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ORIGINAL PAPER

Scenario-based risk framework selection and assessment model development for natural disasters: a case study of typhoon storm surges

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Abstract Many studies have revealed the importance of risk assessment of natural disasters for public safety management, emergency responses and insurance purchases. This paper focuses on three aspects of a risk assessment process: (1) comparing the existing risk frameworks and assessment methods, (2) conceptualizing a *scenario-based* risk analysis approach and (3) specifying a quantitative assessment model. After a close examination of relevant research, we selected the triad of *Hazard*, *Vulnerability* and *Adaptation Capability* as the risk framework for the present study. We also prescribed several scenarios based on the spatiotemporal dynamic environment leading to given disasters. The assessment model is tested with six scenarios of typhoon storm surges striking Yuhuan County in Zhejiang Province, China. Three findings are highlighted in this paper. First, scenario-based simulation has become a dominant approach in risk analysis under the circumstances where disasters of high intensity, complexity and variability tend to occur frequently. This approach allows identification of acceptable risk with a certain probability. Second, the assessment model can reveal the collective enhancing effect of *Hazard* and *Vulnerability* and the mitigation effect of *Adaptation Capability* to the comprehensive *risk*. Lastly, the empirical study of Yuhuan indicates that $R = 0.90 \times H \times V - 0.10 \times C$ is the most feasible model for assessing the risk of typhoon storm surges. In general, the proposed methodology may be adapted for risk analysis of diverse disaster scenarios.

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1 Introduction

Natural disasters pose great threats to human subsistence, economic activities and social development. Many studies have revealed the importance of risk perception for reminding the human society to be highly vigilant, fully prepared and flexibly adaptive for future disasters. Programs and institutes ranging from the International Decade for Natural Disaster Reduction (UN 1989), the Hyogo Framework for Action (UN 2005a), the International Strategy for Disaster Reduction (UN 2005b), the Global Risk Identification Programme (UNDP 2006), to the International Human Dimensions Programme Integrated Risk Governance Project (Jaeger and Shi 2008) and the Institute for Risk and Disaster Reduction (ICSU 2008) have notably promoted the research on disaster prevention and risk reduction in recent decades. Moreover, risk reduction becomes relatively more important in the modern public safety management.

Basically, the rationality of risk framework selection and assessment model development dictates the accuracy of risk perception. Through an examination of in-depth theoretical and empirical research on risk of natural disasters, we obtain a typical classification of widely used risk frameworks and assessment models: (1) *uncertainty-based* category focusing on the disaster occurrence probability (Crichton 1999; Granger 2001, 2003), (2) *components-based* category emphasizing the relationship between risk components such as *hazard*, *exposure*, *sensitivity*, *vulnerability* and *resilience* (Shi 2002, 2010; Zhang et al. 2006; IPCC 2007; Perez and Gotangco 2013) and (3) *scenario-based* category concentrating on various spatiotemporal environments leading to diverse natural disasters (IPCC 2007; Wang et al. 2012). Generally, a gradual but obvious change emerges in risk perception with respect to a renovated method modified from static description of risk distinctions to dynamical simulation of a disastrous event. Furthermore, the literature review also indicates a preference for the *scenario-based* method in studying disasters of exceptional severity or typical return periods.

According to the previous research, most studies (1) emphasize a paradigmatic approach to risk assessment, while somehow ignore the impacts of various spatiotemporal environments and lack accuracy in some rare scenarios, and (2) provide inadequate quantitative analysis to highlight the calculation relationship between components employed in the assessment models. This paper is set out to clarify these two points demanding further discussions and focus on three aspects of a risk assessment process. First, we compared the conventional risk frameworks and assessment models and classify them into typical categories (in Sect. 2). Second, we conceptualized a scenario-based framework based on comprehension of several critical points of risk analysis (in Sect. 3). Third, taking typhoon storm surge as an example, the risk assessment model was quantitatively specified and validated through an empirical study in Yuhuan, Zhejiang, China (in Sect. 4). Finally, some conclusions were drawn for the whole study (in Sect. 5).

2 Typical risk frameworks and assessment models

2.1 Risk *uncertainty-based* category

Regarding the uncertainties persisting in issues about how a natural disaster is bred, when it would occur and what impacts it would cause (Thomalla et al. 2006; Verwaest et al. 2007), quite a few studies yield a definition for *risk* as the combination of potential losses or negative impacts and the occurrence probability of a hazardous event (UNDHA 1992; Smith 1996; Heml 1996; Stenchion 1997; Adams 1998; IPCC 2001; UNISDR 2009) (presented in Table 1). The *risk triangle* initially proposed by Crichton (1999) and further consummated by Granger (2001, 2003) is an agreeable representative for most conventional risk frameworks, showing that *probability* is essential for risk perception and assessment. As presented in Fig. 1, the shadowed triangle represents the *Risk* determined by measured *Hazard*, *Vulnerability* and *Exposure*.

A corresponding assessment model for the *risk triangle* is $R = f(H, E, V)$, indicating that *Risk* is the function of *Hazard*, *Exposure* and *Vulnerability*. According to Granger (2003), since the approach to measuring *Exposure* involves modeling the degree of inundation of assets (buildings, infrastructure, etc.) likely to occur as a result of the storm tide impact of a given annual exceedance probability, the potential loss together with a certain *probability* needs to be initially calculated using probability distribution functions of hazard intensity, hazard loss, etc. This method requires considerable amount of historical data.

The *risk triangle* contributes to highlight the underlying uncertainty and contingency of natural disasters. However, it ignores the influences of various spatiotemporal environments on the formation and occurrence of a disastrous event. The risk assessment might not progress smoothly due to the absence or poor quality of historical data. Furthermore, it is inadequate to quantify the *uncertainty* using a unique *probability*, since it exists in almost each aspect of a disaster process.

2.2 Risk *components-based* category

Disaster-formative environment, *hazard events*, *receptors* (communities, transportation, land use, etc. which might be impacted or destroyed) and *adaptations measures* (relief

Table 1 Examples of conventional *uncertainty-based* risk frameworks

Institutes and researchers	Year	Risk frameworks (definitions)
UNDHA	1992	*Expected losses* (of lives, persons injured, property damaged, and economic activity disrupted) due to a particular *hazard* for a given area and reference period
Adams	1995	A measurement of the combination of *probability* and *negative impact*
Smith	1996	The combination of *probability* and *loss*
Helm	1996	$Risk = Probability \times Consequences$
Stenchion	1997	The *probability* of a *hazard* contributing to a potential disaster, and it involves consideration of *vulnerability*
IPCC	2001	$Risk = Probability \times Impact$
UNISDR	2009	$Risk = Probability \times Negative\ Impact$

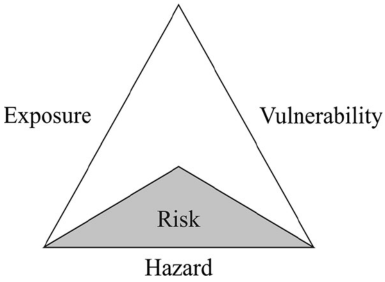

Fig. 1 Typical *uncertainty-based* risk framework (*H–E–V*) (Crichton 1999; Granger 2001, 2003)

logistics, evacuation, restoration, etc.) link the whole course of a disastrous event. *Hazard*, *Exposure* and *Vulnerability*, etc. are frequently employed as the components for definition of the disaster *risk*. However, the understanding of a single component or a synthesized risk framework differs distinctly among researchers (UN 2002; Wisner 2003; UNDP 2004; Liu and Zhang 2004; Yin et al. 2009; Yin and Xu 2012) (presented in Table 2). In the disaster risk community, the most widely used *H–E–V*–AC framework proposed by Perez and Gotangco (2013) (presented in Fig. 2a) reveals that *Risk* is an integration of *Hazard, Exposure*, *Vulnerability* and *Adaptation Capability*. The climate change community concentrates more on *Vulnerability*, which is defined as a function of *Exposure*, *Sensitivity* and *Adaptation Capability* ($V = f(E, S, AC)$) in the IPCC Fourth Assessment Report (2007) (presented in Fig. 2b). In addition, Shi (2002) highlighted the importance of *background environment* (*E*) and asserted that *Hazard* and *Vulnerability* coexist in the spatiotemporal environment where the hazards are bred (presented in Fig. 2c). Zhang et al. (2006) emphasized *emergency response* and *recovery capability*, which also extended the cognition of risk, since adaptation and precaution indeed mitigate the devastating impacts of natural disasters (Kreibich et al. 2005).

Assessment models corresponding to the *components-based* frameworks include $R = (H \times E \times V)/AC$ (*Risk* is a function of *Hazard*, *Exposure*, *Vulnerability* and *Adaptation Capability*) (Fig. 2a), $V = f(E, S, AC)$ (*Vulnerability* is a function of *Exposure*, *Sensitivity* and *Adaptation Capability*) (Fig. 2b) and $R = H \times V \times ES$ (*Risk* is a function of *Hazard*, *Vulnerability* and *Environmental Stability*) (Fig. 2c). Approaches like analytic hierarchy process (AHP) and fuzzy mathematics based on indicator systems are widely adopted to evaluate each single component before calculating the comprehensive *risk* (Büchele et al. 2006; Meyer et al. 2009; Müller et al. 2011). Moreover, the spatial analyst package in ArcGIS (Geographic Information System) also makes risk assessment more efficient in recent years.

Table 2 Examples of conventional *components-based* risk frameworks

Institutes and researchers	Year	Risk frameworks
Wisner	2003	$Risk = Hazard \times Vulnerability - Adaptation$
Liu XL	2004	$Risk = Hazard \times Susceptibility$
UNDP	2004	$Risk = Hazard \times Vulnerability \times Exposure$
Zhang JQ	2006	$Risk = Hazard \times Vulnerability \times Exposure \times Emergency\ Response$ and $Recovery\ Capability$
Yin ZE	2012	$Risk = Hazard \cap Impact \cap Exposure - Vulnerability \cap Resilience$

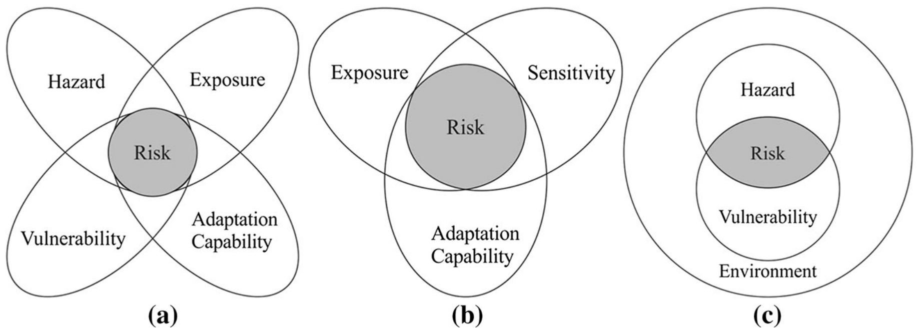

Fig. 2 Typical *components-based* risk frameworks **a** *H–E–V–AC* (Perez and Gotangco 2013); **b**: *E–S–AC* (IPCC 2007); **c** *H–V–E* (Shi 2002)

In terms of the calculation relationship between the components in an risk assessment model, Perez and Gotangco (2013) claims that the collaborative enhancing effect of *Hazard, Exposure* and *Vulnerability* should be represented by ×, and the mitigation effect of *Adaptation Capability* should be represented by ÷, further specifying the model as $R = (H \times E \times V)/AC$. According to Wisner (2003), however, the mitigation effect should be −, hence, the assessment model should be $R = H \times V - AC$. Similar work echoes in Yin and Xu's (2012) and Wang and Tang's (2009) literatures.

The *components-based* framework exemplifies an improvement with respect to a broadened risk cognition. It attaches importance to the effects of spatiotemporal environment and adaptation measures. However, *stability* uniquely is inadequate to explicate the various environmental influences, and more explicit instructions need to be given to use ∩, ×, − or ÷ between the components and quantify a risk assessment model.

2.3 Risk *scenario-based* category

Basically, risk scenario is considered as a situation in which a hazardous event with a certain probability would occur and cause some damage. It represents an overall state during the course of a natural disaster. Prior to this study, the risk scenario has been classified into *natural*, *socioeconomic* and *spatiotemporal* aspects (presented in Fig. 3a). The *natural* part includes *hazard* and *disaster-formative environment*, the *socioeconomic* part includes *population*, *economic* and *land use*, and the spatiotemporal part includes *timescales*, *space scales* and *return periods* (Liu et al. 2012; Wang et al. 2013a). Zhao (2013) divides the risk scenario into *hazard*, *natural and socioeconomic* parts, similarly highlighting the various environmental influences on disaster risk.

$R = \{S_i, p(S_i), X(S_i)\}$ $(i = 1, 2, \ldots, N)$ is an general assessment model corresponding to the *scenario-based* risk framework. Specifically, N is the number of all supposed scenarios; S_i is the ith scenario and $p(S_i)$ is the probability that the ith scenario (S_i) might emerge; $X(S_i)$ is the losses caused in the ith scenario (S_i); R is the comprehensive risk of each scenario. It is actually impossible to list all supposed scenarios; therefore, risk matrices involving natural disasters of severe intensity or typical return periods are usually adopted as a simplified approach to risk assessment in different spatiotemporal units.

In order to reflect the state of various spatiotemporal environments, each scenario is prescribed on basis of distinctive changes in natural and socioeconomic surroundings. In a supposed scenario, the disastrous event of a certain return period also indicates the

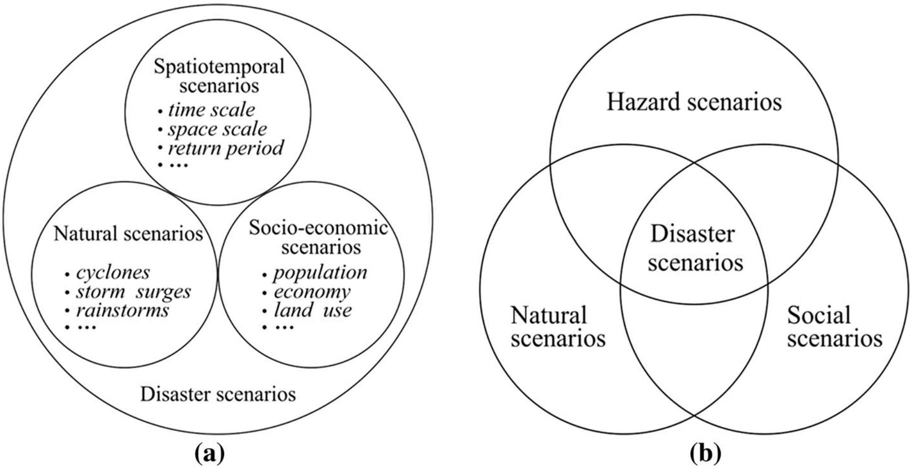

Fig. 3 Classification of disaster scenarios **a** Liu et al. (2012) and Wang et al. (2013a); **b** Zhao (2013)

meaning of *uncertainty* but widely represented by *probability*. Through simulating scenarios such as sea level rise, global warming, land subsidence and land use change, the *scenario-based* method highlights that *risk* is dynamically changing with the spatiotemporal environments. Moreover, it enables risk assessment for extreme natural disasters and allows accurate identification of acceptable risk, while hardly suffering from the negative effects of *probability* to calculate the final *risk*. Despite in its infancy, the *scenario-based* method meets the requirements of modernized risk management under the circumstances where disasters of high intensity, complexity and variability tend to occur frequently with climate change (Xu et al. 2006; IPCC 2007; Wang et al. 2013b).

3 Conceptualization of a scenario-based method for risk analysis

3.1 Explanation for five critical points

3.1.1 Selection of risk components

The literature examination indicates that the conception of *Exposure* generates most controversial views. According to UNDP (2004), *Exposure* describes people, property and ecosystems present in hazard zones and are subject to potential losses. Considerable researches however give a definition of *Exposure* slightly distinguished from *Vulnerability*. Moreover, regarding the impacts of rapid urbanization and climate change, most human habitats especially the coastal areas supporting a large population and economy have been highly exposed to natural disasters (Yin et al. 2013b). In this paper, we consider *Exposure* as a synthesized consequence of *Hazard* and *Vulnerability*. For illustration, the *Exposure* to a flood disaster is jointly determined by flood (*Hazard*) and impacted population, buildings or traffic systems, etc. (*Vulnerability*). Finally, we select a triad of *Hazard*, *Vulnerability* and *Adaptation Capability* and built a linkage among all regular components in previous risk frameworks (presented in Fig. 4).

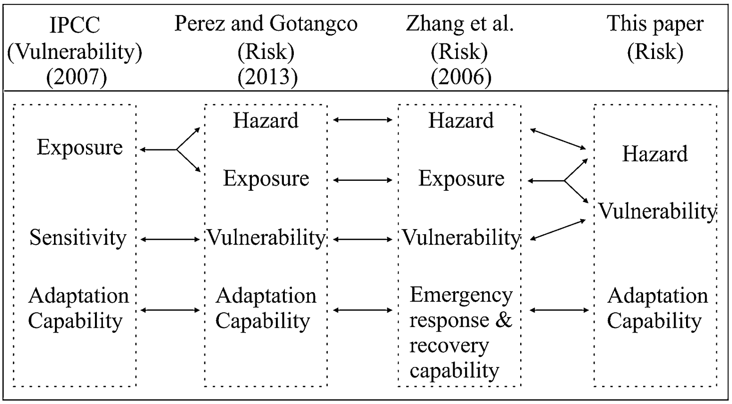

Fig. 4 Linkage between components in different risk frameworks

3.1.2 Spatiotemporal scales

In order to capture the impacts of spatiotemporal environment on risk of natural disasters, we focus on some distinctive changes of *Hazard*, *Vulnerability* and *Adaptation Capability*. These changes take place at various spatiotemporal scales and ultimately integrate in a specific risk scenario, reflecting potential state of the inducements/intensity/impacts of or resilience to a natural disaster (Liu et al. 2012; Wang et al. 2013a). It is critical for an accurate risk identification and assessment to set definite and proper temporal and spatial scales for evaluation of each risk component.

3.1.3 Universality and variability

A universal paradigm for risk assessment is essential for quick warning and loss analysis. However, regarding the complexity in *Hazard*, *Vulnerability*, *Adaptation Capability* and spatiotemporal scales, a paradigmatic model needs to be further specified and validated to conduct risk assessment with a greater sense of sensitivity and pertinence in different scenarios of natural disasters.

3.1.4 Calculating relationship between risk components

It is acceptable to represent the collaborative relationship between risk components using $\cap$ or $\times$, but we select $\times$ for the convenience of calculation. Besides, instead of decreasing the degree of *Hazard* or *Vulnerability* fundamentally, *Adaptation Capability* just mitigates the negative impacts after the occurrence of a natural disaster; thus, in this paper $-$ is considered creditable to represent its mitigation effect.

3.1.5 Uncertainty and probability

In each scenario, the disastrous event of a certain return period also indicates the nature of *uncertainty* which is widely represented by *probability*. For example, a flood event of 10 or 100 years return period equals to the occurrence probability of 0.1 or 0.01. Based on scenario simulation of the flood process, further analysis of impacts is implemented; thus, the degree of *Hazard* and *Vulnerability* is displayed directly, and the flood risk is calculated for each scenario without the *probability* involved. Besides, since people would prefer to stay in the habitats where they have been supported for generations, rather than moving away from potential risk, it is important for them to get adapted to *acceptable risk* (Fischhoff et al. 1981; Vrijling et al. 1998; Klinke and Renn 2002; Shang and Liu 2010). Simulating a natural disaster of typical return periods indeed contributes to identifying the acceptable risk. In general, the scenario-based method has progressed the meaning of risk assessment from "whether the disaster would happen" to "what sort of impacts the disaster would cause."

3.2 A new *scenario-based* risk framework

In the light of five critical points above, we select the triad of *Hazard*, *Vulnerability* and *Adaptation Capability* as a new *scenario-based* risk framework for the present study (presented in Fig. 5). Conceptualization of the new framework is based on both previous research and independent understandings in this paper. Three major improvements are listed here: First, various impacts of the natural and socioeconomic environments on risk of natural disasters are fully considered; second, the calculating relationship between risk components is further clarified; and finally, through scenario simulation, we address *probability* in a different way, which reveals the nature of uncertainty while enables the identification of *acceptable risk.*

Following is an explanation for Fig. 5. The current state of spatiotemporal environments is a foundation for prescribing future scenarios of natural disasters. Each scenario is designed based on potential environmental changes emerge in a coupled dimension of time and space. Around each risk component, there is a scenario circle expanding and contracting in accordance with the changes of *Hazard*, *Vulnerability* and *Adaptation*

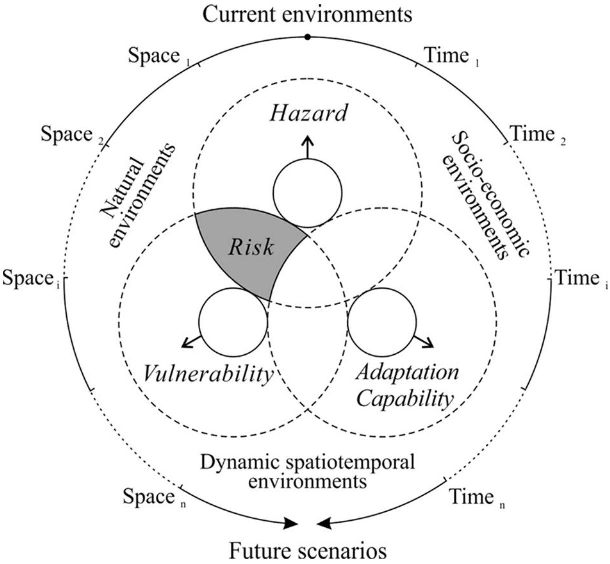

Fig. 5 A new *scenario-based* risk framework (*E–H–V–AC–S*)

Capability. Basically, there is no need to concern about *risk* if changes in natural/socioeconomic environments do not cause distinctive deviation in degrees of *Hazard* and *Vulnerability*, keeping a current state of safety. However, an intersection will emerge with the scenario circles expanding, and the area of intersection represents the degree of *risk*. Additionally, considering the mitigation effect of *Adaptation Capability*, we clip the area where three scenario circles intersect together from the initial intersection and maintain the shadowed area to represent the comprehensive *risk*. If *Adaptation Capability* becomes stronger, its scenario circle expands more, leading to a larger part clipped off and a greater reduction in the comprehensive *risk* of certain natural disasters.

3.3 A new *scenario-based* model for risk assessment

An assessment model corresponding to the new risk framework is $R = \{S_i, H(S_i), V(S_i), AC(S_i)\}(i = 1, 2, \ldots, n; n \rightarrow \infty)$, but it needs further specification before used in a certain study. It has been explained to use × and – representing the calculation relationship between three risk components, while the weights showing the enhancement and mitigation effects of each component contributing to the integrated *risk* should be distinguished as well:

$$R = w_1 \times H \times V - w_2 \times AC. \tag{1}$$

Moreover, if *risk* is a weighted result of *Hazard*, *Vulnerability* and *Adaptation Capability*, it is inadequate to set $w_1 = w_2 = 1$ or $w_1 + w_2 = 1$ as fixed requirements. Thus, we introduce another variable R' by normalizing w_1 and w_2 as follows:

$$R' = [1/(w_1 + w_2)](w_1 \times H \times V - w_2 \times AC). \tag{2}$$

In formula (2), $(w_1 + w_2)$ is a constant excluding 0 since it makes no sense for risk assessment if $w_1 = w_2 = 0$. Basically, risk assessment is based on classifying comprehensive *risk* into different levels, from high to low risk. However, the classification is not decided by absolute *risk* index, but the difference between the maximum and minimum value $(R_{\max} - R_{\min})$. If $R' = [1/(w_1 + w_2)] \times R$, we can figure out that $(R'_i - R'_j) = [1/(w_1 + w_2)] \times (R_i - R_j)$, indicating that the difference between any two risk levels is in direct proportion to the change in absolute comprehensive *risk*. Therefore, the results of risk assessment will not been changed with introducing $1/(w_1 + w_2)$ or using R' instead of R. We further set $\alpha = w_1/(w_1 + w_2)$ and $\beta = w_2/(w_1 + w_2)$; thus, formula (2) is transformed as

$$R' = \alpha \times H \times V - \beta \times AC \tag{3}$$

Hereby, it is credible to set $\alpha + \beta = 1$. Further analysis for quantifying α and β is required before utilizing the model in a certain study.

4 A quantitative model for risk assessment of typhoon storm surges

We employ the new assessment model to evaluate the risk of typhoon storm surges in Yuhuan, Zhejiang Province of China (presented in Fig. 6). According to historical records, Yuhuan has been frequently stricken by severe storm surges (presented in Table 3); thus, it attracts attention of both local authority of public safety and scientific research on typhoon

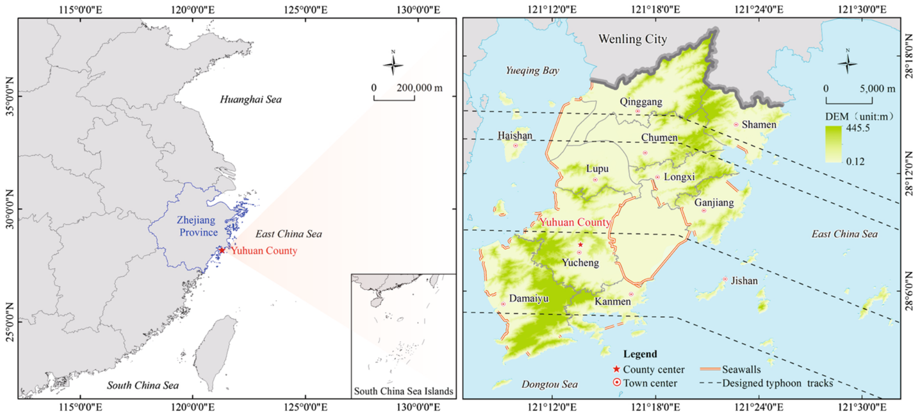

Fig. 6 Location of Yuhuan, Zhejiang Province of China

disasters. We select Yuhuan for the present case study with the purpose of specifying and testing the assessment model to be used in other coastal cities similar to Yuhuan.

4.1 *Scenario-based* method for risk analysis of typhoon storm surges

Typhoon storm surges are generated in complex atmospheric, oceanic and topographic environments. Strong wind is the chief hazard (Yin et al. 2013a). A *scenario-based* method for risk analysis of typhoon storm surges mainly involves the following six procedures (presented in Fig. 7). (1) Designing proper scenarios based on prescribing potential changes in atmospheric, oceanic and topographic environments such as sea level rise, land subsidence, land use change and population growth. (2) Simulating the surge floods in each typhoon scenario and calculating the flood depth and area, to obtain a classification of *Hazard* degrees. (3) Based on land use categories in 2020 predicted according to the pattern of population/economy developments and urban planning policies of Yuhuan, we classify the degree of *Vulnerability* of land use in the current state and in 2020, respectively. (4) We employ a simplified method for assessment of *Adaptation Capability*. Since emergency shelters are direct reflection of investments into the disaster response system, we classify the degree of *Adaptation Capability* according to the capacity share of shelters in each village. (5) Defining the spatiotemporal scales including boundaries of the study area and duration of the flood simulation process. (6) Quantifying α/β and calculating the integrated risk using the assessment model $R = \alpha \times H \times V - \beta \times AC$. Besides, it is acquiesced here that the coastal inhabitants must live with acceptable risk.

The process of flood simulation and *Hazard* classification is put as follows. First, six typhoon scenarios were designed by coupling four track scenarios (landfall at northeast coast, east coast, southeast coast and west coast of Yuhuan, respectively) to each corresponding intensity scenario (central pressure is 915, 925, 935, 945, 955 and 965 hPa, respectively). Each typhoon scenario relates to a typical return period, referring to the certain probability of a typhoon event. Second, the hydrodynamic process of surge floods in each typhoon scenario is simulated using MIKE 21 FM module for 160 h, since the designed typhoons are in parallel with the track of 0608# Saomai which lasted for 160 h from August 5th 00:00 to August 11th 16:00 in 2006 (24-h notation). Lastly, we calculate

Table 3 Direct economic loss caused by typhoon storm surges in the last decade in Yuhuan (unit: million/RMB)

Year	Typhoon	Direct economic loss	Year	Typhoon	Direct economic loss
2004	200414#Rananim	1450	2008	200808#Fung-wong	35
2005	200505#Haitang	292		200813#Sinlaku	49.3
	200509#Matsa	360	2009	200908#Morakot	213
2006	200608#Saomai	47.2	2012	201211#Haikui	28.53
2007	200713#Wipha	178	2013	201323#Fitow	–
	200716#Krosa	162.8	2014	201410#Matmo	–

–: data not available

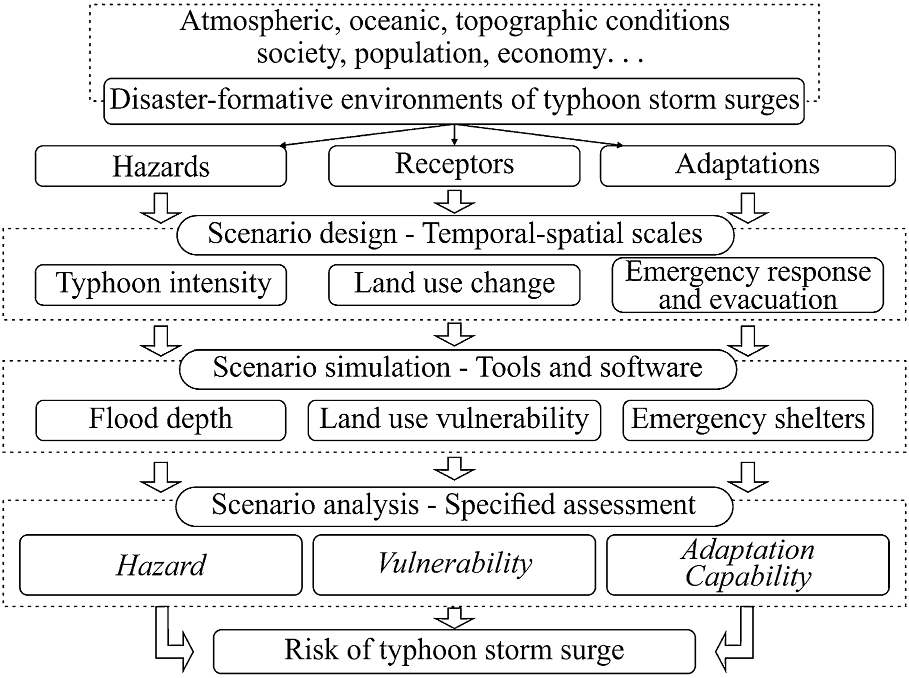

Fig. 7 S*cenario-based* method for risk analysis of typhoon storm surges

the flood depth and area by subtracting the digital elevation model (DEM) from the simulated surge water level for classification of *Hazard* degrees.

4.2 Quantifying the assessment model

First, we set 18 groups of α and β, and in each group $\alpha + \beta = 1$ (shown in Table 4). Subsequently, 18 different models are created. Second, we calculate the comprehensive risk (R) using each model, respectively, and classify R into four levels ranging from *extreme-*, *high-*, *moderate-* to *low-risk*. Third, based on results obtained with each risk assessment model, we separately calculate the area of each risk level in ArcGIS. Lastly, we draw four line charts in MS Excel to figure out the pattern of R changing with α and β (presented in Fig. 8).

As displayed in Fig. 8, obvious fluctuations emerge in all line charts. In Fig. 8a–c, the lines representing the area of *extreme*-, *high*- and *moderate-risk* fluctuate in a similar way, while lines of *low risk* fluctuate conversely as shown in Fig. 8d, implying that when the area of *extreme*-, *high*- and *moderate-risk* decreases, the area of *low-risk* will increase. Figure 8a, b shows that the area of *extreme*- and *high-risk* decreases distinctly if $\alpha = 0.90/\beta = 0.10$, $\alpha = 0.50/\beta = 0.50$ or $\alpha = 0.25/\beta = 0.75$. The most significant change takes place where $\alpha = 0.90/\beta = 0.10$. Regarding the area of *extreme*- and *high-risk* cannot be reduced to a larger extent with the increase in β or decrease in α; hereafter, we quantify the weight of (*Hazard* × *Vulnerability*) as 0.9 and that of *Adaptation Capability* as 0.1 and specify the risk assessment model as

$$R = 0.9 \times H \times V - 0.1 \times AC. \tag{4}$$

Quantifying the assessment model also indicates an optimal investment-benefit mode for planning and construction of a public safety system. For example, more emergency shelters indeed ensure a greater degree of *Adaptation Capability*, but it is important for the decision makers to strengthen *Adaptation Capability* in a resource-saving way, considering the available investment resource is limited in a lot of less developed urban areas (Cardona 2004).

4.3 Risk zoning of typhoon storm surges in Yuhuan

Yuhuan is an island county surrounded on three sides by the East China Sea, the Dongtou Sea and the Yueqing Bay, and there are eleven towns (Shamen, Ganjiang, Longxi, Chumen, Lupu, Qinggang, Jishan, Haishan, Yucheng, Damaiyu and Kanmen) inside it (presented in Fig. 6). In the light of risk assessment results, we further obtain the risk zoning of typhoon storm surges, revealing the spatial distribution of hazard and impacts of surge floods in Yuhuan (presented in Figs. 9, 10). The area of each risk level is calculated as shown in Table 5.

Figures 9 and 10 display a wide range of eastern and northwestern coastal areas susceptible to typhoon storm surges in Yuhuan. If hit by typhoons with central pressure of 915 or 925 hPa, there would be widespread *extreme*- and *high-risk* flood areas, including the center of Shamen and Ganjiang, the eastern part of Yucheng, the northwestern part of Damaiyu and the northern part of Lupu (Fig. 9a, b). If hit by typhoons with central pressure of 935 hPa or 945 hPa, the northern part of Lupu would still be confronted with *extreme-risk*, but central Shamen, Ganjiang and northwestern Damaiyu would turn to *high-risk* areas (Fig. 9c, d); If hit by typhoons with central pressure of 955 hPa, only the

Table 4 Eighteen sets of α and β (α: contributions of *Hazard* (H) and *Vulnerability* (V); β: contribution of *Adaptation Capability* (AC) to the comprehensive risk)

α	1	0.95	0.90	0.85	0.80	0.75	0.70	0.65	0.60
β	0	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40
α	0.55	0.50	0.45	0.40	0.35	0.30	0.25	0.20	0.15
β	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85

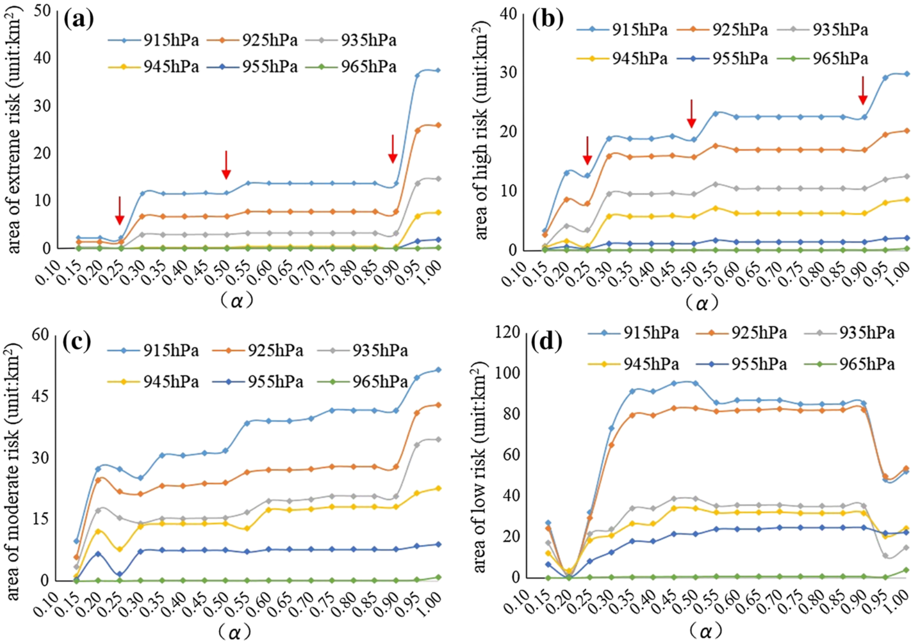

Fig. 8 Pattern of comprehensive risk (R) changing with α and β

southwestern part of Qinggang would be *moderate*- or *low-risk* areas. If hit by typhoons with central pressure of 965 hPa, there would not be any risk. In general, the risk zoning in 2020 is similar to that in the current state, but the *extreme*- and *high-risk* areas slightly expand due to an increase in the areas of high *Vulnerability* especially in Yucheng and Lupu. As shown in Table 5, if hit by typhoons with central pressure of 915, 925, 935 or 945 hPa, the area of *extreme* risk will be increased by 8.55, 5.25, 3.52 and 2.28 km^2 in 2020, respectively. Moreover, the *moderate*- and *low-risk* area will expand with *extreme*- and *high-risk* area shrinking in line with the decrease in typhoon central pressure.

Since the comprehensive risk is classified into different degrees, measures to risk reduction should also be distinguished. As for *extreme*- and *high-risk* areas, it is urgent to make evacuation plans in advance so that the endangered population could be transferred to safe shelters in a timely fashion. For *moderate*- and *low-risk* areas, it is necessary to reinforce dykes or seawalls to withstand the storm surges. Additionally, a proper control of expansion of land use with high vulnerability in the short-term urban planning is also helpful to avoid larger losses in the future.

5 Conclusions

During the course of conceptualizing a *scenario-based* method for risk analysis of natural disasters, we have reached the following major conclusions.

1. The scenario-based risk framework composed of the triad of *Hazard*, *Vulnerability* and *Adaptation Capability* fully considers the various effects of natural/socioeconomic surroundings and environmental changes at different spatiotemporal scales. The

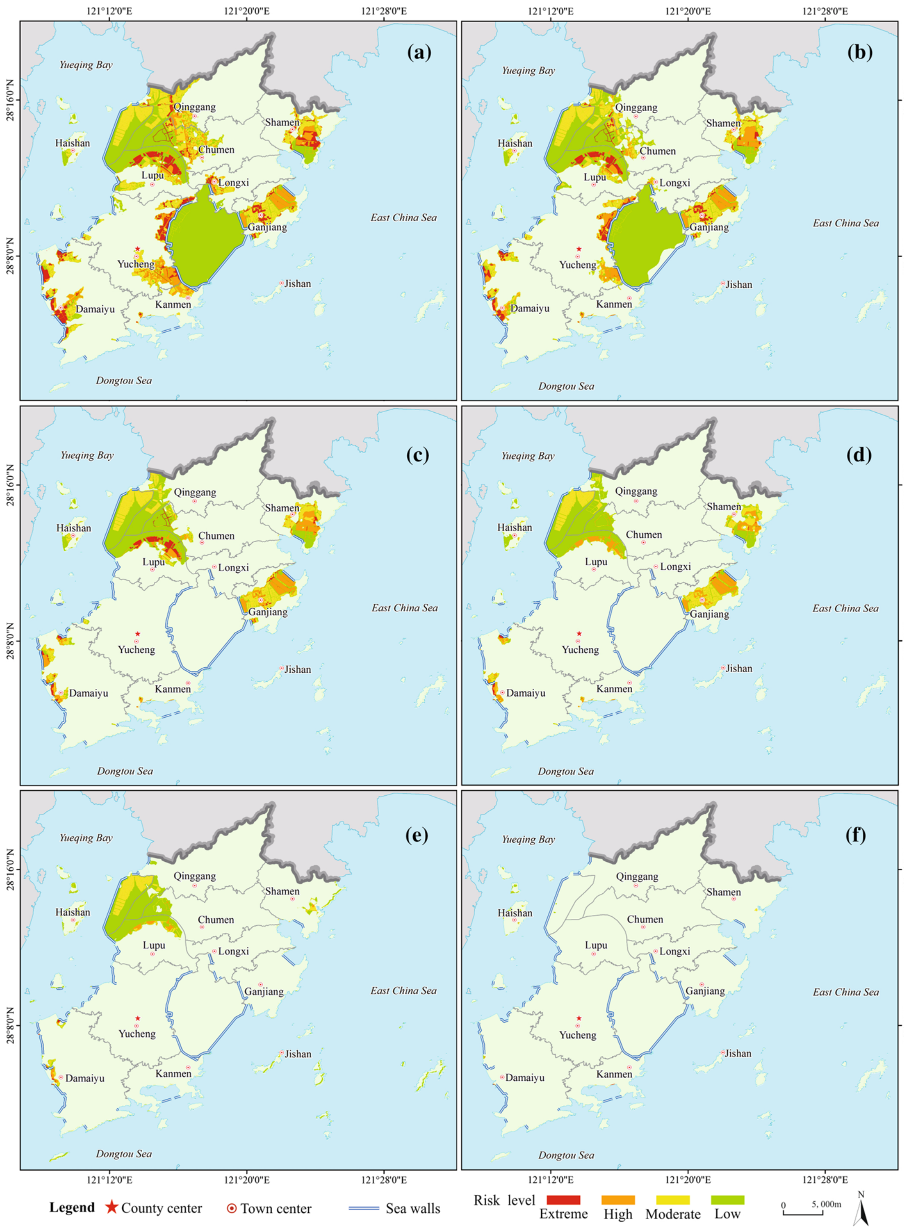

Fig. 9 Risk zoning of typhoon storm surges in Yuhuan (in current state), **a**–**f** six typhoon scenarios with designed central pressure of 915, 925, 935, 945, 955 and 965 hPa

paradigmatic risk assessment model corresponding to the new framework is $R = \{S_i, H(S_i), V(S_i), AC(S_i)\}(i = 1, 2, \ldots, n; n \to \infty)$.

2. $R = \alpha \times H \times V - \beta \times C$ is a model capable of revealing the collaborative enhancement effect of *Hazard* and *Vulnerability* and the mitigation effect of

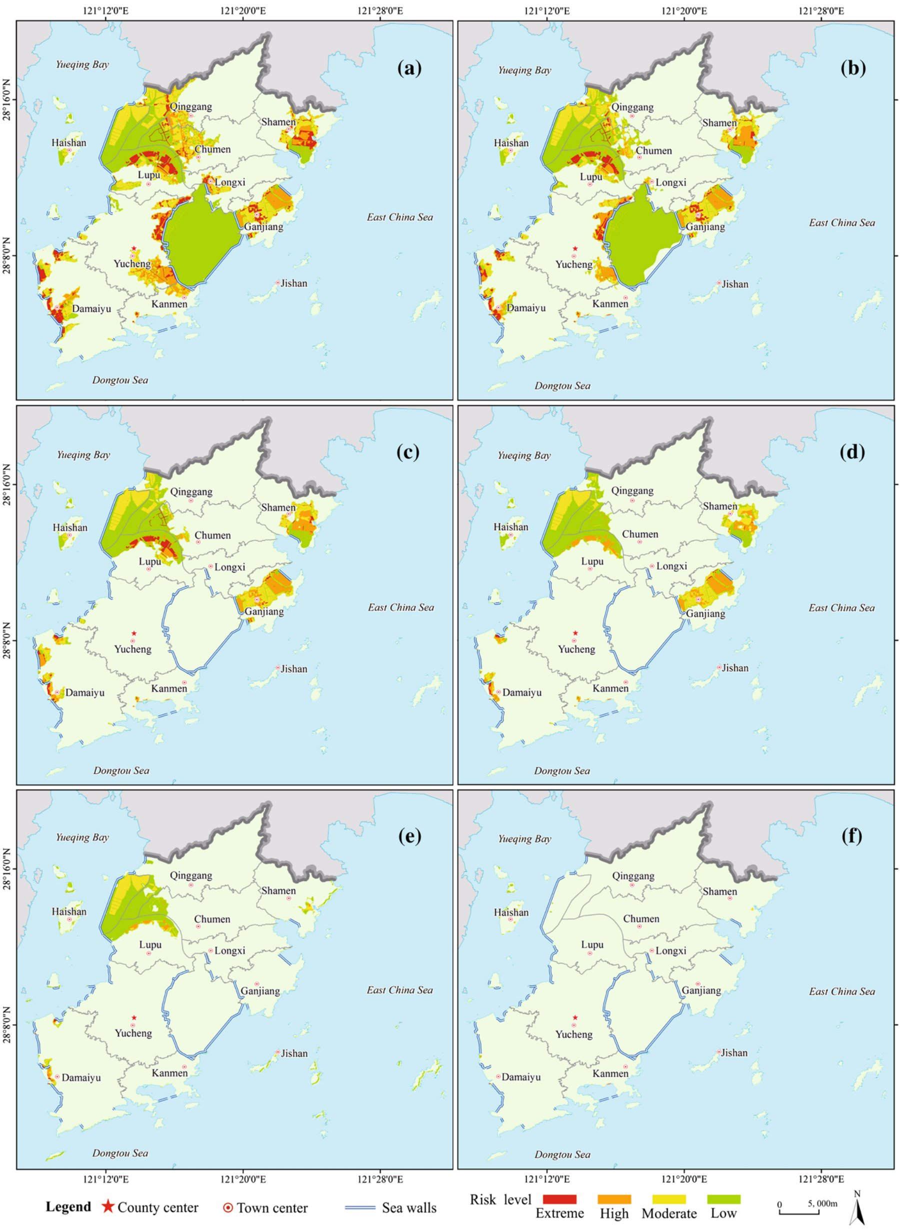

Fig. 10 Risk zoning of typhoon storm surges in Yuhuan (in 2020 state), **a**–**f** six typhoon scenarios with designed central pressure of 915, 925, 935, 945, 955 and 965 hPa

Adaptation Capability, as well as the different contributions of each component to the comprehensive risk. A further specified version of this model enables assessment of extreme risk and identification of acceptable risk in certain scenarios of natural disasters.

Table 5 Area of *extreme*-, *high*-, *moderate*- and *low-risk* in current and 2020 state in Yuhuan (unit: km^2)

Typhoon intensity (hPa)	Risk level	Land use at present	Land use in 2020	Risk area difference	Typhoon intensity (hPa)	Risk level	Land use at present	Land use in 2020	Risk area difference
915	Extreme	37.45	46.00	8.55	945	Extreme	7.59	9.87	2.28
	High	29.88	29.99	0.11		High	8.60	9.82	1.22
	Moderate	51.39	43.74	−7.65		Moderate	22.78	23.33	0.55
	Low	51.93	50.93	−1.01		Low	24.43	20.39	−4.04
925	Extreme	25.92	31.17	5.25	955	Extreme	1.93	2.27	0.34
	High	20.29	22.05	1.76		High	2.04	2.42	0.38
	Moderate	42.96	38.03	−4.94		Moderate	9.05	9.59	0.53
	Low	53.68	51.60	−2.08		Low	22.37	21.12	−1.26
935	Extreme	14.72	18.23	3.52	965	Extreme	0.29	0.52	0.22
	High	12.57	14.54	1.97		High	0.39	0.33	−0.06
	Moderate	34.53	31.81	−2.73		Moderate	0.98	0.97	0.00
	Low	14.86	12.09	−2.76		Low	3.76	3.60	−0.16

3. α and β can be quantified with specific data and analysis. In this paper, a case study of Yuhuan, in Zhejiang Province of China, adapts the model applicable in typhoon scenarios and indicates that $R = 0.90 \times H \times V - 0.10 \times C$ is the most feasible model for risk assessment of typhoon storm surges in Yuhuan.
4. Risk zoning can be implemented based on risk assessment results. The risk zoning of typhoon storm surges in Yuhuan reveals that the eastern and northwestern coastal areas are susceptible to typhoon storm surges. If hit by typhoons with central pressure of 915 or 925 hPa, there would be a wide range of flood areas confronted with *extreme*- and *high-risk*.
5. The risk assessment results are important contributions toward strengthening *Adaptation Capability* to natural disasters. Besides, the major findings and improvements in this study will serve as references for the theoretical and methodological research on *scenario-based* risk cognition of natural disasters in the future.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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