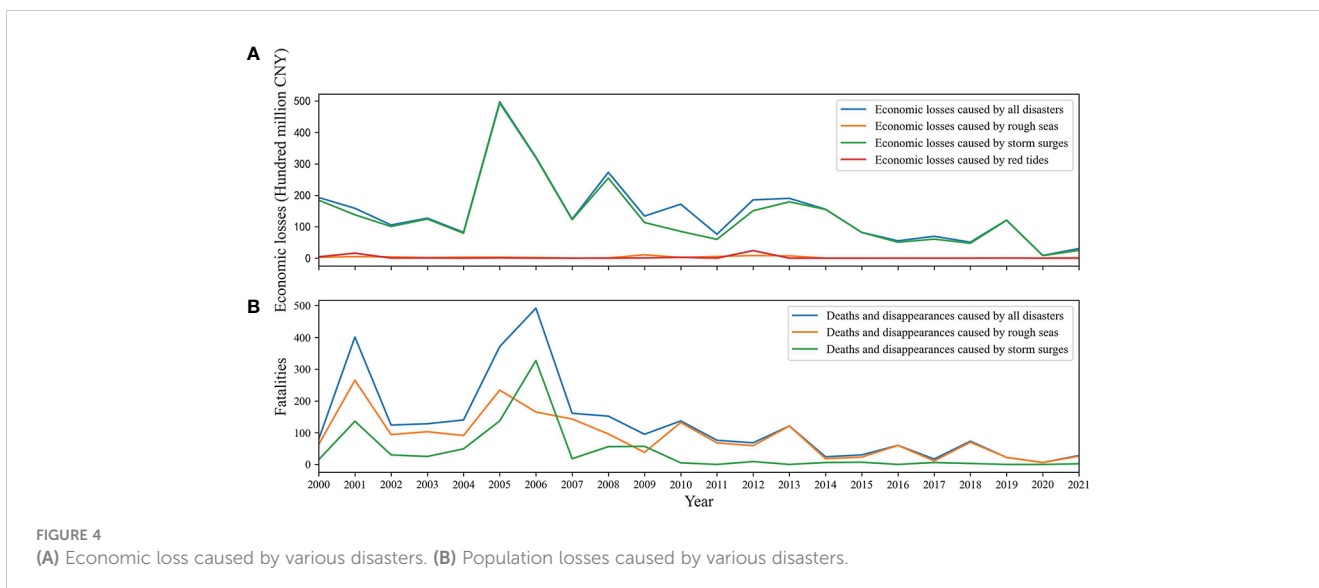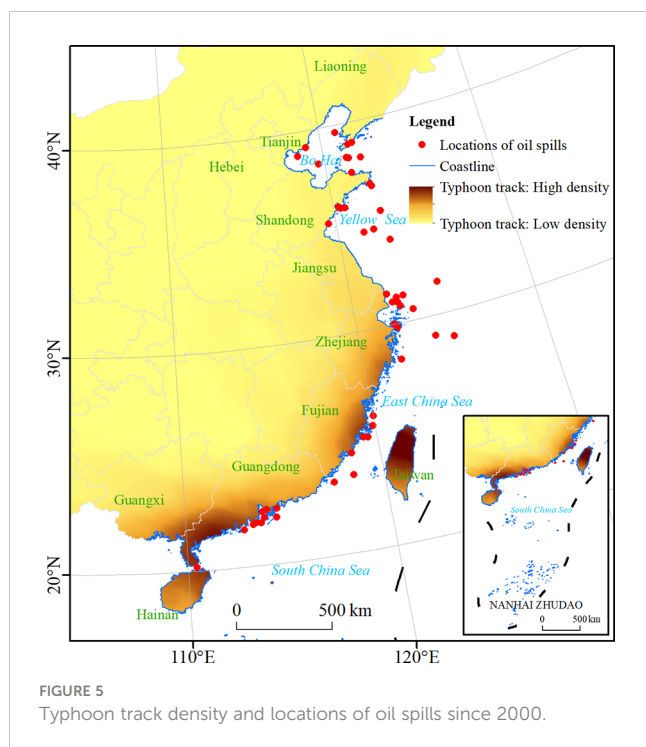

FIGURE 4
(A) Economic loss caused by various disasters. **(B)** Population losses caused by various disasters.

FIGURE 5
Typhoon track density and locations of oil spills since 2000.

2016). In contrast, in China, the disaster system is considered to be composed of three factors: disaster-causing factors, disaster-bearing carriers, and a disaster-prone environment (Ding et al., 2020). In this study, marine disaster risk is assessed based on the product of three independent determinants—hazard, exposure and vulnerability—because this is the most commonly used method in the field of risk research, and because it has been widely used in research on land hazards (Koks et al., 2015; Carrão et al., 2016). Analyzing risks using this framework will be helpful in obtaining a comprehensive understanding of risk characteristics, which will provide a reliable reference for future risk management and risk decision-making. Next, we will focus on the Chinese government's efforts to deal with marine disasters in order to gain a more concrete understanding of disaster resilience.

4.2 Attitudes and efforts for marine disaster prevention and mitigation by the Chinese government

The Chinese government has been committed to improving the resilience to marine disasters for many years. For example, for decades, China has relied mainly on seawalls along its coasts for the prevention and mitigation of storm surges and wind waves (Bao et al., 2020). During the period from 1980 to 2015, the length of hardened engineered coastline in China increased from 5322 km (1980) to 7842 km (1990), 9073 km (2000), 11,407 km (2010), and 13,316 km (2015) (Liu et al., 2019). Chinese coastal engineering has played an important role in reducing damage from storm surge and wind waves. The response to harmful algal bloom disasters is completely different from storm surge response. Prolifera is often pre-salvaged and brought ashore for further disposal to avoid it

affecting densely populated areas (Chen et al., 2022). For red tides, clay dispersal is one of only a few mitigation methods ever applied (Yu et al., 2017). However, there is no public information on China's capacity to address these two disasters, so the ability to prevent these disasters is difficult to quantify. Oil spill mitigation focuses on the construction of emergency equipment. China has built national oil spill emergency equipment warehouses in Dalian, Qinhuangdao, Yantai, Qingdao, Lianyungang, Shanghai, Zhoushan, Ningbo, Quanzhou, Xiamen, Shantou, Guangzhou, Maoming, Zhanjiang, Qinzhou, and Haikou (Xiong et al., 2015). Except for the emergency response capability surrounding the Bohai Sea (Wang et al., 2018), which has been publicly announced, information on the other warehouses has not been released.

In addition, the Chinese government has formed an emergency management system at the government level (Figure 6). The following is a general description of China's marine disaster emergency management system.

4.2.1 Legal system

In China, a series of laws and regulations related to marine disaster management have been issued by the government to meet this challenge. Table 2 shows the related documents. However, there is still a huge gap in China's current legal system for marine disaster prevention and mitigation (Li, 2018; Su and Yang, 2018). One point mentioned often is that China has not enacted special legislation for marine disasters, and the relevant regulations on marine disaster emergency management are scattered in different laws and regulations. This leads to a lack of standardization in marine disaster management, which seriously restricts the development of marine disaster prevention and mitigation capabilities and affects the smooth implementation of marine disaster strategies.

4.2.2 System of organization

China's emergency agencies are vertically segregated into the following four levels: (1) the central government level; (2) province, autonomous region and municipality directly under the central government level; (3) prefecture-level city level; (4) county level. Government agencies are horizontally divided into three main parts: (1) the principals of governments at all levels; (2) the heads of relevant departments, such as the Emergency Management Bureau, the Natural Resources Bureau, the Ecological Resources Bureau; (3) the China Coast Guard. These entities form a three-dimensional disaster management system (Sun, 2010).

Before 2018, the SOA was the marine disaster management department in China. In 2008, the SOA established the Marine Forecast and Disaster Reduction Department. In 2011, a Marine Disaster Reduction Center was created in the SOA, and the marine disaster reduction and emergency management system was initially established. In 2018, the Chinese government experienced an enormous institutional reconstruction. The SOA was incorporated into the newly established Ministry of Natural Resources (MNR). Since then, at the national level, the function of the SOA is maintained, but it no longer exists as an independent, institutional entity (Chang and Li, 2019). China's marine disaster management has been under the responsibility of MNR. Oil spill

■ Legal system
● More than a dozen related laws and regulations issued by NPC and SC

■ System of organization
● Vertically
 · Central government level
 · Province level
 · City level
 · County level
● Horizontal
 · The principals of governments
 · The heads of relevant departments
 · The China Coast Guard

■ Operating mechanism
● Prevention
● Early warning
● Disposal
● Aftermath

■ Contingency plan
● Central government level
● Province level
● City level

FIGURE 6
Disaster emergency management system in China.

disasters are an exception. According to N*ational Emergency Plan for Major Marine Oil Spills*, *the Joint Inter-ministerial Meeting of the National Marine Oil Spill Emergency Management* is responsible for organizing and guiding the national major marine oil spill emergency response work, and the Ministry of Transport (MT) is the main lead department for oil spill emergency response (Zhao, 2018). However, in order to facilitate cooperation among various departments of the local government, temporary institutions such as emergency leading groups are generally formed after a disaster occurs. In this temporary group, work methods based on the

interests of the department may lead to problems such as limited cooperation and poor information communication, which affects the ultimate success of the effort (Chen and Pei, 2021).

4.2.3 Operating mechanism

China's operating mechanism contains four basic parts: prevention, early warning, disposal, and aftermath. Prevention includes the preparation of contingency plans, risk assessment, emergency training, and drills. Early warning includes disaster monitoring, information release, warning adjustment, and

TABLE 2 Laws and regulations issued by the Chinese government.

Laws and regulations	Year	Promulgating Institution
Marine Environmental Protection Law	1982, amended in 1999, 2013, 2016, 2017	The National People's Congress (NPC)
Maritime Traffic Safety Act	1983, amended in 2016, 2021	NPC
Regulations on Environmental Protection Management of Offshore Petroleum Exploration and Development	1983	The State Council (SC)
Measures for the Implementation of the Regulations on the Administration of Marine Dumping	1985	SC
Fisheries Law	1986, amended in 2000, 2004, 2009, 2013	NPC
Regulations on the Prevention of Environmental Pollution from Ship Recycling	1988, amended in 2016	SC
Measures for the Implementation of the Regulations on Environmental Protection Management of Offshore Petroleum Exploration and Development	1989	SC
Regulations on the Prevention and Control of Land-based Pollutants Pollution Damage to the Marine Environment	1990	SC
Regulations on the Prevention and Control of Pollution and Damage to the Marine Environment from Coastal Engineering Construction Projects	1990, amended in 2007, 2017, 2018	SC
Fishing Vessel Inspection Regulations	2003	SC
Measures for the Administration of Entrusting the Issuance of Licenses for Marine Dumping of Wastes	2004	Ministry of Land and Resources (MLR) before 2018
Regulations on the Prevention and Control of Pollution and Damage to the Marine Environment from Marine Engineering Construction Projects	2006, amended in 2017, 2018	SC
Emergencies response Law	2007	NPC

cancellation. Disposal includes delineating warning areas, repairing public facilities, and activating emergency reserve materials. Aftermath includes concluding emergency response measures, carrying out pacification work, implementing reconstruction plans, and conducting an experience summarization. Marine disaster emergency mechanisms are in the prevention and early warning stages. As of the end of 2018, MNR has 124 marine stations, 30 buoys, and 59 volunteer ships. Thus far, China has possessed the capability of three-dimensional observation and monitoring of China's offshore oceans (Gong et al., 2019).

However, there are still some problems with this mechanism. For example, the construction of China's marine disaster emergency mechanism was characterized by cross-regional and cross-departmental collaboration, but the lack of effective theoretical guidance resulted in limited collaboration between different regions and departments. In addition, each participating member had different goals, interests, and resources. Therefore, the relationships among them is not stable (Chen and Pei, 2021).

4.2.4 Contingency plan

China's contingency plan system was established after the SARS incident in 2003. Subsequently, China has successively issued plans for many disasters at the national level (Table 3). After the release of *Storm surge, Tsunami, Sea Wave and Sea Ice Disaster Contingency Plan* and *Red tides Disaster Contingency Plan*, major coastal provinces across the country have successively compiled provincial-level marine disaster emergency plans under the guidance of them. Cities have also compiled municipal emergency plans based on national emergency plans and provincial emergency plans. However, these paper-based plans are limited in that emergency responders cannot easily extract helpful information from them (Ni et al., 2019). Furthermore, these marine disaster emergency plans are generally incomplete because they do not contain an emergency plan for sea fog, coastal erosion, saltwater intrusion, and sea level rise.

5 Suggestions for future risk management

Over the past decades, the Chinese government has recognized that active marine disasters prevention strategies have played a significant role in guaranteeing the security and sustainable development of coastal zones. Although China has achieved many noticeable achievements in marine disaster prevention and mitigation, the main focus is still improving the resilience of disaster systems, and many severe challenges remain in terms of the legal system, system of organization, operating mechanism, and contingency planning. In the future, in addition to making targeted improvements to existing problems, efforts should be made from the aspects discussed in sections 5.1–5.3, considering exposure, hazard, and vulnerability.

5.1 Strengthening management of exposure

It is the consensus of scientists and managers that the marine hazard-prone areas should be managed effectively (Srinivas and Nakagawa, 2008). Economic and population exposure in Chinese coastal areas is trending upward. This trend cannot be reversed in the short term, and disaster risk is set to increase. We need to act immediately to reduce exposure and build capacity and resilience in coastal areas of growing exposure. However, there are not many measures that can be taken. The central government plays an indispensable role in disaster prevention and mitigation (Koyama et al., 2019). We suggest that a central agency should be responsible for comprehensive management of disaster-prone environments and coordinate relevant departments.

5.2 Strengthening management of hazard

We cannot reduce the occurrence and severity of natural hazards, but hazards caused by human activities can be avoided to a large extent. This study proposes the following:

(1) There is evidence that red tides are increasing as coastal pollution worsens (Liu et al., 2013), and aquaculture rafts in north of Jiangsu Shoal are a major source of floating *U. Prolifera* (Zhang et al., 2018). *U. Prolifera*, red tides, and oil spills are all disasters closely related to human activities. Therefore, it is important to pay attention to controlling pollution in coastal zones by balancing economic development and environmental protection.

(2) Storm surge risk management must consider the effects of sea level rise (Shepard et al., 2012). Therefore, it is necessary to deepen our understanding of storm surges in the context of global warming, focusing on long-term changes in their frequency and intensity.

(3) The monitoring, identification, forecasting, and early warning of disasters are keys to the management of hazards. In particular, it is important to note that the occurrence of disasters will give rise to a series of secondary disasters, which could lead to more serious disasters with the stronger cumulative effects (Zhou et al., 2018). Therefore, it is also very important to take measures

to monitor, identify, forecast, and warn people of the secondary effects of marine disasters.

5.3 Strengthening management of vulnerability

Vulnerability relates to a number of factors, such as physical factors, social factors, economic factors, and environmental factors. Reducing vulnerability is one of the main opportunities for reducing disaster risk. Approaches to vulnerability reduction include the following:

(1) Insurance and social protection: Social protection has emerged as a strategy to minimize disaster impacts by building the resilience of vulnerable communities. It is increasingly being used in disaster risk reduction (Rana et al., 2022). Strengthening insurance and social protection in marine hazard-prone areas is conductive to reducing vulnerability.

(2) Emphasis on economic diversity: Development of marine industries is conducive to reducing the damage caused by marine disasters (Xiao et al., 2015; Tian et al., 2020). Loss can be reduced by diversifying marine industrial structures in the coastal zone and offshore waters so that it adapts to the spatial and temporal risk characteristics.

(3) Knowledge and awareness raising: Disaster risk assessment requires a multidisciplinary and interdisciplinary approach. Shortcomings and gaps exist that need to be addressed (Cui et al., 2021). Investment should be increased in research and development activities to provide scientific support for preventing loss or damage. In addition, developing an emergency response plan for each coastal community is essential to disaster prevention and mitigation (Said et al., 2011), but there is still a big gap in community participation in disaster response in China (Li and Liu, 2020). Therefore, disaster prevention and mitigation capacity should be based on community level ideas. Community disaster reduction education, marine disaster risk symptom identification, marine disaster self-rescue, and mutual rescue knowledge should be publicized.

(4) Preparedness measures: Marine disaster mitigation projects play a critical role in disaster prevention. The construction of coastal zone protection and restoration projects should be

TABLE 3   Contingency Plans issued by the Chinese government.

Contingency Plans	Year	Promulgating Institution
National general emergency plan for public emergencies	2005	SC
Storm surge, Tsunami, Sea Wave and Sea Ice Disaster Contingency Plan	2005, amended in 2009, 2015	SOA
Red tides Disaster Contingency Plan	2005, amended in 2009, 2021	MNR
National emergency plan for major marine oil spills	2018	MT
Marine Disaster Contingency Plan	2022	MNR

continuously strengthened, but the focus should change from hard engineered defenses to ecosystem-based measures or to a combination of both kinds of measures (Liu et al., 2019).

6 Conclusion

Conclusions can be summarized as follows: (1) Over the past 22 years, the occurrence frequency of disasters unrelated to human activities, such as storm surge and rough waves, has remained stable, but the occurrence frequency of disasters related to human activities, such as red tides and oil spills, has shown a downward trend. (2) Storm surge causes the heaviest direct economic losses and rough waves cause the most damage to infrastructure. Economic losses and fatalities have shown a downward trend against the backdrop of a continuously growing economy and population. (3) The geographical distribution of various disasters is uneven. TSSs are concentrated on the southeast coast, rough seas can occur in any sea area, oil spills occur near heavily-used ports and shipping routes, red tides occur in areas with frequent human activities, and green tides occur in the Yellow Sea.

Over the past few decades China has implemented effective measures to prevent and control marine disasters through the legal system, system of organization, operating mechanisms, and contingency planning. Although China has made great strides, there are still inadequacies in fighting marine disasters. In the future, management of hazard, exposure, and vulnerability need to be improved and strengthened purposefully so that the safety of the economy, society, and environment can be ensured.

Data availability statement

The original contributions presented in the study are included in the article/supplementary materials. Further inquiries can be directed to the corresponding author.

Author contributions

YW designed and performed the research, analyzed the data, and wrote the paper. YD, RG, and CC collected the data. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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