ABSTRACT
A risk assessment for storm surge disasters can provide scientific support for coastal management as well as marine disaster prevention and mitigation. By taking the Wenchang City of Hainan Province as a pilot area, a risk assessment approach for typhoon-induced storm surge disasters is introduced in detail in this article. First, a numerical simulation system for storm surge inundation is developed, which is applied for the simulation and calculation of the probable maximum storm surge in Wenchang, and the obtained inundation areas and depths are used to assess the storm surge hazard. Then, the data of land use and disaster-bearing bodies are used to classify and assess the vulnerability of Wenchang. Finally, by taking the community as unit, the risk assessment for typhoon-induced storm surge affecting Wenchang is performed by combining the assessment results of both hazard and vulnerability, thereby obtaining a level map of risk distribution. The results show that there are risks of typhoon-induced storm surge in most of the coastal areas of Wenchang, especially for its northeast and east coastal areas, where the risks reach Levels I–II. This approach can be conveniently applied to risk assessments of storm surge in other coastal areas. Note that this approach focuses on the current risk of typhoon-induced storm surge in coastal areas, and further studies will be conducted on the assessment methods for the potential risk.

1. Introduction
China’s east coast, bordering the Northwest Pacific, is the area with the most frequent and widespread typhoon-related disasters over the world. Typhoon-induced storm surges have the potential to threaten public safety and cause economic losses in many
coastal regions. According to statistics, in the past decade (2009–2018), there have been 201 storm surge disaster in China, which caused the direct economic losses of up to 83.45 billion yuan, accounting for 85% of the total direct economic losses from marines (MNR 2019a). Performing the risk assessment of storm surge can enhance the ability of local government in defending against marine disasters, effectively reduce the hazard risk, and further reduce casualties and property losses.

The risk assessment of storm surge is a comprehensive process of evaluating the hazard of storm surges, vulnerability of disaster-bearing bodies and disaster prevention abilities (MNR 2019b). The World Conference on Disaster Reduction, which took place in Kobe, Hyogo, Japan, from 18 January 2005 to 22 January 2005, was a milestone in the progress of disaster risk reduction. The World Conference on Disaster Reduction adopted the Hyogo Framework for Action (2005–2015), that is, Building the Resilience of Nations and Communities to Disasters. The Sendai Framework for Disaster Risk Reduction (2015–2030) was adopted at the World Conference on Disaster Risk Reduction in Sendai, Japan, on 18 March 2015. It was the successor agreement to the Hyogo Framework for Action (2005–2015), and took priority over understanding the disaster risk and strengthening the governance at global and regional levels.

Since the 1990s, regional and multi-hazard risk assessments have been conducted in some developed countries, including the United States (US), Europe and Japan. Furthermore, the results have been effectively applied to disaster reduction programs and social development, which have achieved remarkable effects. William and Arthur (1982) provided a systematic description of the theory, methods and results of risk assessment for storm surge in the US, and the American disaster mitigation policies and management practices were also described. The Federal Emergency Management Agency (FEMA 2014) conducted several risk assessments for hurricanes, floods and other hazards in Miami, Bolt, San Francisco and other cities by using the assessment and simulation system of HAZad United States of Multi-Hazard (Mileti 1999). After Hurricane Katrina occurred in 2005, the study of typhoon-induced storm surges in the US entered a new stage. To assess the dangerousness and risk of storm surge, the FEMA has initiated several projects to explore new approaches for researching typhoon-induced storm surges, improve the numerical simulation technologies and analyze the dynamic processes of typhoon-induced storm surges as well as the corresponding variation rule (Emanuel et al. 2006; Garner et al. 2017). International Institute for Geo-information Science and Earth Observation (2009) pointed out that the risk resulted from the combination of hazards, conditions of vulnerability and insufficient capacity to reduce the potential negative consequences of risk. It was further noted that the risk assessment methods could be summarized as three types—qualitative risk assessment, semi-quantitative risk assessment and quantitative risk assessment. Besides, the advantages and disadvantages, application scope and operational procedures of each method were also described, and the risk assessment of storm surges and dam-break floods were carried out in coastal areas of the Netherlands. Zerger et al. (2002) conducted a risk assessment of storm surge in Australia and compared the impacts of uncertainties in affecting the risk management of storm surge disasters. Benavente et al. (2006) studied the flooding hazards related
to storms in Cadiz Bay Natural Park in Southwest Spain and drew risk zoning maps. Based on the Ise-wan Typhoon, the largest typhoon event in recorded history, Japan has created the storm surge hazard map from the results of possible maximum storm surge (PMSS) inundation for Japan’s coastal areas, providing a scientific support for the disaster prevention and mitigation of the government (Cabinet Office 2004). In addition, the risk assessments of storm surge have also been piloted at the national, provincial, city and county scales in China. Moreover, key technologies such as the calculation methods of the PMSS have been developed (Wang et al. 2018), and the guideline for the risk assessment and zoning of storm surge disasters has been further compiled. By taking Wenchang of Hainan Province as the pilot area, this article introduces in detail the approach for risk assessment of typhoon-induced storm surge,
which provides significant scientific support for the siting and fortification of major coastal engineering projects, the decision making of government for disaster prevention and mitigation as well as the evacuation of people during disasters. Besides, the approach can be conveniently applied to the risk assessment of storm surge in other coastal areas.

Wenchang City is located in the northeastern Hainan, which experiences the most frequent and severe typhoon-induced storm surge disasters in the South China Sea region. Hence, we choose Wenchang as the study area.

The remainder of this article is organized as follows. Section 2 describes the study area, assessment method, datasets, model configuration and verification. The results and analysis are presented in section 3, including the hazard assessment, vulnerability assessment and risk assessment. The conclusions are summarized in section 4, together with a discussion of broader issues.

2. Method, data and model

2.1. Study area

Wenchang (19°21′N–20°10′N, 110°28′E–111°03′E) is located in the northeastern Hainan, which is bordered on the east and southeast by the South China Sea and on the north by the Qiongzhou Strait (Figure 1(a)). The elevation of Wenchang decreases from its southwest (inland area) to northeast (coastal area), and Dongzhai Harbor in the north and Bamen Harbor in the south are vulnerable to storm surge inundations due to the lower elevation. Wenchang is susceptible to the typhoons from the Western Pacific and South China Sea, and the typhoon-induced storm surges often bring great damages to infrastructures and coastal marine industries. Typhoon storm surges affecting Wenchang generally begin in May and end in November, with an average of 2–3 times per year and a maximum of 8 times. Super Typhoon Rammasun (No. 1409) made landfall in Wengtian Town, Wenchang City, Hainan Province, on 18 July 2014, with a central pressure of 910 hPa and a maximum wind speed of 60 m/s. During the landfall, the highest total water elevation in Dongzhai Harbor reached 4.5 m, and the storm surge disaster caused six deaths (including missing) and direct economic losses of 2.732 billion yuan (MNR 2015). On 16 September 2014, Typhoon Kalmaegi (No. 1415) landed in Wengtian Town, with a central pressure of 960 hPa and a maximum wind speed of 40 m/s. The maximum total water elevation at Xiuying tide gauge station reached 4.52 m, setting a historical record. The direct economic losses were up to 926 million yuan (MNR 2015).

2.2. Method

The storm surge risk assessment in Wenchang is performed by four steps: data collection and processing, hazard assessment, vulnerability assessment and risk assessment. The data to be collected and processed include historical hazards, basic geographic information, land use data and the data of disaster-bearing bodies in Wenchang. Moreover, based on the conditions of data collection, additional field surveys may be required if necessary. For the hazard assessment, we first determine the typhoon-
| Data                        | Spatio-temporal coverage                  | Resolution | Source                                                                 | Processing method                                                                 |
|-----------------------------|-------------------------------------------|------------|------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| Ocean bathymetry            | Sea area near Wenchang City               | 1:2000     | Sea charts and ETOPO1                                                  | Modified by nearshore bathymetry                                                |
|                             | Bamen Harbor, Wenchang City               |            | Hainan Academy of Ocean and Fisheries Sciences                       | Convert to the local mean sea level                                              |
| DEM                         | Area below the 10-m contour in Wenchang   | 1:10,000   | Hainan Administration of Surveying Mapping and Geoinformation          | Modified by the coastline survey at Dongzhai Harbor and Bamen Harbor; Convert to the local mean sea level |
| Seawall data                | –                                         | –          | Wenchang Water Authority                                              | Modified by field survey; Convert to the local mean sea level                   |
| Wind field                  | 1949–1999                                 | 2.5° × 2.5°| NCEP reanalysis 1                                                      | Downscaled to 20 km × 20 km                                                     |
|                             | 2000–2012                                 | 1° × 1°    | FNL                                                                    |                                                                                  |
| Typhoon observations        | 1949–2015                                 | 6 h        | Typhoon best-track datasets of 1949–2015 from the Shanghai Typhoon Institute of the China Meteorological Administration (tcdata.typhoon.org.cn) |                                                                                  |
| (wind speed, pressure, etc.)| 1972–2015                                 | –          | Gauge stations near Wenchang, such as Haikou and Qinglan stations      |                                                                                  |
| Land use data               | Wenchang City                             | –          | Land and Resources Bureau of Wenchang City                             |                                                                                  |
| Disaster-bearing body data  | Hospitals, schools, dangerous chemical    | –          | Oceanic and Fishery Administration, Education Bureau, Health Bureau, Administration of Work Safety and Transportation Bureaus of Wenchang, etc. | Spaceplization of data based on GIS                                              |
|                             | facilities, etc.                          |            |                                                                       |                                                                                  |
induced PMSS based on the characteristics of storm surge in Wenchang, and then, calculate the inundation area and submerged depth through numerical simulation to classify the risk levels. The vulnerability assessment adopts land use types as an indicator to perform the qualitative vulnerability classification. The vulnerability level can be adjusted according to the actual situation when there is a critical disaster-bearing body in the assessment unit. The risk assessment of storm surge disaster is carried out based on the hazard assessment and the vulnerability assessment in the study area. Finally, zones with different risk level are divided by considering the spatial homogeneity of risk level distribution and administrative division comprehensively.

2.3. Datasets

The datasets adopted in this article are shown in Table 1. Here, the ocean bathymetry, Digital Elevation Model (DEM) terrain and seawall data are used to build the numerical model for the simulation of typhoon-induced storm surges. The wind field data is used to establish the external forcing field for the numerical model. The typhoon observation data is used to validate the performance of the model and provides data support for the risk assessment of storm surge in Wenchang. The data of land use, seawall and disaster-bearing bodies are used for the vulnerability assessment. The vertical datum used in this study is the local mean sea level, and datasets with other vertical datum are converted to the local mean sea level (Table 1).
2.4. Model

2.4.1. Numerical model configuration

In this article, the numerical model for storm surge inundation in Wenchang is constructed by coupling the ADCIRC (A Parallel Advanced Circulation Model for Oceanic, Coastal and Estuarine Waters) with the third generation Simulating Waves Nearshore (SWAN) model. The computational region in the model is 14.6°N–27.2°N, 105.6°E–126.9°E, including the northern part of South China Sea and part of the Northwest Pacific (Figure 2(a)). The land area contains the area below the 10-m contour in Wenchang (Figure 2(c)). The grid resolution reaches 22–50 m in the coastal area of Wenchang. Besides, the model range contains 446,715 grid points and 874,441 triangular grids. ETOPO1 global data (Amante and Eakins 2009) with a resolution of approximately 1.8 km is used for oceanic bathymetry with nearshore modifications, based on the sea chart bathymetry from the Hydrographic Office of the Chinese Navy (Figure 2(a,b)). The topography over land is described by the DEM terrain data with a resolution of 0.025 km (Figure 2(c)). The time step of the model is set to 1 s, and the initial water elevation and flow rate are 0. A wet and dry scheme is used to simulate inundation and flooding. Tidal elevations at the open boundary during the entire simulation period are computed by using the Oregon State University Tidal Prediction Software (Egbert et al. 1994; Egbert and Erofeeva 2002) with eight tidal constituents (M2, S2, N2, K2, K1, O1, P1 and Q1) being included. The total water elevation or storm surge simulation results are outputted per hour.

The storm surge model is driven by wind stress and atmospheric pressure gradient acting on the surface using the combination of Jelesnianski parametric wind model (Jelesnianski 1966) and National Centers for Environmental Prediction (NCEP) Final Operational Global Analysis (FNL) reanalysis datasets (Table 1). The Jelesnianski parametric wind model is used when radial distance from the typhoon center < 500 km:

\[ V_G = V_{\text{max}} \frac{2r/R_{\text{max}}}{1 + (r/R_{\text{max}})^2}, \]

\[ P_r = \begin{cases} 
    p_c + \frac{1}{4} (p_a - p_c) \left( \frac{r}{R_{\text{max}}} \right)^3 & 0 < r < R_{\text{max}} \\
    p_a - \frac{3}{4} (p_a - p_c) \frac{R_{\text{max}}}{r} & r > R_{\text{max}} 
\end{cases}, \]

where, \( r \) is the radial distance from the typhoon center; \( V_G \) and \( P_r \) are wind speed and atmospheric pressure, respectively, as functions of \( r \); \( p_a \) and \( p_c \) are the ambient atmospheric pressure and typhoon central pressure, respectively; \( R_{\text{max}} \) is the radius of maximum wind speed (RMW); and \( V_{\text{max}} \) is the maximum wind speed.

2.4.2. Numerical model verification

In this article, typhoons Nesat (No. 1117), Rammasun (No. 1409) and Kalmaegi (No. 1415) are selected as examples, all of which made landfall in Wenchang, Hainan and brought severe storm surge damages, and the model’s performance is evaluated by
comparing the simulation results with the observed astronomic tides and storm surges at Haikou and Qinglan stations near Wenchang (Figure 3). The time series of astronomic tides are obtained from $t_{\text{tide}}$ harmonic analysis of total elevations in the simulation and observation (Pawlowicz et al. 2002), and surges (including effect of waves) are measured by subtracting astronomic tidal elevations from the total elevations.

From Figure 3, it can be found that the simulated astronomic tide and storm surge changes are generally consistent with observations. During Typhoon Nesat, the simulated tidal phases have a correlation coefficient of 0.76 at Haikou and 0.84 at Qinglan stations, and the simulated surge phases are strongly correlated with observed surges,

Table 2. Maximum storm surges (m) at representative stations along Wenchang coast under different typhoon approach directions.

| Station | Approach direction ($\theta$) | 67.5$^\circ$ | 75$^\circ$ | 82.5$^\circ$ | 90$^\circ$ |
|---------|------------------------------|-------------|----------|----------|---------|
| 1       |                              | 6.653       | 6.721    | 6.843    | 6.897   |
| 2       |                              | 6.157       | 6.270    | 6.327    | 6.388   |
| 3       |                              | 5.848       | 5.858    | 5.857    | 5.891   |
| 4       |                              | 6.498       | 6.376    | 6.333    | 6.304   |
| 5       |                              | 5.653       | 5.597    | 5.530    | 5.485   |
| 6       |                              | 5.594       | 5.522    | 5.513    | 5.480   |
| 7       |                              | 6.988       | 7.108    | 7.316    | 7.430   |
| 8       |                              | 7.439       | 7.569    | 7.682    | 7.784   |
| 9       |                              | 5.940       | 6.086    | 6.221    | 6.347   |
| 10      |                              | 5.233       | 5.327    | 5.447    | 5.544   |
| 11      |                              | 4.363       | 4.336    | 4.326    | 4.305   |
| 12      |                              | 6.014       | 5.885    | 5.909    | 5.857   |
| 13      |                              | 5.650       | 5.626    | 5.603    | 5.591   |
| 14      |                              | 4.620       | 4.528    | 4.415    | 4.321   |
| 15      |                              | 5.404       | 5.263    | 5.087    | 5.002   |
| 16      |                              | 4.912       | 4.855    | 4.680    | 4.587   |
with correlation coefficients > 0.86 (all correlation coefficients exceed the 95% confidence level based on the Student’s t-test). The tidal amplitudes at Qinglan station are nearly identical as observed, and the peak surges are overestimated <10% compared to observations at both stations (Figure 3(a,b)). During Typhoon Rammasun, all of the correlation coefficients between simulated and observed results are very high (>0.83), especially with regard to the tide at Qinglan and surge at Haikou stations (>0.9). The tidal amplitude at Qinglan station is simulated accurately, and the peak surges have approximately 10% biases at both stations (Figure 3(c,d)). During Typhoon Kalmaegi, the simulated and observed phases have correlation coefficient > 0.84 at Haikou and Qinglan stations, and the peak tides and surges are estimated nearly precisely (Figure 3(e,f)). In general, the performances of the simulations are excellent, demonstrating that the numerical model with the external forcing could be considered reliable for the hazard assessment.

3. Results

3.1. Hazard assessment

3.1.1. PMSS evaluation

The Joint Probability Method (JPM) and the Joint Probability Method with Optimal Sampling (JPM-OS) are recommended in PMSS evaluation by FEMA and researchers (Irish et al. 2009; Resio et al. 2009; Niedoroda et al. 2010; FEMA 2014), which could provide probabilistic surge and flood elevation maps with various annual chance of occurrence. The JPM adopts a parametric storm description involving five or six hurricane descriptors and it develops probability distribution for each parameter. These distributions are each discretized into a small number of representative values, and all possible parameter combinations are simulated using a hydrodynamic model (FEMA 2014). To reduce the computation burden, the JPM-OS is developed, which selects storms for simulation through optimal parameter selection with associated weighting and interpolation methods (Irish et al. 2009; Resio et al. 2009). Yang et al. (2019) compares the results of JPM and JPM-OS, and finds that results of JPM-OS and JPM are very similar. In addition, they compared the performance of various JPM-OS methods.

However, in this article, we do not adopt the JPM and JPM-OS approaches due to the lack of adequate storm surge observations and the shortage of storm climatology knowledge in Wenchang. We employ a determinist-probabilistic approach (Wang et al. 2018) to explore the storm surge climatology through sensitivity experiments and evaluate the PMSS. The hazard assessment in Wenchang is calculated based on the inundation area and submerged depth of the PMSS. In terms of the PMSS in Wenchang, based on historical observations and the results of sensitivity experiments, a set of possible maximum typhoons within a certain area is constructed to simulate the maximum storm surge and maximum total water elevation. The key parameters selected include typhoon central pressure, peripheral pressure, RMW, the typhoon approach speed and approach direction. The determinist-probabilistic approach we use is described in a published article (Wang et al. 2018), and in this article we just cite the conclusions.
3.1.1.1. Typhoon intensity. The mean value of sea level pressure during the typhoon season (from May to October) in Wenchang, which is 1008 hPa, is taken as the peripheral pressure.

The area with a radius of 400 km around Wenchang is set as the assessment area. Based on the typhoon best-track datasets of 1949–2015, the lowest central pressures of the typhoons that have passed through the assessment area over the years are counted. A Gumbel distribution (Gumbel 1958) of annual typhoon pressure extremes revealed the lowest typhoon central pressure for a 1000-year return period was 866 hPa. Therefore, the pressure deficit of 142 hPa (the pressure difference between the peripheral and the central regions) is set as the typhoon intensity of PMSS in Wenchang (Figure 4).

3.1.1.2. Radius of typhoon maximum wind speed (RMW). The lack of RMW observations brought us to empirical methods. Based on the historical observations from Tropical cyclone yearbook (1949–2002) and previous empirical statistical formula, Jiang et al. (2008) obtained a RMW empirical equation that could apply to the Wenchang area:

\[ R_{\text{max}} = 1.119 \times 10^3 \times \Delta P^{-0.805}, \]  

where \( R_{\text{max}} \) denotes the RMW, \( \Delta P \) is the typhoon pressure deficit.

Based on the typhoon pressure deficit of 1000-year return period (142 hPa) calculated in the previous chapter, the RMW of the PMSS in Wenchang is determined as 20.6 km.

3.1.1.3. Typhoon approach speed. Li et al. (2014) used the typhoon best-track datasets of 1949–2011 from the Shanghai Typhoon Institute of the China Meteorological Administration, and analyzed the distribution of typhoon approach speeds with latitudes in Northwest Pacific. The average approach speed of typhoons landing in
Wenchang (19°21′N–20°10′N, 110°28′E–111°03′E) is approximately 20 km/h, so the typhoon approach speed of the PMSS in Wenchang is set to 20 km/h.

3.1.1.4. Typhoon approach direction. The approach direction (θ) is defined as the angle from the direction of Wenchang coastlines to the typhoon moving direction, with the anticlockwise rotation indicating the increasing angle. For the numerical simulation of storm surges in open sea, the peak storm surge reaches the maximum when the other parameters of the tropical cyclone remain constant and θ is between 75° and 90° (Wang 1989). Considering the complex and nonlinear storm surge responses to typhoon approach directions along the irregular coastline of Wenchang, the storm surge cases during the typhoon’s landfall are constructed with θ of 67.5°, 75°, 82.5° and 90°, and the PMSS parameters obtained above are adopted as the values of typhoon intensity, RMW and approach speed. Table 2 shows that the peak storm surges at 16 representative stations (as seen in Figure 1(b)) along the Wenchang coast all reach the extreme values when θ of 67.5° and 90° are chosen. Therefore, 67.5° and 90° are chosen as the typhoon approach direction for PMSS.

3.1.1.5. Typhoon tracks. According to the above calculation, a central pressure of 866 hPa, an peripheral pressure of 1008 hPa, a RMW of 20.6 km, an approach speed of 20 km/h as well as two approach directions of 67.5° and 90° are determined for the PMSS cases. On this basis, 30 tracks are constructed for the approach direction of 67.5° at an interval of 0.25 times of the RMW (Figure 5(a)), and each track corresponds to a PMSS case. The similar procedure is performed for the approach
direction of 90° (Figure 5(b)), so a total of 60 PMSS cases are simulated, covering all of the typhoon tracks that may cause strong storm surges in Wenchang. Note that the continuous computation lasts 90 h for each track, and Figure 5 reveals the typhoon start, landfall, and termination locations of all the PMSS cases.

3.1.1.6. Astronomical tide. The coupling of astronomic tides and storm surges was performed for total water elevation and inundation simulations in PMSS cases. Based on the observations at Qinglan station, the 90th percentile of daily highest tides during 19 years (1998–2016) were chosen as the maximum astronomic tides, which were coupled with the PMSS at peak surge time.

3.1.2. Result analysis
The envelope diagram of inundation ranges and submerged depths for 60 PMSS cases (as shown in Figure 6(a)) is used to perform the hazard assessment of typhoon-induced storm surges in Wenchang. Obviously, there are different extents of inundation along the coast of Wenchang, most notably on the eastern side of Dongzhai Harbor and near Bamen Harbor. The reason is that the terrain on the eastern side of Dongzhai Harbor in the northern Wenchang is relatively flat and the seawall is not closed, which makes it easy for seawater to overflow from the north and south sides of the seawall to the land during storm surges and cause inundation, with the submerged depths up to 2–5 m. Besides, in Bamen Harbor in the south of Wenchang, during the storm surges, the upstream movements of seawater pass through several

Figure 6. (a) Inundation distribution of the PMSS and (b) distribution of hazard levels in Wenchang.
rivers, resulting in the inundation in low-lying coastal areas with the submerged depths of up to 2–6 m.

For the hazard assessment of storm surges affecting Wenchang, the submerged depth is used to classify the hazard levels (Table 4), and the community is set as the evaluation unit. The highest hazard level of each grid in the community is determined as the hazard level of the evaluation unit, thereby obtaining the hazard level distribution of storm surges affecting Wenchang (Figure 6(b)). The hazard level on the east side of Dongzhai Harbor is Level I, for instance, parts of Puqian Town are inundated to a depth of more than 3 m. Most of the areas along the coast of Bamen Harbor are submerged to a depth of more than 3 m, especially in areas where the rivers pass through, and the hazard level reaches Level I, such as some communities in Towns Dongjiao and Wencheng. The hazard Level II appears in the communities in the northern Wenchang and most of the communities along the coast in the east, such as Towns of Jinshan, Wengtian, Changsa and Longlou, with submerged depths between 1.2 m and 3 m. The hazard Levels III–IV (submerged depth of 0.15–1.2 m) are dispersedly distributed in the inland areas of Wenchang. The other inland towns, such

| Number | Land use type                                      | Vulnerability coefficients | Vulnerability levels |
|--------|---------------------------------------------------|---------------------------|---------------------|
| 1      | Cultivated land                                   | 0.1–0.2                   | IV                  |
| 2      | Garden plot                                       | 0.1–0.3                   | IV                  |
| 3      | Forestland                                        | 0.1                       | IV                  |
| 4      | Grassland                                         | 0.1                       | IV                  |
| 5      | Public management and service land                | 0.4–1                     | III                 |
| 6      | Land for waters and water conservancy facilities  | 0.1–0.8                   | II–IV               |
| 7      | Other lands                                       | 0.1–0.5                   | III–IV              |
| 8      | City                                              | 1                         | I                   |
| 9      | Designated town                                   | 1                         | I                   |
| 10     | Village                                           | 1                         | I                   |
| 11     | Scenic spot and special land                      | 0.5                       | III                 |
| 12     | Mining land                                       | 0.6–0.7                   | II                  |
| 13     | Railway land                                      | 0.9                       | I                   |
| 14     | Highway land                                      | 0.7–0.8                   | II                  |
| 15     | Port terminals land                               | 0.6–0.7                   | II                  |

Table 4. Corresponding relationship among the risk level, hazard level and vulnerability level for storm surge disasters (extracting from MNR 2019b).
as Baoluo and Donglu, are classified as no inundation risk zones due to a submerged depth of less than 0.15 m.

3.2. Vulnerability assessment

Based on the land use status data and taking the community in Wenchang as the evaluation unit, the vulnerability assessment is performed by the vulnerability coefficients corresponding to each land use type and the weighted comprehensive evaluation method. The vulnerability coefficients (shown in Table 3) adopt values from the operation guidance for storm surge risk assessment in China, which are developed through an expert scoring method and extensive discussions with central/local governments and groups (MNR 2019b). The evaluation equation is as follows.

\[ A = \sum_{i=1}^{n} a_i V_i, \]

where, \( A \) represents the vulnerability coefficient of a certain community, \( a_i \) is the weight for the land use type of No. \( i \), \( V_i \) is the vulnerability coefficient for the land use type of No. \( i \), and \( n \) is the number of the land use types.
In terms of the assessment units with some critical disaster-bearing bodies, the vulnerability coefficients of the communities need to be revised by considering the vulnerability coefficients of critical disaster-bearing bodies and their corresponding weights. On this basis, the distribution of vulnerability levels in Wenchang city with the community as the assessment unit during storm surges (Figure 7) is obtained based on the relationship between vulnerability levels and vulnerability coefficients for storm surges (Table 4).

Analysis shows that the land use types with the widest distribution in Wenchang are cultivated land, garden plot and forestland, accounting for about 54.9% of the total area of Wenchang city. Areas with higher vulnerability levels include lands used for urban construction, mining, port terminals, railway and highway. The important disaster-bearing bodies in Wenchang are scattered and account for a relatively small proportion of the land area, among which the port terminals are mainly located along the southeast and northwest coasts of Wenchang. Figure 7 shows that the vulnerability Level I mainly distributes in the northeastern Wenchang where 10 communities in total are included, which belong to urban land, railway land, etc. Level II is mainly in the northeastern and eastern coasts of Wenchang, with 20 communities being included. Level III mainly distributes in the eastern coasts of Wenchang, affecting 37
communities. Most areas of Wenchang belong to Level IV, including 223 communities, belonging to cultivated land, garden plot, forestland, etc.

### 3.3. Risk assessment

The risk assessment model for storm surge disaster is as follows.

\[
R = H \times V, \tag{5}
\]

where, \( R \) denotes the risk, \( H \) is the hazard, and \( V \) is the vulnerability. The risk level is evaluated by combining the hazard level and the vulnerability level based on the unit of community. The risk area for storm surge hazard is divided into four levels: extremely high risk zone (Level I), high risk zone (Level II), medium risk zone (Level III) and low risk zone (Level IV). Where an area has no inundation, it is considered that there is no risk in this area (Table 4).

Figure 8 shows that there is a risk of typhoon-induced storm surge disasters in most of the coastal areas of Wenchang. Risk zones of Level I are mainly located in the northeastern Wenchang, including some communities in Towns of Puqian, Jinshan and Wentian. All of those zones have a hazard level of above Level II, while the vulnerability level ranges from Level I to II due to a dense population distribution. Risk zones of Level II are mainly distributed along the eastern coast of Wenchang, including Towns of Wentian, Changsa and Longlou, where the hazard level is Level II and the vulnerability level ranges from Level II to III. Note that there is a hazard Level I along the coast of Bamen Harbor, but with a vulnerability of Level IV. Besides, risk zones of Level III are mainly located in the eastern coastal area of Dongzhai Harbor, with a high hazard level and a high risk of inundation. Nevertheless, the vulnerability level is only Level IV due to the predominance of cultivated land and forestland, so the risk level in these zones is low. The other inland regions are classified as risk zones of Level IV, or no-risk zones.

### 4. Conclusions and discussion

Taking the typhoon-induced storm surge disasters in Wenchang as examples, this article introduces an approach of risk assessment for storm surges, which can be widely applied to other coastal regions. The approach consists of four parts—data collection and processing, hazard assessment, vulnerability assessment and risk assessment. The data of ocean bathymetry, DEM terrain, wind field, typhoon observations, land use and disaster-bearing bodies in Wenchang City are adopted in this article, with the spatio-temporal scales, resolutions, sources and processing methods for each data described in detail.

During the hazard assessment, based on the models of ADCIRC and SWAN, we build a numerical simulation system for typhoon-induced storm surges in Wenchang, and ensure that the system could catch the main characteristics of storm surge disasters by comparing the simulations of historical cases with observations. Based on the typhoon central pressure, the typhoon RMW, typhoon approach speed and direction, peripheral pressure and astronomical tide determined in this article, the PMSS cases
in Wenchang were constructed, and the simulated inundation ranges and submerged depths were used to determine the hazard levels of storm surge disasters in this region. The results show that the hazard level along the coastal area of Wenchang is relatively high (Levels I–II), especially in the east coast of Dongzhai Harbor and the coastal area of Bamen Harbor, where the maximum submerged depth can reach 2–5 m along Dongzhai Harbor and 2–6 m along Bamen Harbor.

By using the data of land use status and disaster-bearing bodies, the vulnerability assessment was conducted based on the corresponding relationship between the classification of land use and the vulnerability levels, which are further classified by taking the community as a unit. Areas with vulnerability Levels I–II in Wenchang account for about 10.6%, mainly in the communities of the northeastern and eastern Wenchang. The areas with vulnerability Level III are mainly located in the eastern coastal area of Wenchang. Most areas of Wenchang are in vulnerability Level IV, which belong to land use types of cultivated land, garden plot and forestland.

The classification of risk assessment integrates both the assessments on hazard and vulnerability. The results show that there are risks of typhoon-induced storm surge disasters in most of the coastal areas of Wenchang. Risk zones of Levels I and II mainly locate in the northeastern Wenchang, the coastal area of eastern Wenchang and Bamen Harbor. Risk Level III mainly appears in the eastern Dongzhai Harbor, and the other inland areas belong to zones of risk Level IV or no risk.

The results of risk assessment for typhoon-induced storm surge disasters play an important role in the disaster prevention and mitigation as well as coastal management for local government, and some targeted and hierarchical risk management measures can be carried out accordingly. For example, in risk zones of Levels I–II, it is possible to raise the flood control standards of seawalls and coastal engineering, and adjust the plan of land use to demonstrate the feasibility of the newly built major coastal projects for storm surge disaster prevention. In addition, it is also essential to establish a comprehensive monitoring and early warning system for storm surge disaster, setup marine disaster shelters, prepare and publish emergency evacuation maps. Furthermore, enhancing the public awareness of marine disaster prevention and mitigation, conducting publicity and education as well as emergency drills of marine disasters are also necessary. In risk zones of Levels III–IV, a strategy of accepting the risk can be adopted, but the monitoring and early-warning for storm surge disasters need to be strengthened, and necessary measures for disaster prevention and mitigation should also be taken.

There are several discussions for this study, as follows.

1. The purpose of this study is to provide a risk assessment for storm surge disasters which is a scientific support for coastal management as well as marine disaster prevention and mitigation. An intuitive and concise risk map is preferred by the local decision makers, so the PMSS scenario is selected to perform the hazard assessment, and then the classification of risk assessment is obtained by integrating the assessments on hazard and vulnerability. The PMSS scenario, which is composed of flooding maps that could capture the range of storm surge possibilities in Wenchang, has taken the most severe disasters into account and is suitable for decision making.
2. The disadvantage of our method is that the flood map is not probabilistic, and the uncertainty is difficult to analyze. However, the shortcomings of our method could be made up by JPM/JPM-OS methods. The JPM/JPM-OS methods could provide probabilistic flood maps corresponding to any return period, and the results are scientifically more robust. However, the methods require abundant observations and a knowledge of the storm climatology of the study region, and JPM-OS method will be used in the future PMSS evaluation when conditions permit.

3. The risk assessment is obtained based on the PMSS, so the results of risk assessment fall within the ranges of possible maximum levels, thus, there is limited guidance for real-time warning of storm surge disasters. For the real-time evaluation on risk levels of typhoon-induced storm surges, it is necessary to assess the risks of typhoon-induced storm surges with different levels and tracks, thereby establishing a multi-scenario risk database of typhoon-induced storm surges.

4. The risk assessment in this study focuses on the current risks in a certain area, but the potential risk of storm surge disasters is poorly estimated. For example, the eastern coastal area of Dongzhai Harbor has a very high hazard level (Level I) but a low vulnerability level (Level IV), so it is classified as the risk zone of Level III. Therefore, it is not easy to attract the attention of administrators in disaster prevention and mitigation. However, if sensitive disaster-bearing bodies appear in the future, these regions will face a very large risk of storm surge disasters. Therefore, weight coefficients will be introduced in future work, thus both the current risk and potential risk could be comprehensively considered in risk assessments of marine disasters.

5. It is important to keep the assessment results up-to-date with different environment situations. In the background of changing risk due to sea-level rise, protective measures such as newly built seawalls and significant changes of disaster-bearing bodies or land use, the risk of typhoon-induced storm surges should be re-evaluated so as to provide more accurate supports to the disaster prevention and mitigation.

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