Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2018-14
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Discussion started: 23 February 2018

Risk Zoning of Typhoon Disasters in Zhejiang Province, China

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Abstract We analyze the characteristics of typhoon disasters and the factors causing them using precipitation and wind data at the county level in Zhejiang Province from 2004 to 2012. Using canonical correlation analysis, we develop an intensity index for the factors causing typhoon disasters and calculate a population vulnerability index for Zhejiang by principal components analysis. Combining these two indexes, a comprehensive risk index for typhoon disasters is obtained and used to zone areas of risk in Zhejiang Province. Southeastern Zhejiang Province is the area most affected by typhoon disasters. The frequency ratio of daily rainfall >50 mm decreases from the southeast coast to inland areas and is at a maximum in the boundary region between Fujian and Zhejiang, which has the highest risk of rainstorms. Southeastern Zhejiang and the boundary region between Zhejiang and Fujian and the Hangzhou Bay area are most frequently affected by extreme winds and have the highest risk of wind damage. The population of southwestern Zhejiang Province is the most vulnerable to typhoons as a result of the relatively undeveloped economy in this region, the mountainous terrain and the high risk of geological disasters. Vulnerability is lower in the cities and coastal areas due to better disaster prevention and reduction strategies and a more highly educated population. The southeast coastal areas face the highest risk, especially in the boundary region between Taizhou and Ningbo cities. Although the inland mountainous areas are not directly affected by the typhoons, they are in the medium-risk category for vulnerability.

Keywords: typhoon disasters, disaster-causing factors, vulnerability, comprehensive risk index, risk zoning

1 Introduction

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Typhoons cause some of the most serious natural disasters in China, with an average annual direct economic loss of about $9 billion. The arrival of a typhoon is often accompanied by heavy rain, high winds and storm surges, with the main impacts in southern coastal areas of China (Zhang, 2009). Zhejiang Province is seriously affected by typhoons—for example, in 2006, the super-typhoon Sang Mei caused 153 deaths in Cangnan county of Wenzhou city, with 11.25 billion yuan of direct economic losses. Therefore it would be of practical significance to develop a system for the risk assessment of typhoon disasters in Zhejiang Province.

Major risk assessment models include the disaster risk index system of the United Nations Development Program (global scale, focusing on human vulnerability), the European multiple risk assessment (with an emphasis on the factors causing disasters and vulnerability) and the American HAZUS-MH hurricane module and disaster risk management system. Vickery et al. (2009) and Fang et al. (2012, 2013) have reviewed the factors causing typhoon disasters. Rain and wind are direct causes of typhoon disasters (Mille, 1958; Emanuel, 1987, 1988, 1995; Holland, 1997; Kunreuther, 1998); stronger typhoons produce heavier rain and stronger winds, resulting in a greater number of casualties and higher economic losses. Much of the research on the causes of typhoon disasters uses a grade index and the probability of occurrence (Yang, 2010; Chen, 2011; Su, 2008; Ding, 2002; Chen, 2007).

In terms of vulnerability, Pielke (1998, 2008) combined the characteristics of typhoons and socioeconomic factors, suggesting that both the vulnerability of the population and economic factors were important in estimating disaster losses. The vulnerability of a population is a pre-existing condition that influences its ability to face typhoon disasters. Among the most widely used index is the Social Vulnerability Index (SoVI) (Cutter, 2003; Chen, 2014). Other researches have focused on the vulnerability of buildings, obtaining a fragility curve by combining historical loss with the characteristics of buildings and the typhoon (Hendrick, 1966; Howard, 1972; Friedman, 1984; Kafali, 2009; Pita, 2014). Studies in China have assessed vulnerabilities to typhoon disasters (Yin, 2010; Niu, 2011). An evaluation index for the assessment of disaster losses was established based on the number of deaths, direct economic losses, the area of crops affected and the number of collapsed houses. This index was used to construct different disaster assessment models (Liang, 1999; Lei, 2009; Wang, 2010).

Previous studies have concentrated on semi-quantitative, large-scale research, with less emphasis on quantitative research at the county level based on large amounts of accurate data. In addition, assessments of typhoon disaster in China have paid more attention to disaster losses and few studies have focused on a comprehensive risk assessment of typhoon disasters coupled with the factors contributing to the disaster and the vulnerability of populations and infrastructure. We analyzed the characteristics of typhoon disasters, established a comprehensive risk index for typhoon disasters in Zhejiang Province and developed risk zoning for typhoon disasters in this region, which may give some reference for future disaster prevention.

2 Study Area

This study was carried out in Zhejiang Province (Figure 1) and included 11 cities along the Yangtze River Delta. Zhejiang Province is in the eastern part of the East China Sea and south of Fujian Province, which is one of the most economically powerful provinces in China.

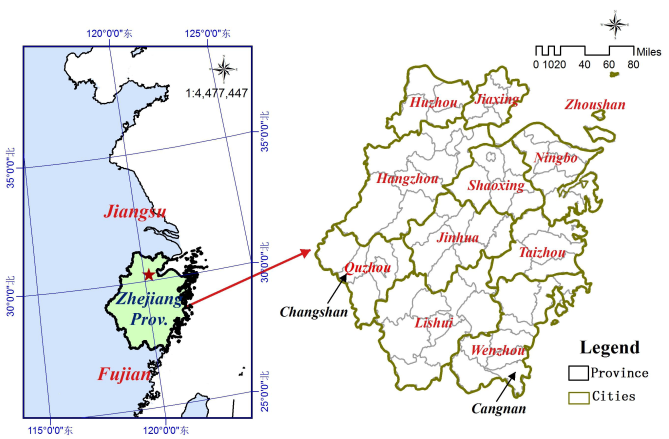

Figure 1. Maps of Zhejiang Province, China showing location and major cities.

3 Data and Methods

3.1 Data

3.1.1 Typhoon, Precipitation and Wind Data

The typhoon data used in this study were the best-track tropical cyclone datasets from the Shanghai Typhoon Institute for the time period 1960–2014. Daily precipitation data for 2479 stations during the time period 1960–2013 were obtained from the National Meteorological Information Center. The

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statistics showed a rapid increase in the number of automated wind measurement stations from 1980. Therefore, to ensure continuity of the data, the wind data used were the daily maximum wind speed at 2419 stations provided by the National Meteorological Information Center from 1980 to 2014. The maximum wind speed is given as the maximum of the 10-minute mean.

3.1.2 Disaster and Social Data

Disaster data for each typhoon that affected Zhejiang Province from 2004 to 2012 were obtained from the National Climate Center and the number of records for each county is shown in Figure 2. Of the 11 cities in Zhejiang Province, Wenzhou and Taizhou recorded the most typhoon disasters, with a maximum of 17. Fewer typhoon disasters were recorded in the central and western regions of Zhejiang Province, particularly in Changshan and Quzhou, which may be because the strength of typhoons weakens after landfall. The population data for 2010 were obtained from the sixth national population census of the Population Census Office of the National Bureau of Statistics of China and the 2010 statistical yearbooks of each city in Zhejiang Province published by the cities' statistical bureaus. Basic geographical data were obtained from the National Geomatics Center of China.

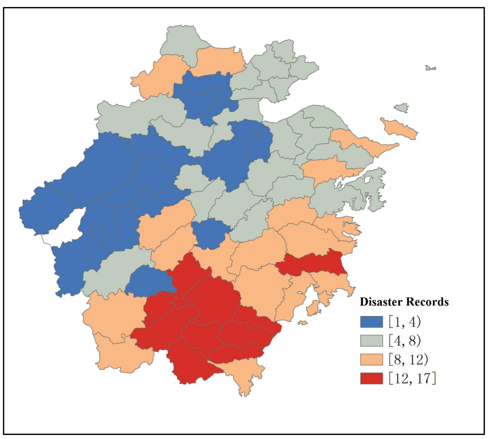

Figure 2. Number of records of typhoon disasters by county in Zhejiang Province from 2004 to 2012.

3.2 Methods

3.2.1 Objective Synoptic Analysis Technique

The widely used objective synoptic analysis technique (OSAT) proposed by Ren (2001, 2011) was used

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to distinguish the precipitation due to typhoons. This method has a high recognition ability. Lu (2016) improved the OSAT method and applied it to identify typhoon winds. We used the OSAT method to distinguish typhoon precipitation and winds from 2004 to 2012.

3.3.2 Canonical Correlation Analysis

We used the canonical correlation analysis method proposed by Hotelling (1992) to determine the relationship between the affected population, the rate of economic damage, and typhoon precipitation and winds.

3.2.3 Data Standardization

We adopted two methods: Z-score standardization and MIN-MAX standardization. The Z-score standardized method is based on the mean and standard deviation of the raw data. The MIN-MAX standardization is a linear transformation of the original data so that the original value maps the interval [0, 1].

3.2.4 Vulnerability Assessment

Based on the SoVI designed for disaster social vulnerability in America, Chen (2014) collected 29 variables as proxies to build a set of vulnerability indexes for the social and economic environment in China. We used this method to calculate the population vulnerability index for Zhejiang Province.

4 Typhoon Disaster Losses and Causation Factors in Zhejiang Province

Based on the distribution of typhoon disaster losses in Zhejiang Province from 2004 to 2012 (Figure 3), the affected areas were mainly located in the southeast corner of the province. The centers with the largest affected population (Fig. 3a), the largest area of affected crops (Fig. 3c) and the highest direct economic losses (Fig. 3d) were in Wenzhou and Taizhou cities, although the losses in Ningbo City were also relatively high. Only part of the plain area was affected by serious agricultural disasters; the other losses were far lower than in the southeast of Zhejiang Province. Cangnan in Wenzhou City was the most severely affected, with the highest cumulative death toll (Fig. 3b). The losses in the affected counties were associated with the frequency and intensity of the typhoons. We therefore analyzed the risk of typhoon precipitation and winds in every county in Zhejiang Province to provide a reference dataset for the factors responsible for typhoon disasters.

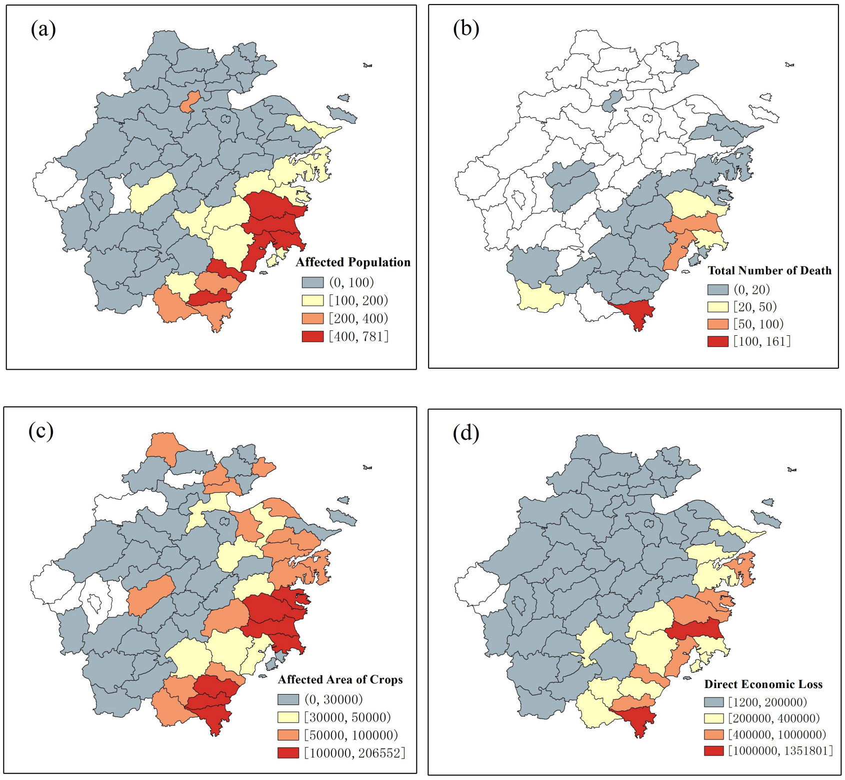

Figure 3. Distribution of typhoon disaster losses in Zhejiang Province from 2004 to 2012. (a) Affected population (unit: millions); (b) total number of deaths (unit: person); (c) area of affected crops (unit: hectares); and (d) direct economic losses (unit: millions yuan).

4.1 Risk of Typhoon Rainstorms

The main hazard of typhoon precipitation is concentrated precipitation, so the average number of days of typhoon precipitation at each site in Zhejiang Province was counted from 1960 to 2013 (Figure 4). The duration of typhoon rainfall was less in inland areas, especially in Quzhou City. Persistent precipitation was concentrated in Wenzhou, Taizhou and Ningbo cities, where there may have been a higher risk of typhoon disasters. Based on the probability of typhoon rainstorms occurring in each county in Zhejiang Province (Figure 5), we found that the annual probability of the occurrence of typhoon rainstorms was highest over the southeast coast of Zhejiang Province from 1960 to 2013, especially in Taizhou City, where the annual probability was 17%. The annual probability of typhoon rainstorms with precipitation >100 mm was lower, but the distribution of probability was consistent

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with the rainstorms with lower precipitation. The probability of torrential rainstorms decreased rapidly in the western and central regions of Zhejiang Province, although the range increased. There were three centers of high risk: Taizhou, Wenzhou and Ningbo cities.

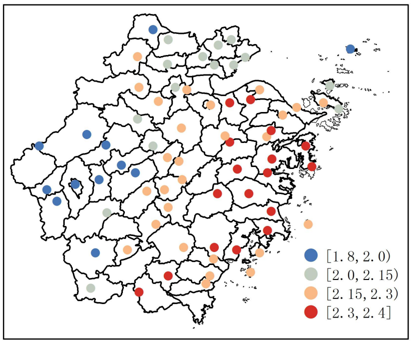

Figure 4. Average number of days with typhoon precipitation at each site in Zhejiang Province from 1960 to 2013.

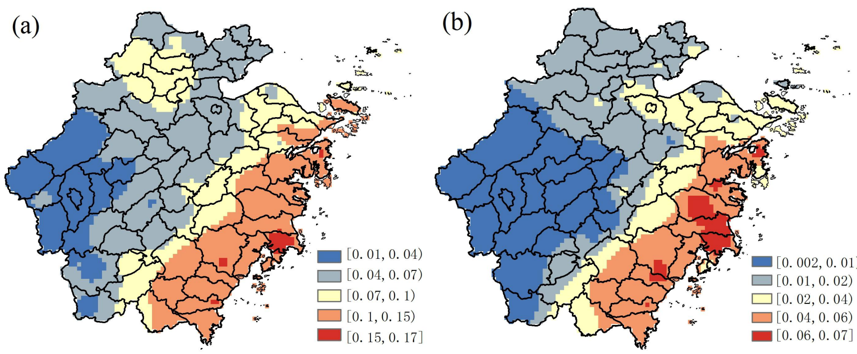

Figure 5. Probability of typhoon rainstorms in Zhejiang Province: (a) rainstorms with >50 mm of precipitation; and (b) torrential rainstorms with >100 mm of precipitation.

4.2 Risk of Typhoon Winds

The average duration of typhoon winds was calculated over six sites in Zhejiang Province (Figure 6). The duration of typhoon winds was relatively short in the central and western regions and the typhoon winds were concentrated in the coastal areas of Wenzhou, Taizhou and Ningbo cities. The longest duration of typhoon winds occurred over the offshore islands.

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The main hazard from typhoon winds is manifested in the destructive force of strong winds and therefore we estimated the probability of the annual occurrence of typhoon winds at or above grades 6 and 12 at each monitoring station from 1980 to 2014 (Figure 7). Typhoon winds at or above grade 6 mainly occurred along the coastal areas of Zhejiang Province, but were rare in the mountainous areas. The probability of typhoon winds at or above grade 8 was lower along the coast of Zhejiang Province, although still much higher than in the interior, with a probability of up to 75% in Hangzhou Bay and over some islands. Typhoons with wind speeds of grade 10 or 12 were much less likely and were only seen in the coastal areas and islands, with a rapidly decreasing probability of occurrence from 71 to 29%. The areas at high risk of typhoon winds were consistent with those with high typhoon rainfall, i.e. Wenzhou, Taizhou and Ningbo cities. The risk of extreme winds associated with typhoons is much higher in coastal areas than inland.

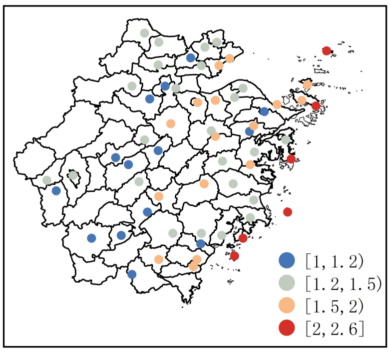
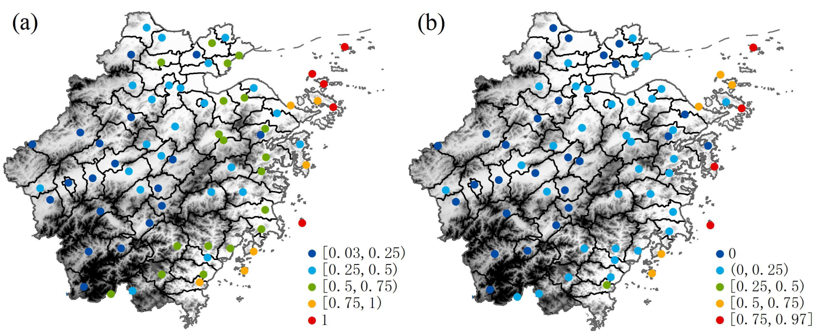


Figure 6. Average duration (days) of typhoon winds at each site in Zhejiang Province from 1960 to 2013.



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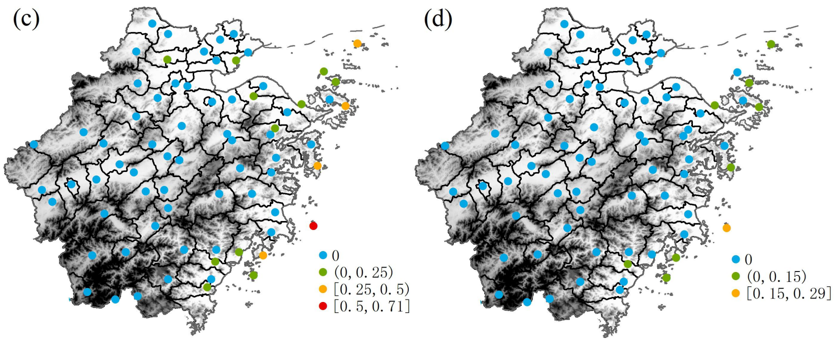

Figure 7. Probability of typhoon winds in Zhejiang Province at (a) grade 6 or above, (b) grade 8 or above, (c) grade 10 or above and (d) grade 12 or above.

5 Risk Assessment and Regionalization of Typhoon Disasters in Zhejiang Province

5.1 Intensity Index for Factors Causing Typhoon Disasters

The main factors causing typhoon disasters are rainstorms, winds and storm surges. The level and intensity of a single causative factor cannot fully represent and describe the impact. Therefore we established a comprehensive intensity index that included a number of different factors involved in typhoon disasters. Taking the county as a unit, we selected all the typhoons that affected the population of Zhejiang Province from 2004 to 2012. The total precipitation and daily maximum wind speed during typhoons measured in each county were used to describe the factors causing typhoon disasters. Using canonical correlation analysis, we determined the impact of typhoon precipitation and winds on the population. We then carried out canonical correlation analysis for all the typhoons that caused direct economic losses in Zhejiang Province from 2004 to 2012 (Table 1). The effect of typhoon precipitation on both the population and direct economic losses was always greater than that of typhoon winds. By averaging typical coefficients for both precipitation and wind, weighted coefficients of 0.85 and 0.65 were obtained within the intensity index for precipitation and winds, respectively.

Table 1. Canonical correlation analysis of factors causing typhoon disasters.

Disastes	Canonical correlation coefficient	Canonical variable coefficient	
		Typhoon	Typhoon wind

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		precipitation	
Affected population	0.45	0.84	0.651
Direct economic losses	0.477	0.863	0.655

Based on the weight coefficients in Table 1, an intensity index of factors causing typhoon disasters was established:

$$I = Ax + By \quad (1)$$

where I is the intensity index of factors causing typhoon disasters, X is the standard typhoon precipitation and Y is the maximum wind speed of the typhoon. A and B are the weighted coefficients for typhoon precipitation and typhoon winds, respectively. Using Equation (1), we calculated the intensity indexes of typhoons at each station (Figure 8). Based on the distribution of these average intensity indexes, we found three high value centers, namely Wenzhou, Taizhou and Ningbo cities, consistent with the results of Chen et al. (2011).

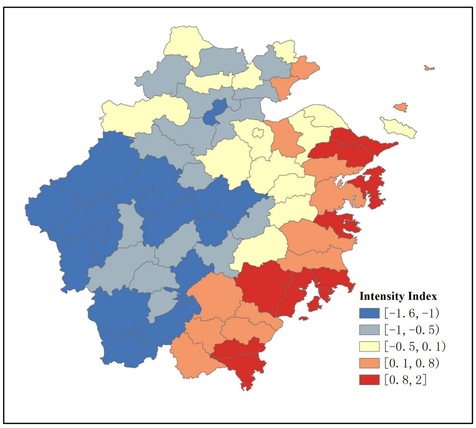

Figure 8. Intensity indexes of factors causing typhoon disasters at each station in Zhejiang Province.

5.2 Population Vulnerability Index in Zhejiang Province

Natural disasters are social constructions and the basic causes of losses are the attributes of human beings and their social system (Jiang 2014). We used the index system of Chen et al. (2011) to evaluate the vulnerability of Zhejiang Province. Based on the extracted population information, 29 variables were identified that may affect social vulnerability (Table 2).

Table 2. The 29 variables affecting social vulnerability in Zhejiang Province.

	Variable
1	Per capita disposable income of urban residents (yuan)
2	Percentage of women
3	Percentage of minority ethnic groups
4	Median age
5	Unemployment rate (calculated − unemployed population/(unemployed + total population))
6	Population density
7	Percentage of urban population
8	Percentage of non-agricultural household population
9	Percentage of households living in rented houses
10	Percentage of employees working in primary industries and mining
11	Percentage of employees working in secondary industries
12	Percentage of employees working in tertiary industries
13	Household size (no. of people/household)
14	Percentage of population with college degree (≥25 years old)
15	Percentage of population with high school degree (≥20 years)
16	Percentage of illiterate people (≥15 years)
17	Population growth rate (2000–2010)
18	Average number of rooms per household
19	Per capita housing construction area (m^2/person)

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20	Percentage of premises without tap water
21	Percentage of premises without a kitchen
22	Percentage of premises without a toilet
23	Percentage of premises without a bath
24	Number of beds per 1000 people in health care institutions
25	Number of medical personnel per 1000 resident population
26	Percentage of population <5 years
27	Percentage of population ≥65 years
28	Population dependency ratio (%)
29	Percentage of population covered by subsistence allowances

After performing factor analysis of the 29 variables, seven components with an eigenvalue >1 were extracted (Table 3). The first component, which reflects the income of the population and the employment situation, contributed 30.1% of the total variance. This factor is positive because the more property there is in an area, the higher the vulnerability to damage. The second component, which reflects the level of education of the population, contributes 15.6% of the total variance. This factor is negative because if the level of education is higher, then the population's awareness of disaster prevention and reduction is greater and their vulnerability will be lower. The third component, which reflects the number of dilapidated houses, contributes 8.7% of the total variance. This factor plays a positive part in vulnerability. The fourth component, which reflects the amount of illiteracy and the number of young people, is positive and represents 8.4% of the total variance. The fifth component, which reflects the household size and the percentage of women, explains 7.7% of the total variance and is positive. The sixth component, which reflects the number of people from ethnic minorities, explains 6.1% of the total variance and is positive. The seventh component, which represents 5.3% of the total variance, reflects the unemployment rate and the housing area and is positive.

The total variance explained by these seven components is up to 81.9%, which can be used to represent the vulnerability of the population of Zhejiang Province. The distributions of the first (positive) component and the second (negative) component are shown in Figure 9. Areas with a low

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employment rate have a high vulnerability, but the vulnerability is low in urban areas with higher levels of education. The seven components thus represent the real situation of the vulnerability of the population in Zhejiang Province to the effect of typhoons. The vulnerability of the population in Zhejiang Province (SoVI) was calculated as:

$$SoVI = factor\ 1 - factor2 + factor\ 3 + factor\ 4 + factor\ 5 + factor\ 6 + factor\ 7 \quad (2)$$

By calculating the vulnerability indexes of each county, we obtained the distribution of population vulnerability in Zhejiang Province (Figure 10). The areas with high vulnerabilities are mountainous regions where the economy is relatively undeveloped, whereas the vulnerability is low in coastal areas, such as Hangzhou and Huzhou cities, where there is a greater awareness of disaster prevention and reduction and houses are of high quality.

Table 3. The seven components extracted by principal component analysis.

Component	No. of drivers	Name	Sign
1	14	Employment and poverty	(+)
2	6	Education	(−)
3	3	Number of dilapidated houses	(+)
4	4	Illiteracy and juvenile population	(+)
5	4	Household size and ratio of women	(+)
6	2	Ethnic minority	(+)
7	2	Unemployment and housing size	(+)

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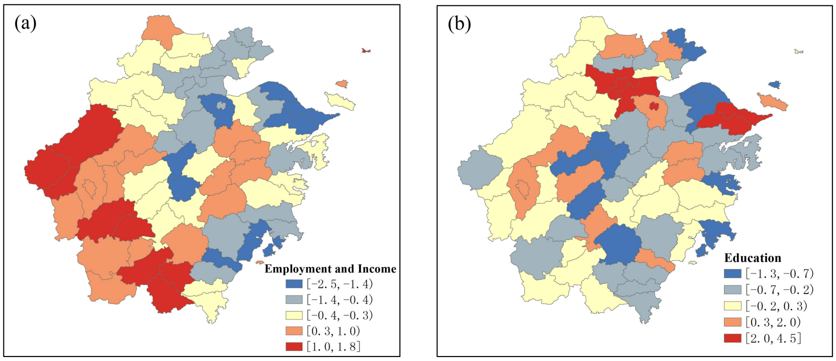

Figure 9. Distribution of population vulnerability index of (a) factor 1 (employment and income) and (b) factor 2 (education).

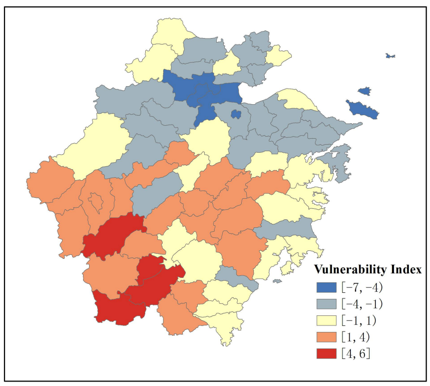

Figure 10. Distribution of population vulnerability index of counties in Zhejiang Province.

5.3 Comprehensive Risk Index for Typhoon Disasters and Zoning of Zhejiang Province

The typhoon disaster risk assessment system considers the factors causing disasters, the vulnerability of the population and the environment. The comprehensive risk index for typhoon disasters is obtained by combining the factors causing disasters and vulnerability, but does not take the sensitivity of the environment into account. After standardizing the intensity index of the factors causing typhoon disasters and the population vulnerability index, the typhoon disaster comprehensive risk index (R) in Zhejiang Province was obtained as follows:

$$R = \text{intensity index of factors causing typhoon disasters } (I) \times \text{vulnerability index (SoVI)} \quad (3)$$

Based on the comprehensive risk index, we defined five risk zones for typhoon disasters in

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Zhejiang Province (Table 4).

Table 4. Disaster risk index and grade.

Risk grade:	High	High–medium	Medium	Medium–low	Low
Risk index:	≥0.3	0.18–0.3	0.13–0.18	0.07–0.13	≤0.07

The index gave a good reflection of the distribution of typhoon disasters in Zhejiang Province (Figure 3), especially in the southeastern coastal areas. The risk zoning of typhoon disasters in Zhejiang Province is shown in Figure 11. The southeast coastal areas face the highest risk, especially in the boundary regions between Zhejiang and Fujian, and Taizhou and Ningbo cities. Overall, the risk of typhoon disasters decreases from the coast to inland areas. Cities are at medium to low risk as a result of their developed economy, high-quality houses and better educated population. The inland mountainous areas have a high vulnerability and, although they are not directly affected by typhoons, they are still in the middle risk areas as a result of their poorly developed economy.

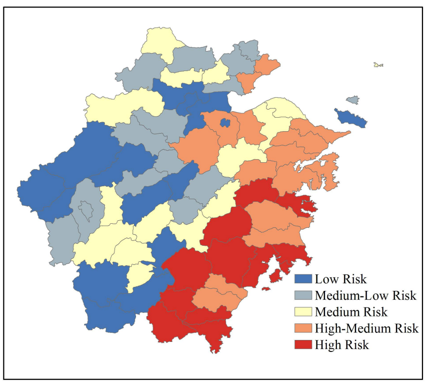

Fig. 11. Risk zoning of typhoon disaster areas in Zhejiang Province.

6 Discussion and Conclusions

(1) The intensity indexes of factors causing typhoon disasters are highest in Wenzhou, Taizhou and Ningbo cities, consistent with the risk analysis. A comparison with the distribution of actual typhoon disasters in Zhejiang Province from 2004 to 2012 shows that the index is a good reflection of the possibility of typhoon disasters in each county.

(2) Seven components were extracted after performing factor analysis of 29 variables affecting

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social vulnerability. These seven factors represent 81.9% of the total variance and are a good reflection of the index of population vulnerability in Zhejiang Province. Southwestern Zhejiang is the most vulnerable as it has a relatively undeveloped economy, more mountainous areas and a higher risk of geological disasters. Vulnerabilities are lower in cities and coastal areas as a result of better disaster prevention and reduction measures and a better educated population.

(3) A comprehensive risk index for typhoon disasters was obtained by combining the factors causing typhoons disasters and vulnerability. Based on the comprehensive risk index, we developed risk zones of typhoon disasters in Zhejiang Province. The southeast coastal areas are at high risk, especially the boundary regions between Zhejiang and Fujian, and Taizhou and Ningbo cities. The risk of typhoon disasters decreases from coastal areas to inland regions. Cities are at medium to low risk because of their developed economy, high-quality houses and better educated population.

Although some interesting results have been obtained in this study, there are still some problems that require further study. As a result of the limited data on typhoon disasters in Zhejiang Province, it is currently impossible to give a long time trend for high-resolution typhoon disaster analysis. It is also unclear whether this methodology can be applied to other regions.

Acknowledgments

This study was supported by the Chinese Ministry of Science and Technology Project No. 2015CB452806.

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Discussion started: 23 February 2018

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