

Quantitative assessment of personal risk during storm surge disaster

Suming Zhang^{1,a}, Zhang Jie^{1,2,b}, Li Xiaomin^{2,c*}

¹College of Oceanography and Space Informatics China University of Petroleum (East China) Qingdao, China

²First Institute of Oceanography Ministry of Natural Resources of China Qingdao, China

Abstract: Storm surge is the most severe marine disaster in China, threatening the lives of coastal residents. Quantitative assessment of personal risk is an important prerequisite for identifying risk areas and designing emergency strategies. This paper aims to propose an economical and efficient quantitative assessment method for personal risk under storm surge disasters, including the assessment of the affected population and emergency relocation population, as well as their number and distribution. Remote Sensing products and Geographic Information System (GIS) technologies are used to form a technical framework, including the method of inundation scenario construction and personal risk assessment, which is realized by GIS spatial analysis. Based on the technical framework, the personal risk caused by “Hato” in Guangdong was assessed. The results show that the affected population is concentrated in the Pearl River Delta and dispersed in surrounding cities. The number of the affected population is assessed as 1,032,455, with an accuracy of 91.48%. The emergency relocation population is concentrated in the coastal areas of Guangzhou, Dongguan and Zhuhai, which have high population density and are far from the safety or partial safety zone. The number of the emergency relocation population is assessed as 199,973, with an accuracy of 87.25%. “Hato” verified that this method is economical, efficient, and accurate. It is expected to enrich and develop the theories and methods of personal risk assessment.

1. Introduction

Storm surge is an abnormal rise and fall of seawater caused by severe atmospheric disturbance. Due to its high frequency, wide distribution, heavy severity, and significant losses, the storm surge disaster become one of the most severe marine disasters [1, 2]. Hence, investigating the risk assessment of storm surge disasters is necessary.

Disaster risk assessment is a quantitative assessment of the likelihood of losses caused by a disaster on people’s lives, lives, property, and other aspects. It is already a widely used disaster management tool internationally. Life and property are, by definition, two essential dimensions of disaster risk assessment. However, over the years, research on disaster risk assessment generally focused on economic (i.e., property) risk while neglecting personal risk. This is related to the fact that the mobility of populations and the randomness of human activities make it much more difficult to assess personal risks than immobile economic risks. Economic loss is reversible, but life and health are not. In the 20th century, there were four storm surge disasters in China that killed more than 10,000 people (in 1905, 1922, 1937, and 1939), and Fred caused 1,216 deaths in Zhejiang Province in 1994. These numbers are

staggering. Therefore, the threat of storm surge disasters to the population should not be underestimated, and the development of personal risk assessment for storm surge disasters should be equally valued as its economic risk assessment.

The traditional storm surge personal risk assessment method is mainly based on surveys and statistics, which is lagging and requires a large amount of workforce, material, and finances. Therefore, the empirical assessment method, which does not require investigation, was developed. The strategy of the empirical assessment method is to establish an indicator system and determine the weight of indicators [3, 4]. Then, the personal risk is obtained by adding or multiplying. Therefore, the high subjectivity and low quantification capacity limit its development. In summary, facing the challenges of personal risk assessment, the severe threat of storm surge disasters to life safety, and the limitations of existing methods, there is an urgent to develop an economical, efficient and quantitative method for storm surge disaster personal risk assessment.

The development of Geographic Information System (GIS) and Remote Sensing (RS) provide powerful tools for personal risk assessment of storm surge disasters. GIS technology, with efficient analysis and excellent visualization abilities, has massive potential in constructing inundation scenarios, calculating inundation depth, and identifying the spatial distribution of disaster-bearing

^asumingzhang@s.upc.edu.cn, ^bzhangjie@upc.edu.cn, ^c*Corresponding author: lixiaomin@fio.org.cn

bodies [5]. Various RS products provide materials for the spatial distribution and density of populations and help to determine their location remotely. The application of GIS technology and RS products for storm surge disaster loss assessment is confirmed [6], and its potential in personal risk assessment needs to be explored.

In conclusion, this paper focuses on the scientific problem of quantitative assessment of personal risk for storm surge disasters. It utilizes GIS technology and RS products to research the quantitative assessment method of storm surge disaster personal risk based on scenario construction and population density. Compared with existing methods, the advantages of this method are reflected in (1) economy, rapidity, objectivity, and efficiency; (2) includes two levels of assessment: the

affected population and the emergency relocation population; and (3) visualization, which can indicate the spatial distribution and geographic location of the threatened population.

2. Materials and Methods

Taking Guangdong Province (China) as the study area, RS images and their products are collected and organized as materials, GIS technologies are used to form a technical framework, and the “Hato” storm surge disaster event is select as a study case to carry out the quantitative assessment of personal risk. The research framework is shown in Fig.1.

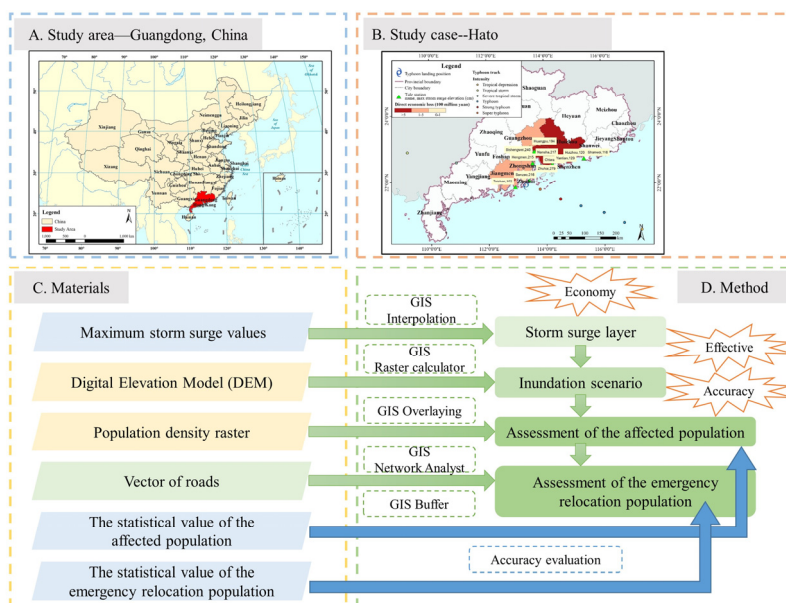


Figure 1. The research framework.

2.1 Study area

Guangdong (20°13′–25°31′ N, 109°39′–117°19′ E) occupies the longest coastline in mainland China, with a coastline of 3,368 km. According to statistics, from 1989 to 2020, 64 storm surge disasters caused damage in Guangdong, accounting for about 35% of the total storm surge disaster events in China, its direct economic losses accounted for about 29% of the national total, and the number of deaths (including missing) accounted for about 13% of the national total. With a resident population of approximately 130 million (top 1 in China) and six coastal cities ranked among the top 10 in China in terms of population density, the importance of personal risk assessment for Guangdong is evident.

2.2 Study case

At 12:50 on August 23, 2017, the typhoon “Hato” landed in the coastal area of Jinwan District, Zhuhai City, Guangdong Province, with a maximum wind speed of 45 m/s and a minimum pressure of 950 hPa, making it the

strongest typhoon landed in the Pearl River Delta (PRD) since 1965. “Hato” gained strength rapidly and made landfall at almost maximum strength. Under the influence of “Hato”, a significant storm surge occurred along the coast from east Guangdong to Yangjiang, causing severe damage in Guangdong.

2.3 Materials

This paper employs the data released by the government of China to ensure authority and availability. Data sources are shown in TABLE 1.

2.4 Methods

Many factors affect the personal risk, such as the danger of the disaster, the accessibility of the geographical location, the effectiveness of disaster prevention and mitigation measures, as well as the characteristics of the residents themselves in terms of their age, gender and health. However, from the perspective of the disaster-causing mechanism, the most fundamental factors affecting residents’ lives are the inundation depth and population

density. Therefore, this paper first follows the principle of storm surge inundation and adopts GIS technology and RS data to construct a visual inundation scenario. Subsequently, based on this inundation scenario, the number of affected populations and their spatial distribution is obtained using population density data. Finally, GIS network analysis is used to analyze the number and spatial distribution of the population in need of emergency relocation further.

2.4.1 Inundation scenario construction

Inundation scenarios are prerequisites for storm surge disaster assessment. Constructing an inundation scenario by GIS, on the one hand, can transfer tabulated values to visual display; on the other hand, it can realize the simulation and analysis of inundation scenarios with spatial differences.

Inundation scenario construction mainly consists of two steps: First, the Interpolation tool in ArcGIS is used to interpolate the maximum storm surge values of partial tide stations during “Hato” to form a storm surge layer with spatial variability within the 20 km range inside and outside the coastline of Guangdong. Subsequently, subtract DEM from the storm surge layer, and the inundation scenario of “Hato” is obtained. This step is realized by using the Raster calculator tool in ArcGIS.

2.4.2 Quantitative assessment of personal risk

In the past few years, methods of assessing economic loss received sufficient attention and developed considerably. However, research on personal risk assessment was still in its infancy, and few independent and systematic studies were conducted on it, which will be detrimental to the security of coastal residents.

This paper will develop the “Population density method” based on RS (Population density in Table 1) and GIS (Spatial Analyst Tools) to realize the quantitative assessment and visualization of the affected population and emergency relocation population.

The assessment of the affected population requires the overlaying of the inundation scenario with the Population density raster. This is implemented through the Overlay function of ArcGIS software. Then, the number of affected people is summed according to (1).

$$PL = \sum_{i=1}^{mp} PD_i \times A_i \quad (1)$$

Where, PL is the number of affected populations. mp refers to the number of rasters exposed to the storm surge disaster. PD_i is the population density of the i-th inundated raster, and A_i refers to the affected area of inundated rasters.

Table 1. Materials and their sources

Category	Name	Source
Information about the “Hato”	Location of tide stations	Frequency Table of Annual Maximum Tide Level of Major Tide Stations in Guangdong issued by The State Oceanic Administration
	Maximum storm surge values at partial tide stations	Bulletin of Guangdong Province Marine Disaster (http://nr.gd.gov.cn/)
	The statistical value of the affected population	Bulletin of the South Sea Marine Disaster (http://scs.mnr.gov.cn/)
	The statistical value of the emergency relocation population	Bulletin of China Marine Disaster (http://www.nmdis.org.cn/)
RS images and products	Digital Elevation Model (DEM)	ASTER GDEM v3 (https://www.gscloud.cn/)
	Population density	The “Chinese population spatial distribution km grid dataset” published by the Resource and Environment Science and Data Center, Chinese Academy of Sciences (https://www.resdc.cn/)
Traffic	Vector of roads	The “Chinese land-use remote sensing monitoring data” published by the Resource and Environment Science and Data Center, Chinese Academy of Sciences (https://www.resdc.cn/) Open street map (https://www.openhistoricalmap.org/)

Emergency relocation of the affected population is an essential means of reducing casualties. In HAZUS software, the loss of life is assessed using the casualty modeling function and the “road-only” evacuation method, in which evacuation path distances are derived using DEM, road networks, and the walking speed of the population [7]. Differently, in China, emergency evacuation is mostly a government-led behavior, often adopting vehicle transportation without the need for individuals to flee on foot. Therefore, the risk of casualties is significantly reduced. Assessing the number and location of the population that needs to be relocated will provide an important scientific basis for emergency rescue and resource allocation in disasters.

According to the study, 1/2 of the residents trapped in water up to 2 m are expected to be injured, while the other 1/2 are expected to die. If the water exceeds 2 m, the mortality rate will reach 99%, and the remaining 1% are expected to be injured [8]. Therefore, the challenge of quantifying the population that needs to be relocated lies in determining the number of residents in different locations at different depths of inundation.

This paper distinguishes whether emergency relocation is required by the evacuation time to a safe zone (dry land, inundation depth = 0 m) or a partially safe zone (inundation depth ≤ 2 m). Due to the rapid development of the storm surge disaster, coupled with the fact that it takes a lot of time for the organization to implement emergency evacuation, this paper sets 10 min of driving as the

threshold to distinguish whether emergency relocation is necessary. This step employs the Network Analyst and Buffer tools in ArcGIS software. The number of emergency relocation populations is calculated by (2).

$$RL = \sum_{j=1}^{mr} RD_j \times A_j \quad (2)$$

Where, RL is the number of emergency relocation populations. mr refers to the number of rasters that can be evacuated to safety or partial safety within 10 min. RD_j is the population density of the j-th raster, and A_j refers to the area of rasters where the population that needs to be relocated is located.

Residents in the danger zone (inundation depth > 2 m) and whose time to the safe or partially safe zone is more than 10 min are considered to have a 99% probability of death. Those under the age of 14 and over the age of 65 will be increased to 100%. This is the strategy for the death assessment.

3. Results and Discussion

3.1 Inundation scenario of “Hato”

Statistically, in the process of “Hato”, the maximum storm surge values at partial tide stations along the PRD appeared at Zhuhai station, which was 2.79 m. The maximum storm surge value along the east coast of Guangdong appeared at Huizhou station, which was 1.20 m. And the maximum storm surge values at Nansha Station, Sishengwei Station, Huangpu Station, Hengmen Station, Chiwan Station, and Yantian Station were 2.17, 2.40, 1.94, 2.15, 2.03, and 1.29 m, respectively (as Fig.1 B shows).

Based on the statistics (in the case of pre-disaster or in-disaster assessment, the storm surge layer is constructed based on the forecast), a storm surge layer was obtained by spatial interpolation, which is shown in Fig.2.

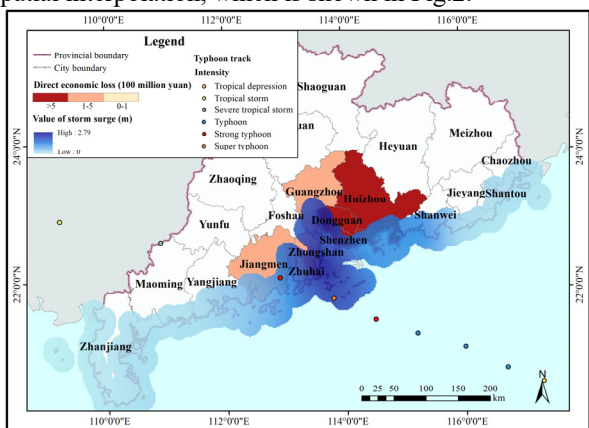


Figure 2. The storm surge layer of “Hato”.

Compared with the boring tabular data, the storm surge layer fills in the values at points except for the stations and forms a continuous, vivid and spatially different storm surge layer in the coastline. In Fig.2, the storm surge of “Hato” towards the PRD along the typhoon track and decreased to the east and west of Guangdong with the PRD as the center. These match the descriptions in the records.

The Spline interpolation method is employed, which makes a smooth surface pass through all input points by fitting a smooth surface with minimum curvature. It’s like twisting a rubber band through all the sampling points while keeping the total surface curvature minimal. Therefore, this method is suited for asymptotically varying surfaces such as elevation, water depth, or pollution. Storm surge creates an asymptotic surface, so interpolating known storm surge data using the Spline interpolation method yields a reliable surface of storm surge values.

Subtracting the storm surge layer from DEM, the inundation layer is obtained (Fig.3).

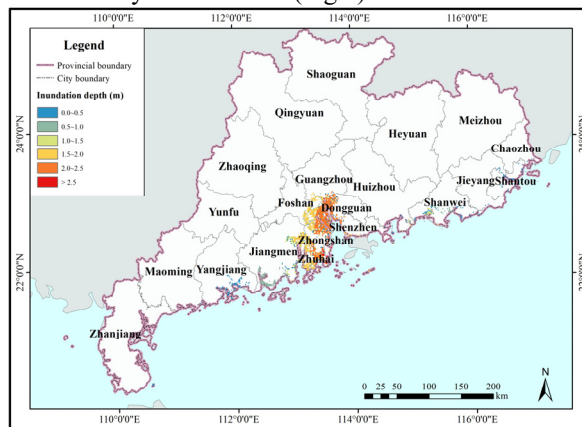


Figure 3. The inundation characteristic of “Hato”.

In terms of the extent of inundation, Zhuhai, Zhongshan, Shenzhen and Dongguan near the PRD are the hardest hit by the storm surge, with a large inundation extent, while Yangjiang, Jiangmen, Huizhou and Shanwei are less affected. This feature is attributed to the landing site of “Hato” in the PRD, which is characterized by a trumpet topography and a deltaic landform. These are conducive to the accumulation of water. The intense storm surge superimposed on the low-lying terrain and the dense river network led to serious backflow of seawater. Moreover, the storm surge disaster only inundated the areas along the coast, indicating that, unlike droughts and floods, the storm surge disaster has a self-limiting character, i.e., its impact mainly expands along the coastline, and the extension from the coast inland is limited to about 20 km.

In terms of the depth of inundation, the inundation depth caused by “Hato” is within the range of 0~3 m. It also shows the characteristics of concentration in the PRD region and self-limiting. Its self-limiting characteristic is reflected in that the inundation depth decreases with the extension distance, from > 2.5 m in the coastal area to 1.0~1.5 m in the inland. The inundation depth of Yangjiang, Jiangmen, Huizhou and Shanwei city is mostly below 1.0 m, which makes little impact on residents.

3.2 Quantitative assessment of Hato’s personal risk

The personal risk assessment carried out in this paper includes two levels: the affected population and the emergency relocation population.

According to the Bulletin of the South Sea Marine Disaster 2018, during “Hato”, the affected population of

Guangdong was 1,288,600, and the emergency relocation population was 229,200. While the assessed affected population of Guangdong is 1,032,455, and the population in need of emergency relocation is 199,973, with the assessment accuracy reaching 91.48% and 87.25%, respectively.

In addition, the distribution of the affected population and the emergency relocation population are shown in Fig.4. As Fig.4 shows, the affected population is concentrated in the PRD and dispersed in surrounding cities such as Yangjiang, Jiangmen and Shanwei. The larger diameter of the yellow circles in Guangdong, Dongguan and Shenzhen indicates that these areas have a high population density and are prone to significant losses in severe storm surge disasters. Although the density of Zhuhai is lower than that of Guangzhou and other cities, almost the entire residents of Zhuhai are shrouded in the threat of “Hato”, which is still a nightmare that many Zhuhai people cannot erase.

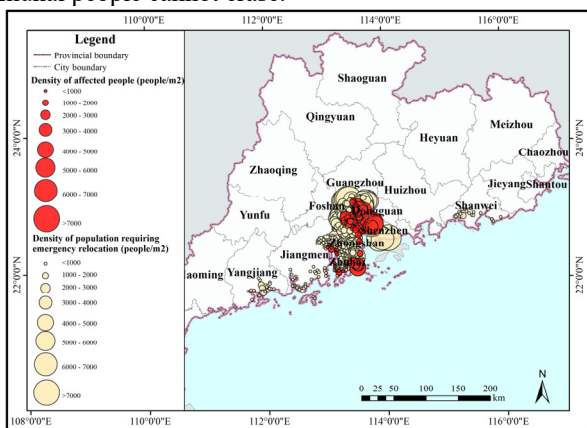


Figure 4. Distribution of Hato’s personal risk.

The population needing relocation is mainly concentrated in the coastal areas of Guangzhou, Dongguan and Zhuhai, which have high population density and are far from the safety or partial safety zone. This demands policymakers to evacuate these residents rapidly before the storm surge disaster hits, preventing roads from being blocked and traffic from being paralyzed. It is worth emphasizing that the assessment results can provide a valuable reference for distributing supplies and preparing rescue workers for emergencies during disasters.

As for the assessment of deaths, the result is 0, while, in fact, six people died (or missing) due to “Hato”. This means there is room for improvement in the death assessment of this method.

This technical framework achieved high accuracy for assessing the affected and emergency relocation populations, but both are underestimated. The underestimate is due to only one risk source, storm surge, which is taken as the input for inundation scenario construction. However, during the “Hato”, the impact of astronomical tides should not be underestimated. If the storm surge overlaps with the astronomical high tide, its risk will be far greater than the risk of the storm surge itself [9]. Coincidentally, the “Hato” met the astronomical high tide. With the understanding of single-risk disasters and the frequent occurrence of multi-risk disasters, the need for

disaster risk assessment considering multi-risk is increasing. This triggered our motivation to explore storm surge risk assessment methods for compound risk sources.

4. Conclusions

The novelty of this paper is reflected in its practicability, which not only takes the essential elements of disaster management (the affected population and emergency relocation population) as the research object, but also proposes an economy, efficiency and visualized method for indicating the geographical location of research objects.

Through a case study on “Hato”, this method achieved an accuracy of 91.48% and 87.25% in affected population assessment and emergency relocation population assessment, respectively. Thus, its feasibility and accuracy are verified. This method provides a scientific basis for government disaster reduction decision-making and risk management. It can be used as a typical demonstration case to enrich and develop the theories and methods of personal risk assessment.

Acknowledgment

This work is supported by the National Key R&D Program of China (No. 2022YFC3105102).

Data are supported by the Bulletin of China Marine Disaster (<http://www.mnr.gov.cn/>), Bulletin of the South Sea Marine Disaster (<http://scs.mnr.gov.cn/>), Bulletin of Guangdong Province Marine Disaster (<http://nr.gd.gov.cn/>), Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM) (<http://www.gscloud.cn/>), the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences (<https://www.resdc.cn/>), Open street map (<https://www.openhistoricalmap.org/>).

We acknowledge Grammarly (<https://app.grammarly.com/>) and DeepL (<https://www.deepl.com/>) for their linguistic assistance during the preparation of this manuscript.

References

1. P. L. Barnard, L. H. Erikson, A. C. Foxgrover et al., “Dynamic flood modeling essential to assess the coastal impacts of climate change,” *Scientific Reports*, vol. 9, no. 1, 2019.
2. H. Simpson R., “Hurricane prediction: progress and problem areas,” *Science*, vol. 181, no. 4103, pp. 899-907, 1973.
3. F. N. T. A. B, and E. Z. B, “Vulnerability to sea level rise: A novel local-scale indicator-based assessment methodology and application to eight beaches in Shoalhaven, Australia,” *Ecological Indicators*, vol. 85, pp. 295-307, 2018.

4. M.-G. A.M., Z. C., D. C.J., and G. J., "Coastal-flood risk management in central Algarve: Vulnerability and flood risk indices (South Portugal)," *Ecological indicators*, 2016.
5. S. Wang, L. Mu, M. Qi, Z. Yu, and E. Zhao, "Quantitative risk assessment of storm surge using GIS techniques and open data: A case study of Daya Bay Zone, China," *Journal of Environmental Management*, vol. 289, no. 3, pp. 112514, 2021.
6. S. Zhang, J. Zhang, X. Li et al., "Quantitative risk assessment of typhoon storm surge for multi-risk sources," *Journal of environmental management*, vol. 327, pp. 116860, 2023.
7. F. E. M. Agency. "Hazard Flood, Hurricane and Tsunami Manuals.."
8. E. Frucht, A. Salamon, J. Rozelle et al., "Tsunami loss assessment based on Hazus approach—The Bat Galim, Israel, case study," *Engineering Geology*, vol. 289, pp. 106175, 2021.
9. R. Zhang, *Natural risk assessment and emergency management of the Maritime Silk Road: PUBLISHING HOUSE OF ELECTRONICS INDUSTRY*, 2023.