

## ARTICLE

# A Vulnerability Curve Method to Assess Risks of Climate-Related Hazards at County Level

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## ABSTRACT

A comprehensive risk assessment of different types of natural disasters at the county level can promote quantitative disaster risk assessment and can provide a scientific basis for the formulation of disaster prevention measures. Focusing on climate-related hazards and based on natural disaster risk assessment theories and methods, this study integrates disaster statistics, meteorological data, geographic information, and other multivariate data to quantify the hazards of various disasters and the vulnerability and exposure of hazard-bearing bodies and conducts an integrated assessment of comprehensive risks of multiple climate-related hazards in Cangnan County, Zhejiang Province. Typhoon disaster risk is high in the central and northern parts of this county and low in its surroundings, with high-risk areas mainly distributed in Lingxi Town to the north. The comprehensive risk distribution patterns of drought and flood disasters in Cangnan County are similar: low in the south and high in the north. With the method of standard deviation, the comprehensive risk of multiple climate-related hazards in Cangnan County shows a distribution pattern of being low in the south and high in the north, with high risk in the northeast and low risk in the northwest and south.

**Keywords:** Climate-related hazards; comprehensive risk; county scale; typhoon; drought and flood.

## 1. Introduction

China is among the countries that suffer many types of heavy disasters, with a wide distribution area and high frequency of occurrence, causing serious losses<sup>[1,2]</sup>. Against the background of global environmental change and frequent natural disasters, China faces a serious situation. In

2020, natural disasters resulted in 138 million person affects and 100,000 house collapses, the area of affected crops was 19,957.7 thousand hectares, and direct economic losses amounted to CNY 370.15 billion<sup>[3]</sup>. Among all natural hazards, climate-related hazards are characterized by their high frequency, extensive impact, and destructive power, and are the type of hazard that

### ARTICLE INFO

Received: September 30, 2022 | Accepted: October 30, 2022 | Available online: November 13, 2022

### CITATION

Shaochuan Wu, Qing Zhang, Xincui Jin. A Vulnerability Curve Method to Assess Risks of Climate-Related Hazards at County Level, *Prevention and Treatment of Natural Disasters*, 2022; 1(3): 10 pages.

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has affected the largest number of people in the last 20 years, seriously affecting the sustainable and stable development of the social economy<sup>[1,2]</sup>. In June 2021, an unprecedented and dangerous heat wave swept across the West Coast of North America, with extreme heat in several cities, including a record-breaking 49.5 °C in Lytton, British Columbia, resulting in nearly 600 deaths. A month later, rare floods were triggered by heavy rainfall in west-central Europe. As of 20 July, more than 200 people have been killed by the floods, including 171 in Germany and 31 in Belgium. The direct economic loss caused by this flood to Germany has reached EUR 3 billion. At about the same time, Henan Province, China, experienced extreme heavy rainfall. The 24-h rainfall in Zhengzhou, the center of heavy rainfall, reached 696.9 mm. Floods caused by heavy rainfall have caused 73 deaths. The direct economic losses exceed CNY 80 billion (approximately EUR 10 billion). Scientific and quantitative judgment of the degree and pattern of natural disaster risk is necessary to gain understanding and can provide important guarantees for policies of risk management and for reducing losses from natural disasters<sup>[4]</sup>.

Currently, natural disaster risk assessment is mainly focused on single-hazard disasters, including typhoons<sup>[5-15]</sup>, earthquakes, landslides, forest and grassland fires, marine, droughts, and flood. However, it is often affected by multiple hazards at the regional scale. Therefore, there is also widespread interest in the comprehensive risk assessment of multi-hazard disasters at the regional level. For example, Bell et al. chose debris flows, avalanches, and landslides as subjects for risk research; Kappes et al.<sup>[16-22]</sup> conducted risk assessments for potential seismic landslides, floods, and storm buildings; and the Federal Emergency Management Agency and National Institute of Building Research conducted a comprehensive risk assessment of earthquake, hurricane, and flood disaster in the United States. With the continued expansion of natural disaster risk research, the assessment methods are becoming more varied

and moving from qualitative to quantitative. It is generally believed that multi-hazard risk is the total risk caused by multiple hazards in a region. According to the complexity of the structure and functional characteristics of the disaster system, it can be divided into three categories: disaster cluster, disaster chain, and disaster compound. At present, the main methods for disaster risk assessment include probability statistics, artificial neural networks, index system methods, model simulations, and disaster statistics. In addition, disaster risk assessments are conducted on a demand-driven basis with assessment units at different scales. The Disaster Risk Index (DRI), developed by the United Nations Development Programme (UNDP), evaluates population mortality risk worldwide using countries as assessment modules. The Munich Reinsurance Company assesses the risk of economic loss for the world's 50 largest cities or urban agglomerations. Ge et al. selected three research areas with different spatial scales in cities, counties, and villages to conduct comprehensive risk research.

In China, local governments, other than special administrative regions, are generally divided into three levels: province, city (county), and township (town). There are 2856 administrative areas at the county level, covering basically all of China's land and accounting for more than 85% of the population. Generally speaking, the scope of impact of many serious natural disasters is concentrated within county-level administrative regions, which are also the grass-root units responsible for implementing policies and practices for disaster risk management<sup>[23-29]</sup>. As a result, county-level governments are often front-line leaders and important participants in dealing with major natural disasters, with their agencies carrying out disaster risk prevention and emergency management to be efficient and effective. Comprehensive risk assessment of natural disasters at the county scale is carried out with a small degree of dispersion and more accurate loss estimation. Previous studies have focused on assessing disasters at the county level. Wang et al.

evaluated multi-hazard intensity and the level of urbanization in China with county-level administrative regions as the basic unit and obtained urban natural disaster regionalization of the country. Shi et al. selected 12 major natural disasters in China and completed a comprehensive multi-hazard risk assessment and mapping based on county-level administrative units. These studies used the county as the unit to explore natural disaster risk patterns on a macro scale. Most studies lack quantitative assessment and pattern analysis of disaster risk within counties.

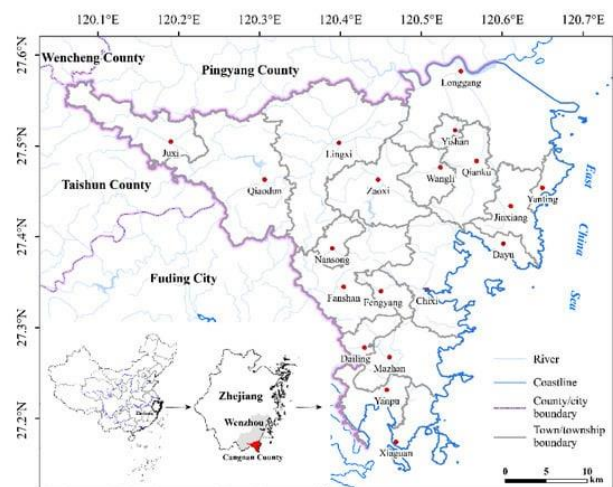
In view of this, this paper takes Cangnan County, Zhejiang Province, China, as an example, collecting climate-related hazard disaster loss, typhoon track, meteorological, and socioeconomic statistical data from 2000 to 2016. Based on natural disaster risk assessment theories and methods, a comprehensive risk assessment of multiple climate-related hazards—typhoons, droughts, and floods—in Cangnan County was carried out by integrating the hazards of disaster-causing factors and the vulnerability and exposure of disaster-bearing bodies and by combining a risk assessment model and geographic information technology in order to correctly and comprehensively understand the climate-related hazard risk level of each township in Cangnan County and to improve the disaster prevention, mitigation, and relief capabilities of the county and each township and the capabilities of the natural disaster database.

## 2. Materials and Methods

### 2.1. Study Area

Cangnan County, located in the southernmost part of Zhejiang Province, was established in June 1981 as one of the five counties under the jurisdiction of Wenzhou (Figure 1). At the end of 2018, Cangnan County covered 17 towns and 2 ethnic townships, with a total population of 1.34 million, ranking first in Zhejiang Province and 40th in the country; GDP totaled CNY 56.06 billion, ranking

about 80th in the country, with a per capita GDP About CNY 42,000, lower than the national average. In addition, Cangnan County had a sown grain area of 20.83 thousand hectares, an agricultural output value of CNY 1.86 billion, and a grain output of 129.08 thousand tons. The geographical coordinates of Cangnan County are  $27^{\circ} 30' N$  and  $120^{\circ} 23' E$ , and it belongs to the subtropical maritime monsoon climate, warm in winters and cool in summers, with an average annual temperature of  $17.9^{\circ} C$  and average annual precipitation of 1670.1 mm, with the flood season lasting about six months. Most of Cangnan's territory belongs to the Aojiang River system, with higher terrain in the southwest and lower terrain in the northeast. The total area is 1261.08  $km^2$ , the sea area is 37,200  $km^2$ , and the coastline is 155 km long. In summary, Cangnan County is densely populated, has a relatively low level of overall economic development, and is heavily influenced by the monsoon climate.



**Figure 1:** Study area, Cangnan County, located in Zhejiang Province, East China

Cangnan County is one of the high-risk areas for climate-related hazard. Since 1949, typhoons that landed in Cangnan County accounted for 17% of the total number of typhoons that landed in Zhejiang Province. Among them, the landing of super typhoon “Saomai” in 2006 caused the collapse of 20,310 houses, 153 deaths, and direct economic loss of CNY 9.124 billion. Drought and flood disaster risk in Cangnan County is also at a high level, seriously threatening local socio-economic development.

Comprehensive risk assessment of climate-related hazards is of great significance for Cangnan County to prevent and mitigate natural disasters.

## 2.2. Data Sources

In this paper, climate-related hazard disaster loss, typhoon track, meteorological, and socioeconomic statistical data were used. The data sources are detailed below.

The climate-related hazard disaster loss data were provided by the National Disaster Reduction Center of China and were used to calculate the loss rate of disaster-bearing bodies. The center recorded a total of 41 climate-related hazards in Cangnan County from 2000 to 2016, including 28 typhoons, 5 floods, 3 droughts, 3 freezes, and 2 hailstorms. It is difficult to construct a vulnerability curve due to the infrequent occurrence, small social and economic losses, and lack of recorded data on freezing and hailstorm disasters. Therefore, typhoons, floods, and droughts were selected in this study for comprehensive risk assessment.

Typhoon track data were from the Shanghai Typhoon Institute of China Meteorological Administration (CMA-STI, <http://tcdata.typhoon.org.cn/en/index.html>, (accessed on 3 December 2020)). Based on the track data of 28 typhoons landing in or affecting Cangnan County combined with the disaster loss data, the vulnerability curve of typhoons between the intensity level and the loss rate of disaster-bearing bodies was established.

Meteorological data came from the China Meteorological Administration, which was used to calculate the intensity of flood and drought disasters in Cangnan and its surrounding area. The vulnerability curve of flood and drought between the intensity level and the loss rate of disaster-bearing bodies was established.

Socioeconomic statistical data at the community level (2016) was provided by official Cangnan County government agencies and was considered as a measure of population, economic, crop, and house

exposure.

We used the Critical Appraisal Skills Programme's Qualitative Research Checklist and the National Institute of Health Quality Assessment Tools for Cohort and Cross-sectional and Case-Control Study Designs as means of critical comparison (refer to Additional file 3). In the case of mixed-methods studies, we evaluated the qualitative and quantitative components separately. We positively scored the appropriateness of the article or report's methodology if it matched at least one of its outlined aims and objectives. The final question in the Critical Appraisal checklist is a subjective determination of value. We rated value based on the article or report's provision of nuanced information and practical recommendations for stakeholders. The research team used these tools in comparing quality, rather than in inclusion and exclusion decisions, which is in-line with the Cochrane Handbook's guidance for systematic reviews.

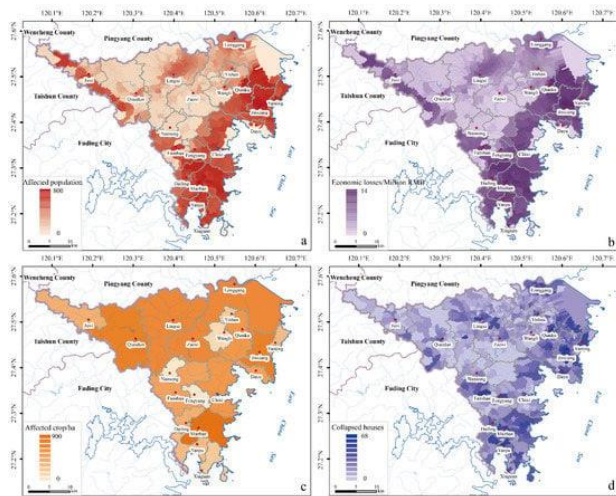
## 3. Results

This section presents an evaluation of the socioeconomic risks of typhoons, floods, and droughts and the comprehensive risk of multiple climate-related hazards based on the natural disaster risk assessment model and the multiplicity of the standard deviation method. Given the more significant changes and impacts of severe hazards and the need for disaster prevention and mitigation, the following analysis focuses on the risk distribution of severe hazards. The risk patterns of strong tropical storms, typhoons, and strong typhoons with regard to typhoon hazard can be seen in the Supplementary Materials.

### 3.1. Typhoon Risk

A super typhoon in Cangnan County would affect 127,500 people, collapse 4087 houses, cause economic losses of CNY 2.29 billion, and affect 3593 hectares of crops. The distribution patterns of

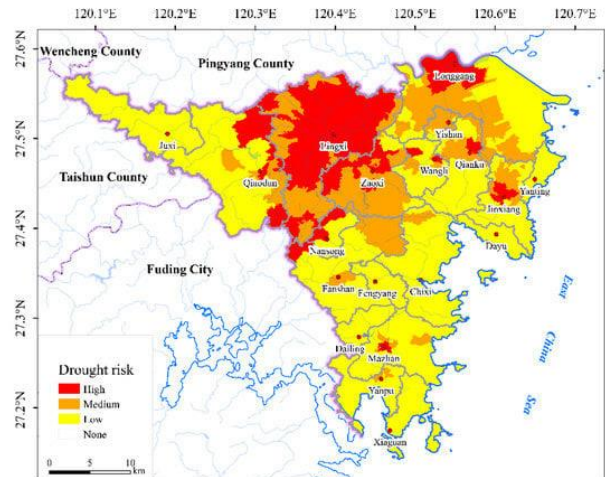
population, economy, house, and crop risks caused by a super typhoon are relatively balanced in the whole region, implying significant losses across the region due to a large amount of energy. The distribution patterns of population and economic risks are high in the southeast and low in the northwest, with the highest risk in Mazhan, Xiaguan, Yanpu, Dailing, and Jinxiang Towns. Mazhan has the largest area of affected crops, followed by Qiaodun and Jinxiang. The highest risk of house damage is in Jinxiang and Fanshan. Among the three elements that constitute risk, hazard has the greatest impact on



the high risk of a typhoon.

**Figure 2:** Spatial patterns of super typhoon risk in Cangnan County: (a) population, (b) economy, (c) crops, and (d) houses.

The distribution pattern of comprehensive drought risk in Cangnan County was obtained by synthesizing the risk to the population, economy, and crops caused by mild, moderate, and severe drought. Spatially, the comprehensive drought risk pattern is low in the south and high in the north, with high-risk areas mainly concentrated in northern Longgang, Lingxi, and Qianku; central Jinxiang; eastern Qiaodun; northern Zaoxi and Nansong; and central Mazhan and with middle-risk areas mainly distributed in central and southern Longgang, western and southern Lingxi, central and southern Zaoxi and Yishan, central Qianku, northern Jinxiang, central and eastern Qiaodun, and central Mazhan and Yanpu (Figure 3).



**Figure 3:** Spatial pattern of comprehensive drought risk in Cangnan County.

## 4. Discussion

East China has the highest level of natural disaster risk in the country, and the main contributing disaster-bearing bodies include water resources, the cryosphere, ecosystems, agriculture, transportation, energy, livelihood, and health. Therefore, we first determined the scope of the selection of typical regions in East China. Then, according to the literature, areas with high hazard intensity and exposure to disaster-bearing bodies were selected for evaluation, considering the availability of disaster loss data. Finally, Cangnan County was selected as a typical area for the study. Compared with other regions, the terrain is mainly mountainous and hilly, natural disasters occur frequently, and the population density is large, so natural disasters have a far-reaching impact on social and economic development. In addition, Cangnan County completed a preliminary risk survey in 2017, compiling the basic data needed for risk assessment (see Section 2.2 in Materials and Methods), which laid the foundation for this work.

According to a series of reports from the Intergovernmental Panel on Climate Change (IPCC), disaster risk results from the interaction of hazards with the vulnerability and exposure of human and natural systems. Therefore, disaster risk depends not only on the hazard but also on the exposure and vulnerability level of the disaster-bearing body. Taking typhoon disaster in Cangnan County as an example, the

hazard intensity of super typhoons is the worst but the risk to the population and crops is lower than that of severe typhoons. The main reason is that the exposure of eastern regions affected by super typhoons is lower than that of central and northern regions affected by strong typhoons.

This study provides a comprehensive quantitative method for assessing the risk of single and multiple hazards at the county level. This method is a significant improvement over the semi-quantitative assessment of regional natural disaster risk by grade. Comprehensive multi-hazard risk is calculated using equal-weighted overlap analysis. Before obtaining the scientific weight, this is a feasible choice that can avoid underestimating the risk of events with small probability and large loss.

Comprehensive risk is the possible damage to the society, economy, and resources, and environment caused by multiple natural disasters. Quantitative assessment is needed to support risk prevention. We quantify the loss risk from three elements. The interaction of multiple elements will lead to complex results. It is difficult to merge and classify the research objects. In addition, the research area is small (and the village is the evaluation unit) and there are many disasters, also to avoid fragmentation of risk levels within the towns and townships and to facilitate risk management. Therefore, the division of the three risk levels of high, medium, and low is more conducive to the display space pattern, which is more suitable than the four levels of high, medium-high, medium, and low or the five levels high, medium-high, medium, medium-low, and low. In summary, this study uses the multiplicity of standard deviation method as the basis for risk classification. Taking the direct economic loss risk of a severe typhoon in Cangnan County as an example, the high risk is roughly the 80th percentile of this type of hazard/hazard-bearing body risk.

The county unit is a unique administrative unit in China and an important part of disaster impact and relief. It is important to carry out a quantitative assessment and pattern analysis of disaster risk within

counties to correctly and comprehensively understand the risk of natural disasters; to improve the capacity of disaster prevention, mitigation, and relief; and to complete the database of natural disaster capacity. Taking Cangnan County as an example, this study relied on high-precision meteorological and geographic information data to calculate the hazards of different disasters as well as the exposure and vulnerability of disaster-bearing bodies based on official survey data. According to the natural disaster risk assessment mechanism, county-scale disaster risks were obtained by calculating the functions of hazard, exposure, and vulnerability, thus laying a methodological foundation for county-scale risk assessment.

At the same time, due to limitations in data availability, many indicators (for example, loss records from earthquakes, hailstorms, snowstorms, lightning, and other disasters as well as survey results on disaster-bearing bodies such as roads and public service facilities) were not obtained, which might have a certain impact on the results of the risk assessment. However, in this paper, the data of disaster-bearing bodies were accurate at the village and town levels. Although the samples were limited, this ensured data aggregation, less dispersion, and more accuracy in the loss estimation. Overall, this paper clarifies the definition and formation mechanism of main disaster risks at the county scale; quantifies the regional hazard of disasters and the vulnerability of disaster-bearing bodies; improves the assessment level of main disaster risks; and is expected to provide scientific support for disaster prevention, mitigation, and emergency management at the county level.

## **5. Conclusions**

This paper comprehensively analyzed the socioeconomic risks of typhoons, droughts, and floods in Cangnan County and reached the following conclusions:

The distribution pattern of comprehensive risk of multiple climate-related hazards in Cangnan County is low to the south and high to the north, and the high-risk areas are mainly located in Lingxi and

Longgang Towns in the north. The high risk in most areas is affected by the combined effects of three types of climate-related hazards.

The probability of typhoon occurrence in Cangnan County changes from a pattern of being high in the west and low in the east to be high in the south and low in the north as the level increases, and the risk shows a pattern of being low in the north and west and being high in the west and east, with high-risk areas mainly distributed in Lingxi Town. The spatial patterns of drought and flood risks in the county are similar, showing a pattern of being low in the south and being high in the north, with high-risk areas mainly concentrated in Longgang, Lingxi, Qianku, and Zaoyi Towns. The distribution of typhoon risk is mainly affected by hazards, while the distribution of drought and flood risk is most influenced by exposure.

Due to the high concentration of population, houses, economy, and arable land in the north-northeast, the possibility of climate-related hazards is also high, resulting in a high-risk level in this area; the high exposure of arable land and vulnerability in the south makes it a high-risk area after the north-northeast. According to the risk characteristics of climate-related hazards, based on strengthening the early warning of climate-related hazards, in areas with dense population, houses and economy, reinforce coastal embankments and set up multi-level defense system urban flood relief area planning; in areas with high exposure of arable land, the standard of agricultural production against typhoon, flood, and drought should be improved. In addition, attention should be paid to coastal wetland protection and ecological reconstruction in coastal areas.

This work proposes a new method for comprehensive risk assessment of multiple climate-related hazards, and selects Cangnan County as a typical area, considering three disasters: typhoon, flood, and drought. The evaluation method proposed in this work is scientific and universal, easy to operate, and can be widely used in risk assessment at the district and county levels. However, natural disasters have

obvious regional differentiation characteristics in China. The disasters and disaster-bearing bodies selected in this study have strong regional characteristics, and it is necessary to consider the disaster-causing and disaster-forming mechanisms of the region when using this method in other regions, which can be done in the following three aspects: firstly, consider the regional dominant disasters, such as earthquake disaster, geological disaster, meteorological disaster, hydrological disaster, forest fire disaster, and marine disaster; secondly, consider the distribution of regional disaster-bearing bodies and select the appropriate ones for the assessment in conjunction with the vulnerability level; finally, the comprehensive risk of multi-hazards could determine the respective weights according to the risk level of single hazards. The single-hazard risk and the comprehensive risk of multi-hazard in this study are divided into three levels according to the risk value. The risk assessment results can be provided to government decision-makers, business leaders, and the public to facilitate the formulation of risk management plans from disaster prevention, resilience, and relief, and encourage stakeholders to actively participate in the process. This can provide the necessary response measures for the management of different levels of risk, reduce the risk of natural disasters, enhance the awareness of natural disaster prevention, optimize the early warning system of natural disasters, and realize the sustainable development of the regional social economy.

Disaster cluster refers to hazards clustering in space and time without any linkage, which is mainly affected by the disaster-generating environment in a specific area (such as climate type, topography, and surface interface characteristics) and can be used to measure the severity of disaster clustering in a specific area or a specific period. For example, influenced by atmospheric circulation and topographic fluctuations, large-scale heatwaves, floods, and periodic droughts occurred frequently in the middle reaches of the Yangtze River in 2018. The quantitative assessment model of comprehensive risk of multi-hazard proposed in this work provides a feasible idea for disaster cluster risk assessment. A

disaster chain is a series of disaster phenomena caused by a kind of disaster, which can be divided into concurrent disaster chain and serial disaster chain according to the chain characteristics. The earthquake has a strong disturbance on the surface, leading to the occurrence of many secondary mountain disasters, and the disaster chain behaves strongly. Disaster encounter is the simultaneous or successive occurrences of two or more disaster events that have no root cause relationship. Even if a single event is not extreme, its extreme will be expanded due to the effect of the encounter. The most obvious example is that in the context of sea level rise, the encounter of storm surges and astronomical high tides will create the most extreme water levels. For the disaster chain and disaster encounter, the hazard factors have a genetic connection, which is manifested as the cascading effect or superposition effect between the hazard factors. The risks need to strengthen the research of the vulnerability curve or the vulnerability surface and carry out risk assessment through a probability model.

## Conflict of interest

The authors declare no conflict of interest.

## Funding

No Fundings.

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