



# Assessment and zonation of storm surge hazards in the coastal areas of China

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## Abstract

Storm surge is one of the most devastating marine disasters in China, leading to tremendous economic damage and a large number of casualties. Combined storm surge hazard assessment and zonation is an important method for coastal disaster risk reduction and mitigation management. Based on observational data from tide-gauge and hydrological stations in coastal areas, we analyzed storm surge hazard intensity and generated a storm surge hazard map at the county level using the expected values of storm surge and over-warning water levels. The results show that 87, 67, 62, and 40 counties along the coast of China are exposed to the first (highest), second (higher), third (medium), and fourth (low) degree of hazard level, respectively. The areas with the highest risk of storm surge are the coasts of Bohai Bay, Laizhou Bay, and the Yangtze Delta, the coast from the north of Fuzhou to the south of Zhejiang, and the coastal area of Huizhou, Pearl River, and Yangjiang in Guangdong Province. This assessment, which is based on a national storm surge hazards map, can provide decision-making support for the government's urban planning of coastal cities and site selection in large national projects.

**Keywords** Storm surge · Over-warning water level · Expected value analysis · Hazards map

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## 1 Introduction

Storm surge refers to the abnormal increase in extreme sea level caused by strong winds pushing the water surface that are associated with atmospheric disturbances such as tropical cyclones and strong extratropical cyclones (Feng et al. 1999). A storm surge with an astronomical high tide usually leads to extreme sea levels that in turn lead to coastal flood disasters and bring great economic losses and casualties to coastal areas (Fang et al. 2017). China is one of the countries most severely affected by storm surge disasters. Storm surges may occur in every season and everywhere in the coastal areas of China from the south to the north of the country. Storm surge disasters with different levels of severity in China's coastal regions demonstrate a significant spatial distribution (Shi et al. 2018). According to the official estimate, storm surges caused a total of RMB 98.2 billion in economic loss directly and 146 deaths (including people missing) in China from 2008 to 2017 (State Oceanic Administration of China 2018). The most destructive storm surge disaster was caused by typhoon Winnie in 1997, which claimed the life of 1482 people and caused economic damage of over RMB 14 billion in Zhejiang Province (Yu et al. 2015). Therefore, it is of great importance to investigate the storm surge hazard to reduce the disaster risk in coastal areas.

Hazard analysis of storm surge mainly includes numerical simulation and the empirical statistical method. Varied numerical simulation models have been developed to improve the accuracy of the reappearing single storm surge process in the past few decades. Examples are the Early British Sea Model, the SPLASH and SLOSH models in the USA, the Dutch DELFT3D model, and the Danish MIKE21 model. These models have been widely applied to simulate the storm surge process in countries and regions from the USA to the European Union (Niedoroda et al. 2010; Scheffner et al. 2015). A set of typhoon parameters combined with a storm surge numerical model is usually used to simulate the inundated area under different assumptions for storm surge hazard assessment in local or small areas (Yin et al. 2013; Wu et al. 2018). Recently, more accurate storm surge numerical models like POM, ECOM, FVCOM, ELCIRC, and ADCIRC have been developed and used for storm surge monitoring and simulation. These models have largely improved early warning of storm surge hazards, and the number of deaths caused by storm surge disasters has decreased significantly (Shi et al. 2015). The development of these mathematical models makes the accurate simulation and prediction of storm surge hazards more possible than before, and thus the risk assessment and zonation of storm surge becomes a useful tool for coastal disaster risk reduction. Single-station hazard analysis based on observational data using the empirical statistical method is widely used for storm surge hazard assessment and coastal engineering design (Xu and Huang 2011; Jia et al. 2016; Feng and Jiang 2015). It aims to evaluate different return periods of storm surge based on observational data using a parameter estimation model (Wahl et al. 2017; Kang et al. 2016).

Storm surge hazard assessment and zonation can also contribute to disaster risk reduction efforts through policies (Li and Li 2013; Gao et al. 2014; Liu et al. 2018a). Great effort has been made to draft the national large-scale disaster storm surge risk map. The Chinese 11th 5-Year Plan of the National Science and Technology Support Program initiated the project Key Technology Research and Demonstration of Integrated Risk Prevention. In this project, the National Marine Environment Forecasting Center cooperated with Beijing Normal University, producing hazard, vulnerability, and risk maps of the coastal areas based on the coastal gross domestic product, population distribution, and the pre-alert records of historical storm surges published by the government (Fang et al. 2011; Shi 2012). The

output of this project is the first national-scale storm surge risk map in China, but data from only 37 tide-gauge stations were used and the grid resolution of the storm surge hazards results is close to 1°, which is not sufficient for storm surge prevention and mitigation in coastal areas. After the 3.11 earthquake in 2011 off the Pacific coast of Tohoku in north-east Japan and the accompanying devastating tsunami, the State Oceanic Administration of China launched a marine disaster risk assessment and zonation project, which aims to evaluate marine disaster risk and improve prevention and mitigation in the coastal areas of China. Storm surge is included and is considered to be the most important marine disaster. The project complies with the *Technical Guidance for Risk Assessment and Zonation of Storm Surge Disasters* (Liu et al. 2018b) and aims to make storm surge risk maps at four different scales including the national, provincial, municipal, and county levels.

This paper contributes to the methods and practice of storm surge hazards assessment and zonation. The annual maximum observed water level from tide-gauge and hydrological stations along the coastline of China and the warning water-level value of each station were collected for analysis. The typical return period and expected value of each station's surge and over-warning water level were calculated by the Gumbel model and interpolated for each 10 km of coastline. Finally, this paper evaluates the hazard levels of storm surge exposure at the county level by integrating the expected values of storm surge and over-warning water level.

## 2 Data and methods

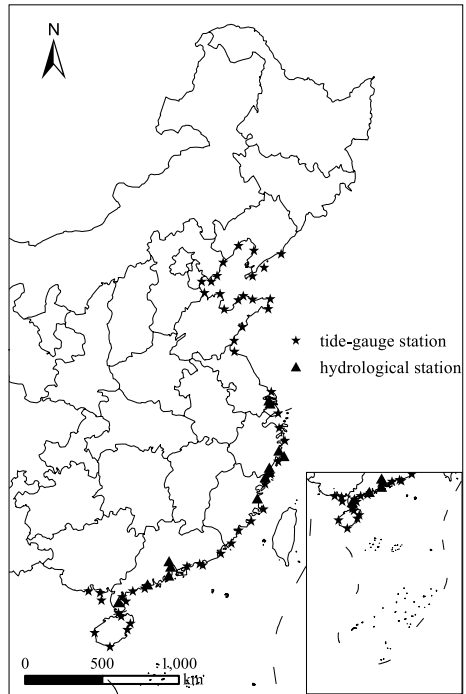
### 2.1 Data

The observed annual maximum water-level and storm surge data from tide-gauge and hydrological stations are used in this study. There are 126 tide-gauge stations along the coast of China, and data from 49 stations were screened and used in this analysis. The station selecting principles were: (1) the number of selected stations is sufficient to cover the coastal regions from north to south, and each coastal city contains at least one station; (2) data from the station are representative of storm surge hazards that have occurred in the area, and the station is no more than 10 km from the coastline; (3) sequential observational data have been collected at the station for at least 20 years, which will ensure that the calculation of storm surges with different recurrence periods and the expected values are accurate enough; (4) stations located on islands and offshore were excluded. Based on these four principles, 49 tide-gauge stations were selected (Fig. 1).

The estuary areas are the coastal areas most affected by storm surge, but they have few tide-gauge stations. To further portray the hazard characteristics of storm surge hazards in estuary coastal areas, data from hydrological stations located at the Yangtze Delta and Pearl River Estuary were also collected. Similarly, only the data from stations with records lasting at least 20 years were included for analysis. This resulted in the selection of 13 hydrological stations (Fig. 1).

The selected station information includes the annual maximum water levels and storm surge data, and the attributes include the station ID number, name, and location (longitude and latitude). The value of warning water level at the tide-gauge and hydrological stations was also collected (two stations missing), and all values were unified to the 1985 elevation datum. The warning water level refers to the potential value of the water level that may appear dangerous or cause a tidal disaster along the coast of the protection zone. An area with a warning water

**Fig. 1** Tide-gauge and hydrological station distribution in coastal China



level needs to enter a state of alert or disaster relief. The actual water level minus the warning water level equals the over-warning water level.

## 2.2 Expected value analysis

Based on the annual maximum observational data of the tide-gauge and hydrological stations, the Gumbel model was used as a frequency analysis method to evaluate the return period value of the storm surge and the water level at each station. The Gumbel distribution model is shown as follows (Coles 2007):

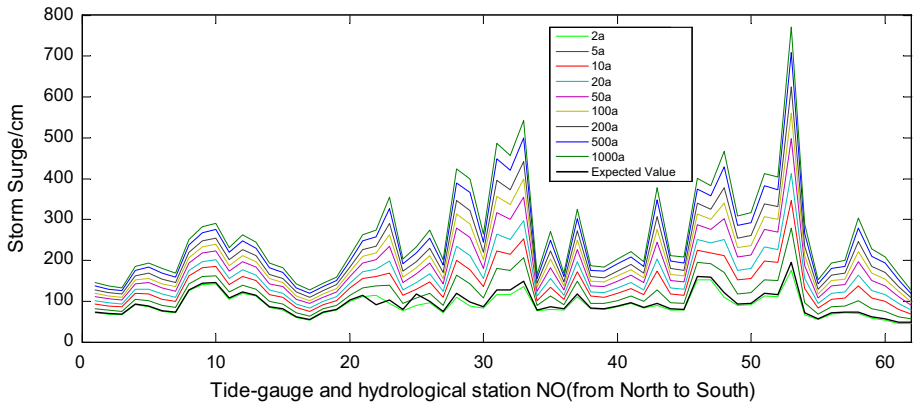
$$F(x) = e^{-e^{-\frac{x-\mu}{\beta}}} \quad (1)$$

In this equation,  $x$  refers to the annual maximum sample sequence,  $\mu$  refers to the position parameter, and  $\beta$  refers to the scale parameter. The moment estimation method, ordinary least squares technique, and maximum likelihood method are the commonly used parameter estimation methods. The moment estimation method is chosen to obtain  $\mu$  and  $\beta$  in this study.

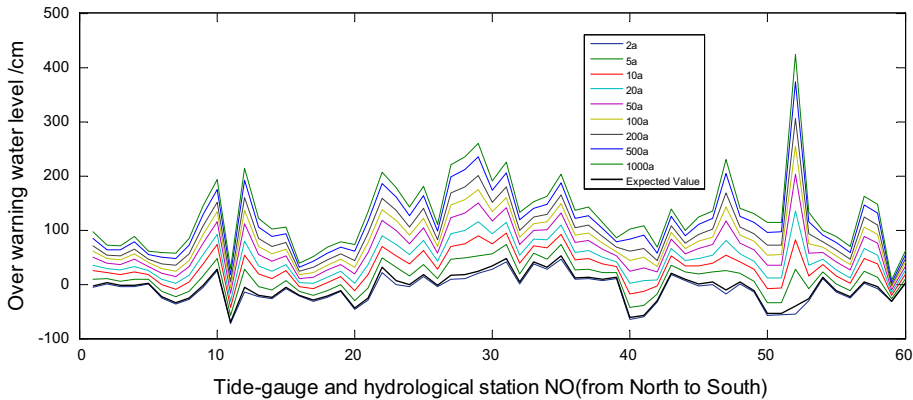
The different return period value of storm surge and water level is calculated by the following equation:

$$X = \mu - \beta \ln\left(-\ln\left(1 - \frac{1}{T}\right)\right) \quad (2)$$

$X$  denotes the corresponding storm surge or water level that occurred once in  $T$  years, and the calculation equation is as follows:



**Fig. 2** Typical storm surge return periods and expected water-level values at tide-gauge and hydrological stations (from north to south)



**Fig. 3** Typical over-warning water-level return periods and expected water-level values at tide-gauge and hydrological stations (from north to south)

$$T = \frac{1}{1 - F(X)} \tag{3}$$

For the Gumbel distribution, the expected value is computed by the equation as follows (Simiu and Heckert 1996):

$$E(X) = \mu + \gamma\beta \tag{4}$$

In this,  $\gamma$  refers to Euler’s constant of 0.5772. Each station’s expected values of storm surge and over-warning water levels were calculated based on these methods (Figs. 2, 3).

### 2.3 Classification of hazard levels

The coastline was divided into equidistant 10 km shore sections, and we numbered the sections sequentially from north to south starting from 1. The shore number represented the

coordinate value of each shore section in a one-dimensional coordinate system. The nearest shore section of each tide-gauge or hydrological station was found, and the values of storm surge and over-warning water level were assigned to the corresponding shore section. Linear interpolation was used to calculate the value of storm surge and over-warning water level for each shore section. For the shore section between two adjacent stations,  $a_i$  referred to the value of storm surge or over-warning water level,

$$a_i = \frac{i - 1}{n - 1} * (x_1 - x_2) + x_2 \tag{5}$$

$x_1$  and  $x_2$  refer to the value of storm surge or over-warning water level for the two adjacent stations,  $n$  refers to the total number of shore sections between the two adjacent stations, and  $i$  refers to the serial number between the two adjacent stations. Taking the expected values of storm surge and over-warning water level of each station into consideration, the storm surge hazard levels were divided into four levels for each of the two indicators (Table 1). The ranking from the first to the fourth level indicates the degree of hazard level from high to low.

### 3 Zonation of storm surge hazards

Storm surge and over-warning water level were chosen as indicators to reflect the storm surge hazards in this study. According to the nearest neighbor principle, the value of the nearest station storm surge and over-warning water level was assigned to each coastline section. The expected values of storm surge and over-warning water level of each section were calculated using the linear interpolation method (Fig. 4). Consequently, the storm surge hazard level of each coastal county was determined.

The hazard level of storm surge is represented by  $H_z$ , and that of the over-warning water level by  $H_s$ . For each 10 km shore section, the higher level of these two indicators was selected as the section’s final hazard level, which is represented by  $H$  (Fig. 5):

$$H = \text{Max}(H_z, H_s) \tag{6}$$

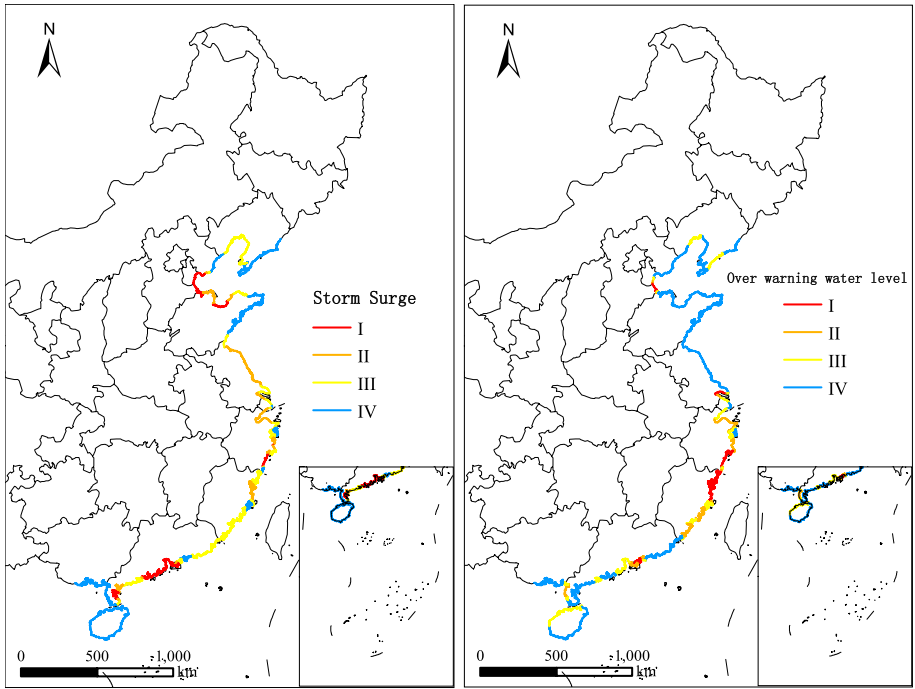
The highest value of the sections within a county was used as the hazard level of storm surge of that county if the county contained several sections, as calculated by:

$$H_c = \text{Max}(H_1, H_2, \dots H_n), \quad n = 1, 2, \dots i \tag{7}$$

Each coastal county’s storm surge hazard was evaluated and classified into one of four different levels based on the distribution of the storm surge final hazard levels as shown in Fig. 6. We counted the number of coastal counties included in each risk level. The statistical results are shown in Table 2. It is found that among the total 256 coastal counties of China, the storm surge hazard level of 87 counties is labeled as I-Level, 67 as II-Level, 62 as III-Level, and 40 as IV-Level. The data indicate that the number of counties with the

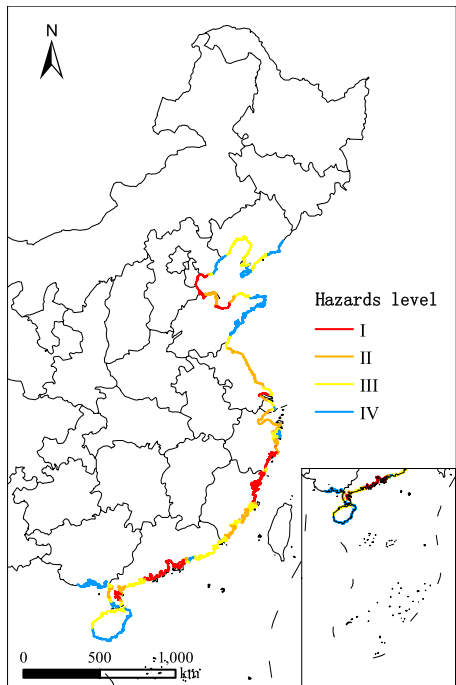
**Table 1** Classification of hazard levels

Hazards level	I	II	III	IV
Storm surge/cm	[120, +∞]	[100,120)	[80,100)	(0,80)
Over-warning water level/cm	[20, +∞]	[10, 20)	[0,10)	(−∞, 0)



**Fig. 4** Hazard-level distribution of storm surge (left) and over-warning water level (right)

**Fig. 5** Integrated storm surge hazard levels in the coastal areas of China



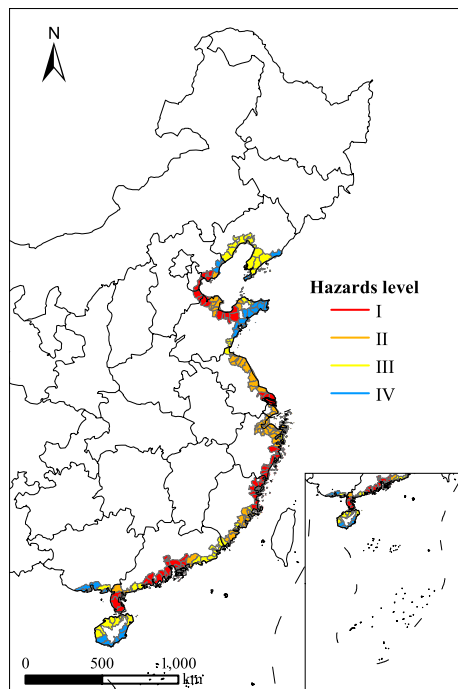
I-Level hazard ranks the highest at one-third, which means that the need to prevent and mitigate storm surge disasters on the coast of China is urgent. The I-Level areas are the most dangerous areas and are mainly located along the coast of Bohai Bay, Laizhou Bay, and the Yangtze Delta, the coast from the north of Fuzhou to south of Zhejiang, and the coastal area of Huizhou, Pearl River, and Yangjiang in Guangdong Province.

## 4 Conclusion

This paper has assessed storm surge hazards in coastal China and zoned the risk levels by county. Observational data from 62 representative tide-gauge and hydrological stations along the 18,000 km coastline were collected and used. Four risk categories of storm surge hazard exposure were assigned to the 256 coastal counties, and the counties with the highest risk were identified for further disaster risk reduction. This assessment and zonation of storm surge hazards at the national scale can provide valuable knowledge and information for local government's disaster risk reduction needs and urban planning, as well as national industrial park site selection. China has a long and twisted coastline that is affected by various natural disasters including storm surge.

With fast development and people's continued concentration in coastal areas, it can be expected that more disaster risk reduction efforts will be needed (Hinkel et al. 2014). Disasters, such as extreme storm surge events, can be a great threat to people living along the coast and can cause severe property damage and casualties. The I-Level areas with highest risk identified in this study face much higher exposure to storm surge hazards, and disaster risk mitigation efforts, such as seawall building, land-use planning, and evacuation

**Fig. 6** Distribution of final hazard levels of China's coastal counties





**Table 2** Zonation of storm surge hazards by county

Hazard level	Number of counties	Distribution areas
I	87	Along the bottom coast of Bohai Bay Coast of Laizhou Bay Coast of Yangtze River Estuary Coast from Fuzhou in northern Fujian to Taizhou in Southern Zhejiang Coast from Huizhou, Guangdong, Pearl River Estuary to Yangjiang East Coast of Leizhou Peninsula
II	67	Coast of Yellow River Estuary Shoal along the Northern Coast of Jiangsu Coast of Hangzhou Bay Coast from Putian, Fujian to Zhangzhou
III	62	Northern Part of the Yellow Sea Coast of Liaodong Bay Northern Coast of Jiaodong Peninsula Coast of Jiayang, Shantou and Chaozhou, Guangdong Coast of Zhangzhou and Quanzhou, Fujian
IV	40	Coast of the Yalu River Estuary Northern Coast of Qinhuangdao and Tangshan, Hebei Coast from Chengshantou to Qiangdao Coast of Port of Fangcheng, Guangxi Southeastern and Southern Coasts of Hainan

planning, by both local and national government are needed. Moreover, disaster preparedness efforts such as community emergency response team building, emergency response exercise and drills, disaster knowledge education, and increasing the public's risk awareness should be conducted with the mitigation efforts to increase the resilience of coastal communities.

## 5 Discussion

Although this study has contributed to the methodology of storm surge hazard assessment and zonation, more efforts should be conducted to keep improving the accuracy of the assessment, such as adopting numerical modeling to simulate the historical storm surge process to generate sufficient storm surge samples in the coastal areas where the tide-gauge information is insufficient. Only the Gumbel model was used to establish the frequency distribution curve of storm surge and warning water level, and different extreme value model or parameter estimation methods may lead to uncertainty in the estimation results of the site. Sea-level rise will increase the long-term risk of storm surge for coastal areas (Feng and Tsimplis 2014; Little et al. 2015). The contribution caused by climate change and sea-level rise (Wu et al. 2017), the social vulnerability and resilience dimensions should be taken into consideration in evaluating the risk levels of storm surge in the future research.

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