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VULNERABILITY OF METRO SYSTEM DUE FLOODING IN LARGE ASIAN CITIES

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Abstract: Climate change aggravates the frequent occurrence of extreme weather events, and flood disasters show significant characteristics of increasing intensity, expanding scope and worsening urban impacts. As hubs of population and wealth concentration, the vulnerability of cities is exposed in disasters. The hardened surface leads to the decrease of rainwater permeability, and the disorderly expansion makes the newly built urban area occupy the flood channel, forming a vicious circle of chronic waterlogging during rainfall events. We analyze the correlation between urban structural and morphological influencing factors and flood disasters in large asian cities, based on which we obtain the relationship between each influencing factor and flood disasters. We use complementary AHP calculate the flood vulnerability across East, South, and Southeast Asian countries. We also analyse the contribution to the city vulnerability due to existance of metro system. We find that the most vulnerable cities are Pearl River Delta in China, then, the cities from southeastern China, Japan, and major cities in India. The development of underground space in cities has a "double-edged sword" effect. It can improve transportation efficiency but also increases the vulnerability of the urban system. The metro system significantly enhances economic vulnerability, but has a limited impact on casualty vulnerability.

Keywords: Climate change, flood, urban structure, metro system, vulnerability.

1. INTRODUCTION

According to the Intergovernmental Panel on Climate Change (IPCC, 2023), global warming persists, driven by both natural factors and human activities, notably carbon emissions (IPCC, 2023). This ongoing global warming is leading to a more uneven distribution of temperatures worldwide, resulting in increased instances of extreme precipitation in various regions (Lyu et al., 2023). These extreme precipitation events often trigger floods and geological disasters, significantly impacting societal well-being and economic stability (Davenport et al., 2021). Flood disaster, characterized by the overflow of rivers or surface water due to heavy rainfall or snowmelt, causes the inundation of urban and rural areas and pose significant threats to lives and property of residents. Particularly in densely populated urban centers, existing drainage systems struggle to cope with the effects of intense rainfall, leading to issues like waterlogging, traffic disruptions, and structural failures. Globally, extreme precipitation events are becoming more intense and frequent, heightening the risk of flooding, especially in urban areas. While some areas may experience an increase in extreme precipitation, others may witness a decrease, highlighting regional variability (Myhre et al., 2019).

IPCC underscores the substantial impact of extreme precipitation on infrastructure and human settlements. Projections for the future indicate a sustained rise in both the frequency and intensity of extreme precipitation events under various climate change scenarios. East, South, and Southeast Asia are frequently subjected to flood disasters. As illustrated in Figure 1, the spatial distribution of flood-induced fatalities across national jurisdictions in these regions from 2014 to 2024 demonstrates that most countries experienced mortality exceeding 100 fatalities. This impact is particularly pronounced in high-population-density nations such as India and China. Concurrent with global economic development, continuous expansion of urban areas has accelerated the growth of built-up environments and road infrastructure. These developments have exacerbated flood-induced economic losses, rendering urban flood vulnerability a critical challenge for all affected nations.

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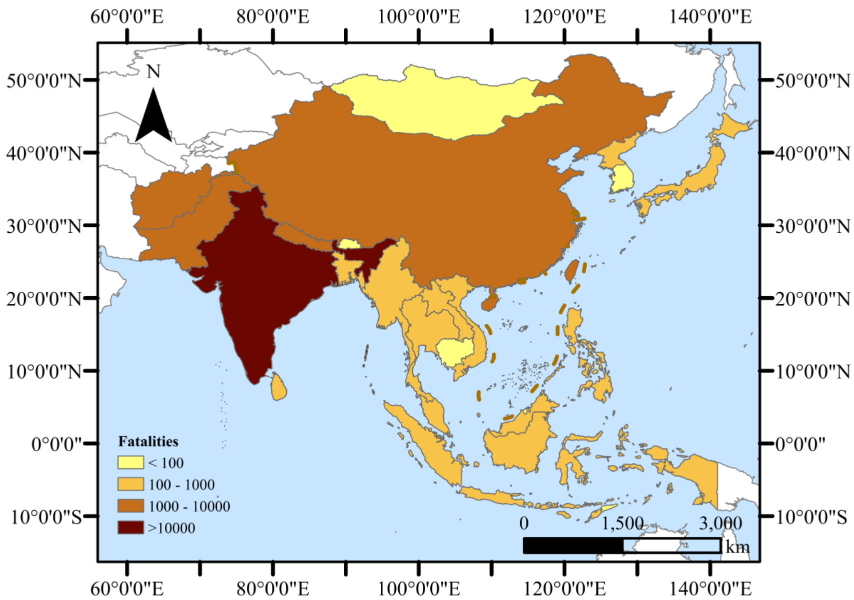

Figure 1. *Flood-induced fatalities across southeastern Asia from 2014-2024 (Data from GDDP)*

Many studies have showed that socio-economic and demographic factors are influencing urban flood vulnerability. With the uneven development of economy and population, and different degrees of extension to urban infrastructure, the spatial distribution of urban flood vulnerability is also different in the world. Concurrent with rapid economic growth, urban expansion has accelerated built-environment development at an unprecedented scale. Asia's built-up area increased by 58,000 km² (2010-2020), while road infrastructure grew by 1.2 million km—predominantly in floodplains (Seto et al., 2017). This uncontrolled spatial development has directly exacerbated flood vulnerability, transforming episodic hazards into systemic crises. Annual flood-induced economic losses in the region now exceed US$32 billion, with infrastructure damage accounting for 67% of total costs (UNDRR, 2023).

While socioeconomic drivers of vulnerability (e.g., GDP, population density) are established (Hallegatte et al., 2020), critical knowledge gaps persist regarding: (1) The quantifiable role of infrastructure configuration (e.g., metro systems) in modulating vulnerability; (2) Spatially explicit interactions between urban morphology and flood consequences. This study addresses these gaps through a novel analytical framework integrating multi-source geospatial data with historical disaster footprints.

2. MATERIAL AND METHODS

2.1. Complementary AHP

The Analytic Hierarchy Process (AHP), proposed by Saaty in the 1970s (Saaty, 1977), is a systematic, simple, flexible, and effective decision-making method that combines qualitative and quantitative approaches. Dong (1996) first introduced fuzzy theory into AHP, developing an improved AHP method that eliminates the need for consistency testing—namely, the 0.1–0.9 scale complementary AHP. This approach employs a 0.1–0.9 five-point scale to construct a complementary judgment matrix, which is then transformed into a fuzzy consistent judgment matrix using a conversion formula, ultimately deriving the priority vector. However, the traditional AHP method primarily relies on empirical knowledge or expert judgment during the decision-making process. In this study, we utilize the correlation coefficients between each factor and historical flood disaster consequences as empirical values to determine and quantify the relative importance of pairwise factors, thereby obtaining the weight ranking of each factor. Finally, in ArcGIS, the weights of each factor are integrated with their corresponding numerical values through raster calculation to generate the risk ranking of urban flood vulnerability and its visualized spatial distribution.

In the complementary fuzzy scale, a value of 0.1 indicates that Factor A is more important than Factor B, whereas a value of 0.9 denotes that Factor B is more important than Factor A. Thus, we established a relationship in the difference Δ of correlation coefficient between the two factors and the complementary fuzzy scale value.

2.2 Data on urban characteristics

To explore the relationship between various factors of urban form and structure and the consequences of flood risks, we conducted a correlation analysis of the data of these factors and historical flood consequences. Based on the boundary vector data of 243 countries, we respectively tallied the flood death toll, economic losses, GDP, population, built-up area of cities, road length and metro length of each corresponding country. This study utilized the geopandas library in Python to handle geospatial data. We transformed the coordinate systems (CRS, Coordinate Reference System) of the national boundary vector data and the built-up area data of cities into EPSG: 3857, that is, Web Mercator projection, to facilitate spatial analysis. We used intersects as the connection condition for spatial linking between datasets, meaning that the geometry of buildings intersects with national boundaries. Then, we used the geometry.area attribute in geopandas to calculate the area of each building, and finally aggregated the area of all buildings by country. The method for calculating the road length of each country was the same.

3. RESULTS

3.1 Analysis of urban characteristics and flood disasters

Through correlation analysis of 243 countries, we quantified how urban structural factors influence flood consequences, revealing that economic losses are predominantly driven by GDP, metro infrastructure and population, while fatalities correlate most strongly with population and road networks . Utilizing national-scale aggregations of global road networks and built-up areas, we implemented a novel 0.1–0.9 scale complementary AHP method that substitutes empirical correlation coefficients for subjective expert judgments in pairwise comparisons. This approach identified population and GDP as paramount vulnerability determinants (Figure 2), with population exhibiting the greatest consequence-dependent variability, while effectively mitigating scoring biases inherent in traditional AHP frameworks.

We use correlation coefficients to calculate the difference Δ between each two factors, and complementary AHP can calculate the weights of each factor in various situations. When we consider the situation of metro system, the impact of the population on economic loss vulnerability is the greatest, and the weights of other factors are the same. The impact of the GDP on casualty vulnerability is the greatest. The impact of the metro system ranks second. When we disregard the influence of the metro, the impact of population on economic vulnerability remains the greatest. With all other factors remaining the same, GDP has the greatest impact on casualty vulnerability, and all other factors are the same. It can be seen that the correlation coefficients between the weak factors and the flood consequences are relatively close, and their influence weights are the same. Population, GDP and metro distribution are the three most crucial factor.

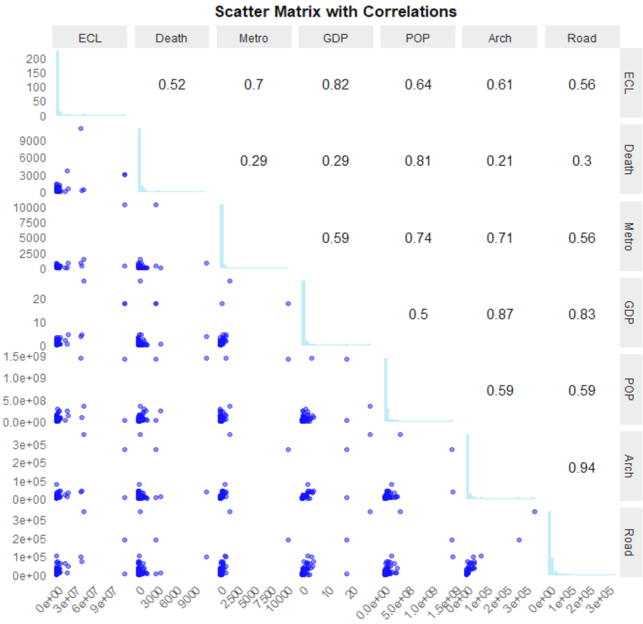

***Figure 2.** The scatter matrix and correlations of each factor*

3.2 Intensity distribution of urban vulnerability

We use the integrated methodology to assess spatial heterogeneity in flood vulnerability across 24 East, South, and Southeast Asian nations. These outputs were benchmarked against 2018 observed economic loss and death patterns. Critically, metro infrastructure was incorporated as a dynamic variable—reflecting both its inevitability in urban development and disproportionate exposure to subsurface flooding—with comparative scenarios presented in Fig. 3 and 4.

Figure 3 presents the spatial distribution of urban flood economic vulnerability contrasted against 2018 observed losses. GDP constitutes the primary determinant, while metro infrastructure demonstrates significant secondary influence, though exclusively applicable to economically advanced, high-density nations. Spatial analysis reveals: absent metro considerations, vulnerability peaks in China's Pearl River Delta, with secondary clusters in Southeast China, Japan, and India; Incorporating metro exposure elevates vulnerability in the Pearl River Delta, followed by Southeast China and the Tokyo metropolitan region. Crucially, 2018 loss epicenters (Japan, South India, Southeast China) align with high-vulnerability zones (orange/purple markers), exemplified by Japan's record 10 billion dollars losses—its most severe event in 45 years—occurring within a core economic vulnerability hotspot.

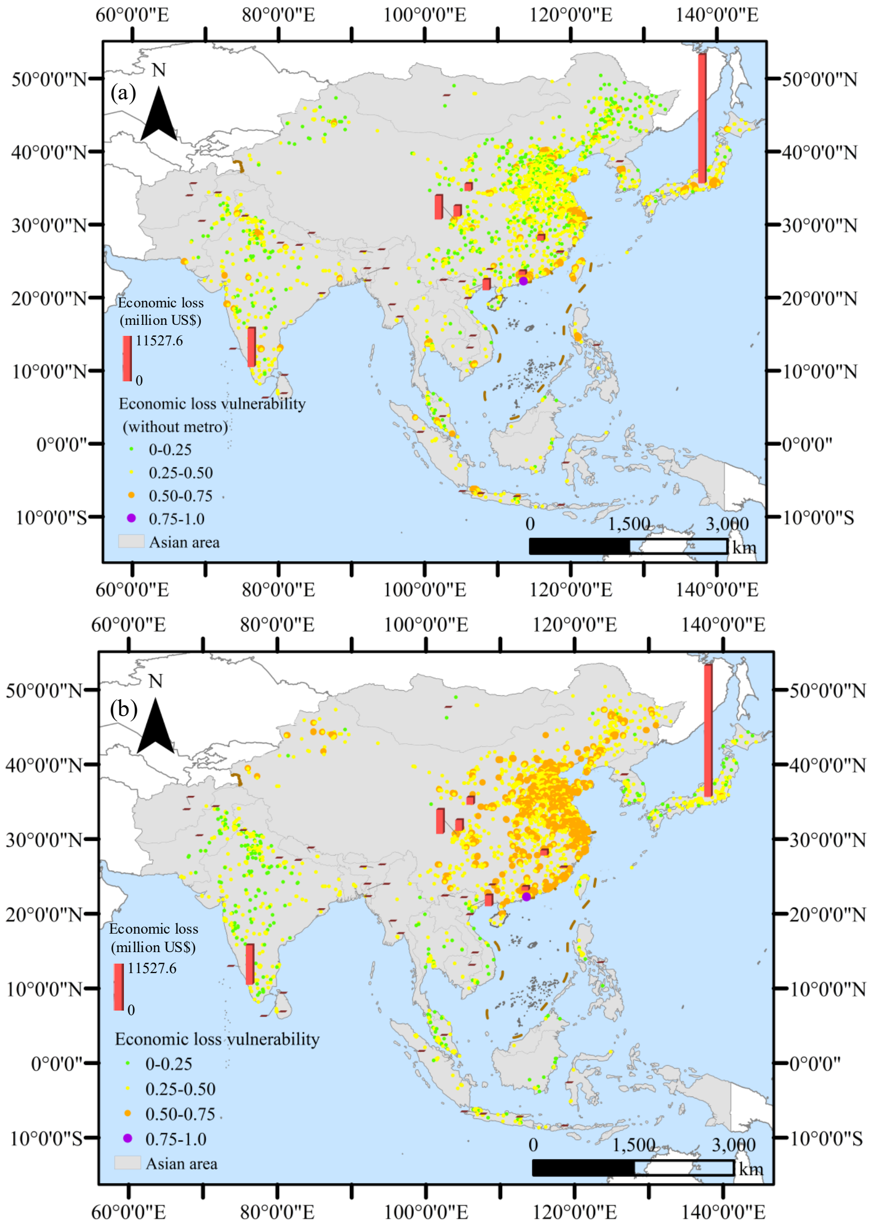

Figure 3. *Flooding induced economic loss in 2018: (a) without metro, (b) with the effect of metro*

Figure 4 shows the distribution of the intensity of urban vulnerability and makes a comparison with the actual number of deaths in 2018. For vulnerability, population distribution is the most significant factor of correlation. The calculation results indicate that the areas with higher vulnerability include the southeast of China, Delhi, Mumbai, Bangalore in India, North Korea, Tokyo in Japan, Bangkok in Thailand, Manila in the Philippines, Jakarta in Indonesia, and the regions of Nigeria in Africa and China, Japan, India, and Vietnam in Asia. If the influence of metros is considered, the correlation coefficient is 0.29, indicating that compared to the vulnerability of economic losses, the impact of metro construction on vulnerability is relatively small, and the most significant factor is still population.

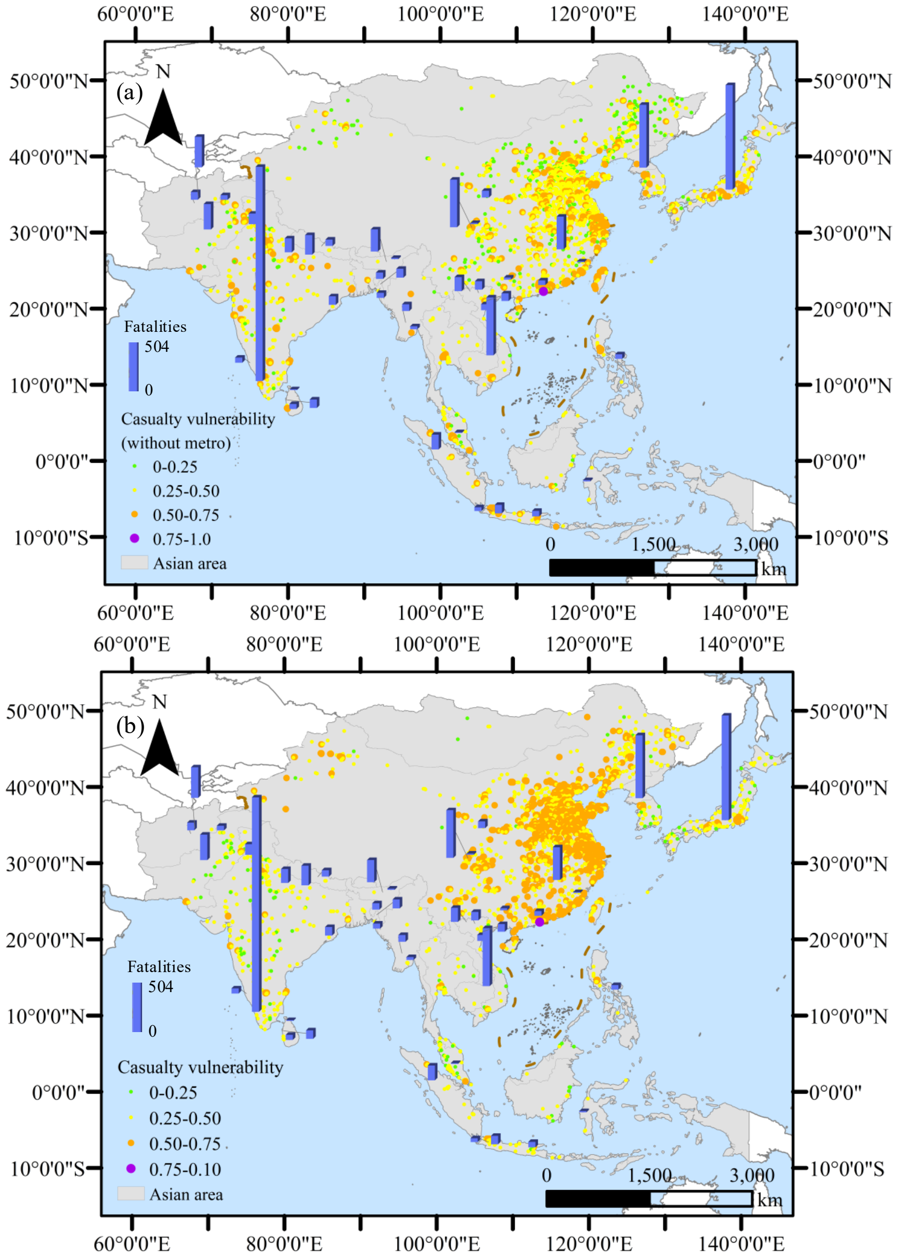

Figure 4. *Flooding induced fatalities in 2018: (a) without metro, (b) with the effect of metro*

4. DISCUSSION

This study utilized a vast global dataset to explore the degree of correlation between urban structure and flood risk consequences, as well as the evaluation of urban flood property and health vulnerability under different urban structures. Due to the uneven spatial distribution of various urban structures and the varying importance of influencing factors, the economic losses and casualties caused by floods are affected. This understanding is beneficial for providing effective references for future urban planning, mitigating urban flood risks, and for the government to formulate relevant policies. The urban characteristic factors in our study are based on the data from 2018. However, with the development of society and economy, the indicators of each factor will also change every year. Based on this study, we can predict the future economic vulnerability of urban floods and provide research support for flood risk management.

The results show the distribution of flood-related economic losses and health vulnerability across various cities under the combined factors. At the same time, it also indicates that some developed cities, such as Hong Kong, Shanghai in China, Tokyo in Japan, have higher economic loss vulnerability. Their GDP and population distribution remain high, and the management and renovation of urban buildings and transportation infrastructure should be given more attention to avoid causing more flood-related economic losses. In addition, in places like Delhi in India, Mumbai in India, Manila in the Philippines, etc., the population density is high and the vulnerability of human deaths is high, but the infrastructure development is lagging behind. International rescue, local government urban development planning, and flood prevention awareness publicity should also be given more attention.

We will also consider the development of the metro as a separate factor. This is because, with the advancement of society, many countries are expanding their underground space resources, and the construction of underground rail transit is also developing year by year. Therefore, this study believes that it is necessary to consider the metro as an important factor. However, the study used the total length of metro in each country， that is to assume that the length of the metro in each country and each region is its total length. When calculating using ArcGIS, the point data of metro lengths in the same country were the same. Therefore, the calculation results can be used as a reference. The accuracy of the results still needs to be determined by collecting the actual distribution density of metros in various countries in the future. However, from the calculation results, China is a country with the fastest metro development, and metro transportation is also the most affected by floods globally. The Chinese government should pay attention to the development of urban underground space and take corresponding protective measures.

5. CONCLUSIONS

(1) There is significant spatial heterogeneity in the vulnerability of urban flooding. Regions in East Asia, South Asia, and Southeast Asia have become global hotspots of vulnerability due to high population density and rapid urbanization (such as the Pearl River Delta in China, Delhi in India, and Tokyo in Japan). The dominant factors for different consequences vary. Economic loss vulnerability has a strong positive correlation with GDP, while casualty vulnerability is mainly driven by population density. Meanwhile, metro systems have a "double-edged sword" effect, improving transportation efficiency but increasing system vulnerability. The metro systems significantly enhances economic vulnerability but has a limited impact on casualty vulnerability.

(2) To enhance flood disaster management, governments should adopt a tiered mitigation strategy tailored to regional vulnerability profiles: For high economic vulnerability zones (GDP exceeding $1 trillion), such as major metropolitan areas, implementing upgraded metro flood protection standards is critical—exemplified by China's post-Zhengzhou 7.20 incident (DIT-SC,2022) regulations mandating 50-year flood-resilient design benchmarks. In high fatality vulnerability zones (population density surpassing 5,000 inhabitants/km²), like densely populated urban corridors, deploying mobile network-based early warning systems modeled after Jakarta's successful implementation should be prioritized.

(3) Meanwhile, emerging metro cities undergoing rapid urbanization (e.g., Hanoi, Bangkok) must incorporate compulsory underground floodgate installations and vertical evacuation route networks into their infrastructure planning. This comprehensive approach addresses both economic asset protection and life safety considerations through targeted, evidence-based interventions that account for each region's distinct risk characteristics and development stage.

6. ACKNOWLEDGMENTS

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