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A Multi-Hazard Risk Assessment Framework for Urban Disaster Prevention Planning: A Case Study of Xiamen, China

Shutian Zhou [1,*] and Guofang Zhai [2]

[1] School of Art (School of Architecture), Nantong University, Nantong 226019, China
[2] School of Architecture and Urban Planning, Nanjing University, Nanjing 210093, China; guofang_zhai@nju.edu.cn
* Correspondence: shutian_zhou@ntu.edu.cn

Abstract: Understanding and measuring the relative risk level of a city facing multi-hazards is fundamental to improving its disaster prevention planning and schemes. A comprehensive risk evaluation approach stands at the intersection of risk management and disaster system theory. It is also an important interdisciplinary field of catastrophology, economics, and urban infrastructure planning. We believe that current attempts to define and measure comprehensive urban natural disaster risks have certain limitations. Therefore, we propose an Urban Multi-hazards Risk Assessment Framework (UMRAF) which draws on definitions, methods, and experience from risk management, evaluation of property, the value of statistical life, and disaster system theory. It contains local disaster identification, place-based risk assessment (taking into account more than one hazard at a time), urban anti-disaster capability assessment, and relative composite risk index measurement. In our case study of Xiamen, China, to check the feasibility of our UMRAF, we examined local multi-hazards risk distribution and urban anti-disaster capacity layout. We then expanded and visualised the spatial distribution of the relative composite risk index of each evaluation unit across the city via our analyst tool, thereby helping to tailor measures that can reduce risk at a local level.

Keywords: multi-hazards risk assessment; urban natural disasters; urban anti-disaster capability; relative composite risk index; comprehensive assessment

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1. Introduction

Recent catastrophic events, such as tsunamis, earthquakes and floods, have shown that the distribution of disaster consequences across a city is diverse, just as both the level of preparedness and response of affected areas may differ. Cities tend to suffer the most serious losses of life and damages to infrastructures in natural disasters owing to their high densities of population, facilities, and economic activities. In parallel with the observed greater frequency of natural disasters worldwide, natural disaster risk assessment becomes an important part of risk management and stands at the core of disaster risk research. Mapping urban multi-hazard risk and visualising the spatial distribution and concentrations of risks located throughout a city thereby contribute to more refined mitigation and prevention strategies [1].

Natural disaster risk refers to the degree of expected damage caused by a specific natural phenomenon that may occur in a specific area at a specific time [2]. The idea of risk has been successfully explored and applied in many disciplines and technological fields in both theoretical research and practice. It is defined as the combination of the consequences of an event and the associated likelihood of occurrence in the risk management area (ISO31000:2009 definition 1.1). On the other hand, risk is also seen as a combination of natural hazards along with society's exposure and vulnerability to them in the disaster system literature and risk assessment studies [3,4]. Therefore, it is often assessed by respective or overall evaluations of these subsystems. Much previous research on disaster risk assessment was based on disaster system theory in order to establish assessment models for simulating and predicting the probability of disaster occurrence and its possible impact degree with regard to disaster causes, natural conditions, and social economy and disaster prevention engineering. Yet, in the face of multi-hazard risk contexts, it becomes difficult to reflect accurately the difference in frequency and consequences of different disasters when synthesising disaster risks through traditional superposition or coupling approaches.

In this article, we propose the Urban Multi-hazards Risk Assessment Framework (UMRAF) as a new approach from an economic perspective. The UMRAF duly adapts ideas from the basic conception of risk and draws on relevant definitions and methods in the literature on risk management, property evaluation, value of statistical life, and disaster system theory. It offers a place-based model for annual expected direct loss as a basis for urban risk analysis, and further focuses on the balance of local multi-hazards risk and its anti-disaster capacity, with the introduction of a relative composite risk index. Our UMRAF has three main characteristics and potential benefits. Firstly, the multi-hazards risk assessment model considers the probabilities of consequences of different urban disasters with a legible structure. Its use of place-based annual expected direct loss also makes the assessment of loss of life as important as economic disaster loss. Secondly, the results can support the planners, risk analysts, and policy makers in identifying the shortage and surplus of local anti-disaster resources through the examination of the relative composite risk index and its distribution pattern. Thirdly, it is a dynamic framework for long-term comprehensive urban risk management and strongly adaptive for diverse disaster types and local data availability.

The remainder of this paper is formatted as follows. Section 2 reviews the literature on multi-hazards natural risk assessment and disaster loss evaluation, including common calculation logics for disaster risk assessments and key research aspects, methodology, and models. Section 3 provides our view of disaster risk applied in our UMRAF as well as key steps with supporting calculation formulas and an assessment index system. With the use of data collected from Xiamen, China, Section 4 takes earthquakes and floods as examples to verify the feasibility of proposed approaches in the UMRAF. Section 5 discusses the application scope and key features of our UMRAF. See Section 6 for our conclusion.

2. Literature Review

Natural disaster risk assessment is an important part of risk management, standing at the core of disaster risk research. From a broad risk management perspective, risk analysis of a natural disaster involves the exploration of its probability and consequence. Multi-hazards risk assessment requires consideration of both the different power sources and characteristics of disasters as well as the possible impact of disasters on residents' personal safety and that of their property [5]. Huang proposed the basic model of comprehensive natural disaster risk assessment through a series of functions, such as probability density function, dose–response function, and their syntheses, to show the risk [6]. Furthermore, he proposed a risk matrix of disaster consequences and their likelihood of occurrence, thereby helping to determine the level of disaster risk [6].

At present, the main paradigm of natural disaster risk assessment is from the perspective of disaster system theory, to establish assessment models for three constituent systems, namely, hazard factors, disaster-bearing environment, and disaster-bearing bodies. Current disaster risk assessment approaches are focused just on hazard factors in their narrow sense [7,8], or comprehensively on the evaluation of all three constituent systems. A widely used framework comprising hazard, exposure, and vulnerability is often adopted to assess natural disaster risks [9–16]. The scope of disaster risk evaluation has gradually widened over time to include the capacity of the community to face risks [17–19], anti-disaster capability [20], disaster resilience [21,22], and risk communication or risk acceptance [23–26].

The development of refined risk assessment models for urban disaster risk reduction remains limited. Risk assessment models commonly used worldwide for single disasters include risk identification, risk hazard analysis of disaster-causing factors, vulnerability and exposure analysis of disaster-bearing bodies, risk classification, and impact analysis, e.g., UNDRO, NOAA, SMUG, APELL, etc. Of these, the UNDRO model is considered more suitable for urban planning owing to its emphasis on spatial characteristics [27,28]. Yet, in practice, the indicator selection process in assessment is strongly influenced by the scale of the research object, historical disaster data, and availability of index data. We welcome the further exploration of applicable multidisciplinary methods for disaster risk assessment as this should help with the requirements of urban comprehensive disaster prevention and mitigation goals.

Urban risk measurement, which is typically restricted to single-hazard disasters, may lead to an underestimation of the risk level [29]. Most existing studies on multi-hazards risk assessment are delivered on the disaster system theory basis, through risk synthesis approaches from the perspectives of superposition and coupling. The essential difference between them is whether the interaction between different disasters is considered in their synthesis process. From a superposition perspective, the multi-hazards risk is measured through the synthesis of all the single-disaster risk results [30–34], only with different disasters in different weights, or through the synthesis of hazard factors [35–39]. Unfortunately, this type of approach lacks consideration of spatial comparison and the effects of different hazard factors. The determination of index weight for disasters is also significantly influenced by the scale of the research object and historical disaster data availability. For the coupling perspective of disasters, the multi-hazards risk is assessed through the simulation of different coupling relations such as adjoint relationship, trigger relationship, coupling relationship, cascade effect, disaster chain, domino effect. Indeed, the approaches require some subjective and qualitative coefficients in key coupling rules and model construction processes. Some rely greatly on the coupling rules between disasters with the same disaster-causing factors [40–42], while other studies from the coupling perspective are still theoretical [37,43,44]. Therefore, within current risk superimposing and coupling approaches, it is difficult to accurately show the differences in intensity and frequency of disasters with different hazard factors. Consequently, it is a challenge to meet the growing urban risk management goals and spatial characteristics. An innovative and alternative perspective for multi-hazards risk assessment is needed to overcome these shortcomings and provide a more scientific and intuitive basis for comprehensive disaster risk prevention.

The research methods of quantitative ex ante disaster risk and loss assessment are mainly based on the induction of historical empirical data and computer numerical simulation. They tend to rely on the application of various types of software, such as the working platforms of ArcGIS, for spatial analysis and visualisation process in the HAZUS [45,46], PAGER [47], and HAZ-China [48] systems, etc. Although disaster casualties are inevitable, few models put loss of human life and economic loss on the same level of disaster risk assessment. According to the value of life theory, the value of a rational person's life can be monetised through statistical methods [49–51]. Natural disasters have diverse spatial distributions across a city and all represent public risk that cannot be reduced by economic means such as market exchange, hence the relatively few historical studies of value of statistical life (VSL) loss in the urban disaster literature. Research on disaster risk from an economic point of view can help effectively identify and measure the loss of life and economic loss in the same context, thereby enhancing risk perception, projection, evaluation, and mitigation. Zhou, Zhai, Lu, and Shi used an improved human capital approach to evaluate the loss of VSL in earthquakes, which provides a way of monetising the direct and average impact of the deaths of local people in all age groups [52]. This makes a breakthrough in the interdisciplinary fields of catastrophology, economics, and urban disaster prevention planning by applying approaches of VSL evaluation in disaster risk assessment.

3. The Proposed Assessment Framework

In areas such as insurance, economics, engineering, and catastrophology, potential consequences and events and their likelihoods of occurrence are viewed as a matter of rule for their inherent risk. The United Nations Disaster Relief Organization (UNDRO) [53] defines natural disasters as the expected loss value of life, property loss, and economic activities caused by a natural phenomenon and specific risk elements. By measuring the expected loss value within a certain period, the size of a risk resulting from a natural disaster can be explained and quantified in economic terms.

The idea of expected loss value follows the law relating to natural disasters, i.e., "the greater the intensity, the lower the probability of occurrence". Understanding and measuring disaster risks through this idea enables an assessment result which recognises the differences in frequency and consequences. This allows for the comparison of the risk magnitude of different types of disasters, as well as the risk magnitude of the same disaster with different intensities, while the values of risks within the same spatial unit become cumulative. In addition, after identification at the very outset of the types of disasters and evaluation of their expected loss values, the synthesis process ensures they are not ignored or underestimated on a local multi-hazards risk level. We then propose to assess urban anti-disaster capacity and relative composite risk index in order to analyse and present the local risk situation more comprehensively and to further support decision making and plan making in urban risk management and disaster mitigation. In the subsections below, we discuss each step within the whole assessment framework and illustrate their uses with key calculation formulas and the assessment index system for the application of the UMRAF in our case study.

3.1. Step 1: Identifying the Disaster Types with Their Intensities and Direct Losses

The probability of exceedance refers to the chance of occurrence of hazards at a given intensity. In this study, the possibilities of disasters are considered within a one-year period to help calculate the annual expected loss value. This "one-year period" does not refer to a particular year, but to any year, because the probability of a certain disaster of a certain intensity is the same in every year. Therefore, in the first step of our UMRAF, risk analysts need to identify the major disaster types facing a city according to its historical records and examine the annual possibility of occurrence as per its noted intensity of disasters. We take earthquakes and floods as examples to show how to calculate their annual frequency of occurrence and brief ways to estimate direct loss as a result.

For local earthquakes, the Poisson distribution is a classic probabilistic seismic-hazard model to calculate the probability of the occurrence of earthquake intensity, representing the homogeneous and spatially random characteristics of earthquake occurrence in a region [54,55]. In China, according to the seismic fortification division in the seismic code Seismic Ground Motion Parameters Zonation Map of China (GB18306-2015) [56], a city's seismic fortification intensity is determined by its basic ground motion intensity. The seismic fortification intensity is defined as the ground motion intensity with a probability of 10% under general site conditions in a 50-year period. Earthquakes with 63% and 2% probabilities of exceedance within the next 50 years are specified, respectively, as frequent and rare earthquakes. By checking the seismic fortification intensity of a city given by the seismic code, risk analysts can calculate the probabilities of exceedance of three characteristic earthquakes in a one-year period through the following formula (Equation (1)) [52].

$$P_1(I_i, 0) = 1 - [1 - P_{50}(I_i, 0)]^{\frac{1}{50}} \tag{1}$$

where $P_1(I_i, 0)$ denotes the likelihood that the earthquake of intensity I_i degrees occurs in one year; $P_{50}(I_i, 0)$ denotes the probability of the earthquake of intensity I_i degrees of a place given in the seismic code.

Massive construction damages represent the major causes of economic losses and casualties in earthquakes, especially in urban areas. The direct economic losses (including structural losses and indoor property losses) and the number of casualties caused in characteristic earthquakes in our framework are suggested by reference to local building and infrastructure investigation data through models and value ranges of parameters given in the Chinese code of Classification of Earthquake Damage to Buildings and Special Structures (GB/T24335-2009) [57] and the seismic code GB18306-2015 [56]. The code Post-earthquake Field Works—Part 4: Assessment of Direct Loss (GB/T18208.4-2011) [58] also provides value ranges of relevant parameters for calculations. The monetised life loss of potential deaths is suggested by determination through the improved human capital approach proposed in our previous study [52].

For annual frequency analysis of local rainstorm-driven floods, rainstorm or flood frequency (return period) of a certain magnitude refers to the recurrence probability of this disaster event in a certain period. The average annual probability of occurrence of a rainstorm-driven flood of a certain magnitude has a reciprocal relationship with its return period (Equation (2)). The return periods of rainstorms of certain magnitudes are determined through calculations of the long-term hydrological record of a place and given by local meteorological and hydrological sectors.

$$P_j = \frac{1}{T_j} \tag{2}$$

where P_j denotes the annual average probability of a rainstorm with magnitude j; T_j denotes the return period of a rainstorm with magnitude j.

The direct loss estimation of different local rainstorm-driven floods has three parts. First, the spatial distributions of rainstorm-driven floods are simulated in an SCS-CN hydrological model [59,60] on the ArcGIS platform based on DEM geographic elevation data, local river water area data, soil type, surface vegetation cover type, and local historical precipitation data. Second, the multiple linear regression function of rainfall intensity, the area affected by rainstorm flood crops, and the direct total economic losses are then constructed according to the survey and statistical data of local historical flood disaster losses in the evaluation area. The value of local economic flood loss records is collected. Then, the correlation test of linear correlation between the variables of rainfall intensity, disaster scope, and direct economic loss is implemented in order to fit the proposed local storm-driven flood loss function (Equation (3)). Third, the expected direct economic loss of each evaluation unit is estimated in the rainstorm with a certain return period.

$$L\left(T_j\right) = b_0 + b_1 * I_{rainfall}\left(T_j\right) + b_2 * A_{submergence}\left(T_j\right) \tag{3}$$

where the $L\left(T_j\right)$ denotes the direct economic loss in the storm-driven flood of return period j (unit: ten thousand CNY); $I_{rainfall}\left(T_j\right)$ denotes the strongest daily rainfall in the storm-driven flood of return period j (unit: mm); $A_{submergence}\left(T_j\right)$ denotes the disaster area in the storm-driven flood of return period j (unit: ten thousand square metres); and b_0, b_1, and b_2 are coefficients for economic adjustment, rainfall disaster loss, and disaster-bearing area loss.

3.2. Step 2: Measuring the Urban Multi-Hazards Risk Level

The place-based hazard risk of a certain intensity, $Risk(I)$, is calculated as the product of its annual probability of occurrence, $Probability(I)$, and the direct loss, $Loss(I)$, namely, the annual expected value of direct loss in this disaster scenario (Equation (4)). Here, the value of impacts means not only the direct economic loss, $L_{DE}(I)$, but also the loss of VSL in disasters, $L_{VSL}(I)$ (Equation (5)). This model contains the basic principle of natural disasters; the larger the impact, the smaller the possibility of occurrence. Thus, the risk of one disaster can be represented by the sum of the annual expected values of the impact of each disaster-intensity scenario. The multi-hazards risk can be presented as the sum of all the annual expected values of the impacts of different disasters by considering each possible natural disaster faced by an area within a one-year period (Equation (6)).

$$Risk(I) = Probability(I) \times Loss(I) \tag{4}$$

$$Loss(I) = L_{DE}(I) + L_{VSL}(I) \tag{5}$$

$$R_{multi} = \sum_{m=1}^{M} R_m = \sum_{m=1}^{M} \sum_{t_m}^{T_m} L(t_m)_m \times P(t_m)_m \tag{6}$$

where R_{multi} denotes the multi-hazards risk of all local natural disasters; M denotes the total number of natural disaster risks that the study area faces; m denotes the m^{th} type of disaster among the total number of M; R_m denotes the risk of the m^{th} type of disaster; T_m denotes the total disaster intensity of the m^{th} type of disaster; t_m denotes the ${t_m}^{\text{th}}$ type of disaster intensity of m^{th} type of disaster; and $L(t_m)_m$ and $P(t_m)_m$ denote the direct loss and the possibility of occurrence of the m^{th} type of disaster of its ${t_m}^{\text{th}}$ type of disaster intensity.

In this place-based disaster risk measurement, the more types of disasters taken into consideration, the greater the value of R_{multi}, and the accuracy of the evaluator's understanding of the local multi-hazards risk level and spatial distribution. More specifically, when the value of R_{multi} in each geographical unit is calculated, the distribution pattern of a city's multi-hazards risk can be visualised with the help of ArcGIS 10.3 software.

3.3. Step 3: Assessing the Urban Anti-Disaster Capacity

The local level of disaster prevention, reduction, and emergency response is vital for resisting catastrophic events, protecting residents' lives and property, and mitigating the consequences of disasters. At each stage, pre-disaster, during-disaster, and post-disaster, our framework concept of urban anti-disaster capacity describes and assesses this level including infrastructures, management measures, and short-term emergency relief. The overall objective of urban anti-disaster capacity is divided into three subsystems, pre-disaster prevention infrastructure capacity, during-disaster management capacity, and short-term post-disaster rescue capacity. By reviewing assessment aspects and indicators involved in the relevant literature and practice [61–64], we attempt to represent the above three subsystems with a whole-process, place-based, and multi-factor index system (Table 1). The indicators are chosen according to the principles of single structure, ease of measurement, horizontal comparison, and ease of statistical calculation. This index system is also ready for the separate assessment of urban disaster resilience or anti-disaster capacity, and in other practical cases, some indicators can be added or replaced, according to the availability of local data. An expert scoring method and analytic hierarchy method (AHP) are suggested to determine the weight of each subsystem index and individual indicators.

Since the indicators have different units, after data collection, a linear transformation of the original data matrix is needed, through the standardisation transformation of positive indicators (Equation (7)). The standardised index data matrix is also to be tested through the Cronbach's α reliability coefficients, with the help of the statistical software SPSS 19.0.

$$A_k = \frac{a_k - \{a_{min}\}}{\{a_{max}\} - \{a_{min}\}} \times 100 \tag{7}$$

where A_k denotes the standardised value of the k^{th} datum of an index; a_k is the original value of the k^{th} datum of this index; $\{a_{min}\}$ is the minimum value in all the original data of this index; and $\{a_{max}\}$ is the maximum value of all the original data for this indicator.

Table 1. Assessment index system for urban anti-disaster capacity status in the UMRAF.

First Layer	Second Layer	Third Layer (Indicators)
A Urban anti-disaster capacity	B1 Pre-disaster prevention infrastructure capacity	C1 Stormwater pipe network density C2 Area of emergency shelters per capita C3 Number of emergency shelters C4 Number of underground civil air defence projects
	B2 During-disaster management capacity	C5 Number of civil air defence alarm points C6 Number of meteorological monitoring stations of all levels C7 Number of emergency operations centres of all levels
	B3 Short-term post-disaster rescue capacity	C8 Number of hospital beds per thousand C9 Number of medical facilities of all levels C10 Number of police stations C11 Number of fire stations of all levels C12 Road network density

The evaluation result of each subsystem is the sum of the product of the standardised value of the corresponding third-layer index and each weight plus its second-layer index (Equation (8)). Furthermore, the evaluation result of the urban anti-disaster capacity equals the sum of the product of the standardised value of the corresponding third-layer index and each weight plus the first-layer index (Equation (9)).

$$d = \sum_{j=1}^{t} v_j \times A_{ij} \qquad i = 1,\ 2, \cdots,\ n,\ j = 1,\ 2,\ \cdots,\ t \tag{8}$$

where d denotes the evaluation value of the subsystem of urban anti-disaster capacity and v_j denotes the weight of the j^{th} third-layer indicator to the second-layer index, within n third-level indicators in total. A_{ij} denotes the standardised value of the i^{th} data point of the j^{th} third-layer indicator, within t evaluation units, which is 93 here.

$$D = \sum_{j=1}^{t} \omega_j \times A_{ij} \qquad i = 1,\ 2,\ \cdots,\ m,\ j = 1,\ 2,\ \cdots, t \tag{9}$$

where D denotes the evaluation value of urban anti-disaster capacity and ω_j denotes the weight of the j^{th} third-layer indicator to the first-layer index, within m third-level indicators in total, which is 12 here. A_{ij} denotes the standardised value of the i^{th} data point of the j^{th} third-layer indicator, within t evaluation units, which is 93 here.

3.4. Step 4: Analysing the Relative Composite Risk Index

A practically higher urban multi-hazards risk value and a lower urban anti-disaster capacity value imply a more serious threat of disasters and potential impacts on a city, and vice versa (see Figure 1). We see that the urban multi-hazards risk analysed in Step 2 and the urban anti-disaster capacity analysed in Step 3 are a couple of opposing concepts. In our UMRAF, we put forward a relative composite risk index (denoted here by C) to integrate the ideas of urban multi-hazards risk R and urban anti-disaster capacity D into the same context for a more comprehensive understanding. It objectively describes their coordination status and further represents the mismatch between them in a relatively direct form. Highlighting the places with high risk and low anti-disaster capacity in the city further helps facilitate the tailoring of measures that can reduce risk and improve facility efficiency at a local level. After the reliability and validity tests on the data, the value of C is determined by the ratio between the standardised values of R and those of D in each evaluation unit of the study area.

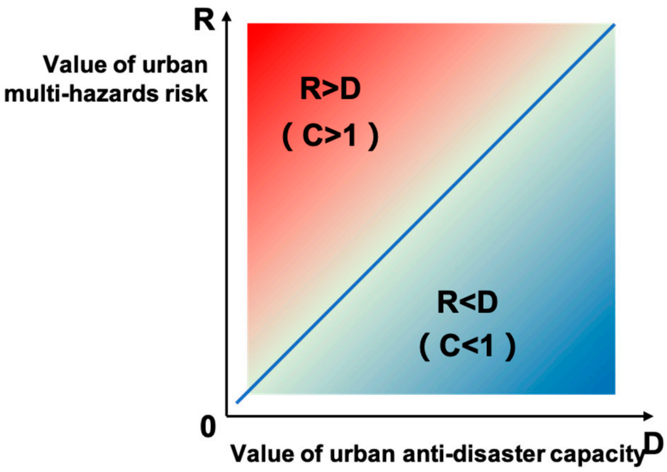

Figure 1. The two-dimensional coordinate system diagram for urban multi-hazards risk (denoted here by R) and urban anti-disaster capacity (denoted here by D).

For all the evaluation units, the higher the value of C, the higher the local multi-hazards risk, meaning a greater need to improve urban anti-disaster capacity. The unit for the urban multi-hazards risk assessment results is CNY, which is represented and calculated using the value of annual expected direct loss, while the value of urban anti-disaster capability is processed based on standardised data, ranging between 0 and 1, without a unit. Thus, before analysing the relative composite risk index, we converted the two sets of data from the above assessments from dataset $\{R_n, D_n\}$ to dataset $\{R'_n, D'_n\}$ through the extremum method (Equations (10) and (11)). The value of the relative composite risk index in each evaluation unit is then calculated using Equation (12). Theoretically, when $R'_n = D'_n$ and $I_n = 1$ in some evaluation unit, it can be recognised that this place neither faces excessive risk nor has excessive anti-disaster resources, indicating a relatively ideal state.

$$R'_n = \frac{R_n - \{R_{min}\}}{\{R_{max}\} - \{R_{min}\}} * 100,\ R'_n \in [0,\ 1] \quad (10)$$

$$D'_n = \frac{D_n - \{D_{min}\}}{\{D_{max}\} - \{D_{min}\}} * 100,\ D'_n \in [0,\ 1] \quad (11)$$

$$I_n = \frac{R'_n}{D'_n},\ I \in [0, +\infty) \quad (12)$$

where R'_n and R_n denote the standardised value and the original value of multi-hazards risk value in the n^{th} evaluation unit, respectively. $\{R_{min}\}$ and $\{R_{max}\}$ denote the minimum value and the maximum value of all the original multi-hazards risk values, respectively. $\{D_{min}\}$ and $\{D_{max}\}$ denote the minimum value and the maximum value of all the original anti-disaster capacity values, respectively. D'_n and D_n denote the standardised value and the original value of anti-disaster capacity in the n^{th} evaluation unit, respectively. I_n denotes the relative composite risk index value the n^{th} evaluation unit.

The analysis results directly examine and represent the balance between the potential disaster risks and their levels of disaster prevention, reduction, and emergency response of different places in a city. Furthermore, by reviewing the situations of their subsystems of anti-disaster capability, it becomes clear and efficient to find out those weak spots for improvement. Through scientifically grading and natural classification (with help of the ArcGIS platform), the results effectively display the relative composite risk index distribution in the study area.

4. Case Study of the UMRAF

4.1. Site Identification and Data Source

The city of Xiamen in Fujian Province is one of the main economic centres and ports on the southeast coast of China, with a population of more than 3.8 million. Our empirical research covers Siming District and Huli District on its main island and the four coastal districts of Xiamen, namely, Haicang District, Jimei District, Tong'an District, and Xiang'an District (Figure 2). The city is situated in the middle of the Binhai Seismic Fault Zoneand, 200~300 km west of the Western Taiwan Seismic Belt. According to the Chinese Code for the Seismic Design of Buildings [65] (GB50011-2010) and the Seismic Ground Motion Parameter Zonation Map of China [56] (GB18306-2015), Xiamen has a seismic fortification intensity of VII degrees, and the peak horizontal ground acceleration is 0.15 g. Historic disaster statistics in local meteorological and hydrological sectors show that Xiamen suffers from a catastrophic flood disaster about every 6 years on average, with low-lying coastal, agricultural, and old urban areas particularly vulnerable to storms and floods.

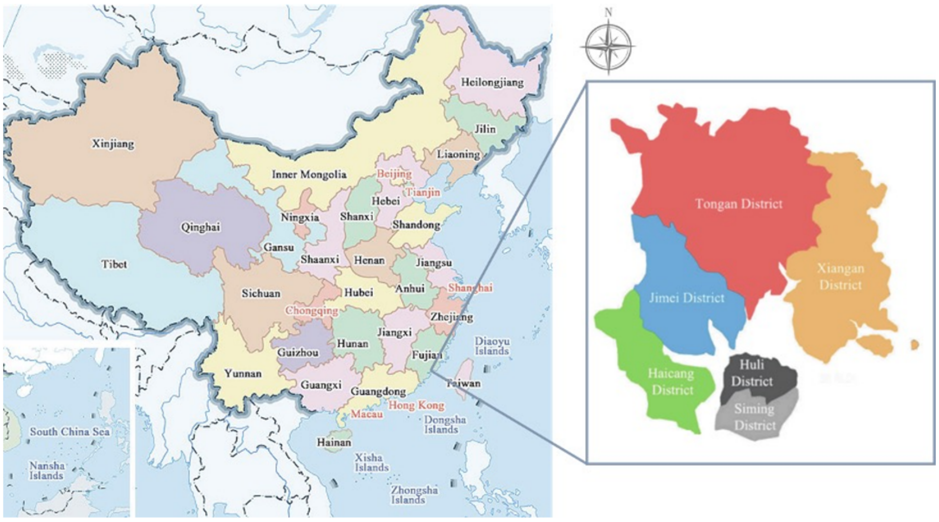

Figure 2. Map of Xiamen with geographical position of each district.

Data acquisition and database establishment are the foundations of empirical risk assessment. The evaluation unit for data collection and empirical assessment is community unit, in line with the division unit used in the Masterplan of Xiamen (2017–2035) and the Urban Comprehensive Disaster Prevention Plan (2017–2035), which is smaller than the traditional assessment scale of urban multi-hazards risk research. There are 93 community units in total, of which 17 are in Siming District, 11 in Huli District, 14 in Haicang District, 14 in Jimei District, 15 in Tong 'an District, and 22 in Xiang'an District. A multi-source urban risk database may be compiled from traditional socioeconomic data; demographic statistics; local building and infrastructure data; historic disaster statistics and emergency facilities; local DEM geographic elevation data; local river, soil, and surface vegetation data; local historical precipitation data, etc. (Table 2).

4.2. Results

4.2.1. Measurement of Disaster Probabilities and Direct Losses

According to the Seismic Ground Motion Parameters Zonation Map of China (GB18306-2015) [56], the seismic fortification intensity in Xiamen is VII degrees. We focus on the local seismic risk analysis considering the scenarios of three characteristic earthquakes, which are a frequent earthquake (a seismic intensity of VI degrees, with a probability of 63% under general site conditions in a 50-year period), an earthquake of fortification intensity (a seismic intensity of VII degrees, with a probability of 10% under general site conditions in a 50-year period), and a rare earthquake (a seismic intensity of VIII degrees, with a probability of 2% under general site conditions in a 50-year period). The possibilities of their occurrence in a one-year period are calculated through Equation (1): $\mathrm{P}(I_6) = 0.019688642$; $\mathrm{P}(I_7) = 0.002104992$; $\mathrm{P}(I_8) = 0.000403973$.

Table 2. Types and sources of data.

Type of Data	Data Source
Demographic statistics	Statistical yearbooks and economic census data of Xiamen
Socioeconomic data	
Population of each community unit	Xiamen urban design and planning institute
Building structure data	
Local disaster prevention facilities data	
Local river, soil, and vegetation surface data	
Land use data	Xiamen municipal bureau of land resources and urban planning
Administrative division boundary data	
Local DEM geographic elevation data	
Medical resources and emergency facilities	
Historical storm and flood records	Xiamen municipal meteorological and hydrological sectors
Historical precipitation data	
Data of local emergency shelters	Xiamen municipal bureau of civil air defence
Data of local civil air defence facilities	Xiamen municipal bureau of earthquake
Building and infrastructure location information	Open data from Baidu map API (Application Programming Interface) (http://lbsyun.baidu.com) (accessed on 8 August 2021)
Construction area	
Number of building floors	
Building function data	
Building age information	National meteorological science data sharing service platform (http://data.cma.cn/) (accessed on 10 September 2021)

The evaluations of direct economic loss in the three earthquake scenarios in each evaluation unit include both structural and indoor property losses with different extents of construction damages. Our measurements involve consideration and estimations of building structure types, economic damage loss ratios, replacement unit prices of main structures, building functions, cost loss ratios of indoor property, the economic development level of different areas, etc. The losses of VSL in each earthquake scenario are calculated by multiplying the expected number of deaths in each earthquake and the average loss of VSL caused by the death of residents in an earthquake (or other disasters). The value of VSL, which we use here, is CNY 4,935,500 per capita in Xiamen, according to Zhou et al.'s case study and calculation through an improved human capital method [52]. Measurements of the expected numbers of deaths in earthquakes involved population distribution and estimations of indoor population density, different extents of construction damage and building areas, etc., in each evaluation unit. The location-based seismic risk in the three characteristic earthquake scenarios is thus calculated, respectively, through Equations (3) and (4).

We choose three characteristic storms with return periods of 2 years, 5 years, and 50-years, with the strongest daily rainfall of 133.9 mm, 194.3 mm, and 335.3 mm, respectively, to help represent and analyse the local risk level of storm-driven floods. Through

Equation (2), the possibilities of their occurrence in a one-year period are: $P_2 = 0.5$; $P_5 = 0.2$; $P_{50} = 0.02$.

Based on data processing in the ArcGIS platform and the use of the SCS-CN model, we have the simulation and determination of local submergence depth and submergence range, and we obtain the corresponding disaster area in the three storm scenarios. In the function fitting stage, the values of economic flood loss records in Xiamen during 2005–2016 are collected according to Equation (3), which help figure out the values of its coefficients (Equation (13)). The expected direct economic loss of each evaluation unit is estimated through Equation (13). The location-based storm-driven flood risk in the three characteristic storms is calculated, respectively, through Equation (4).

$$L(T_j) = 45.782 * I_{rainfall}(T_j) + 7.516 * A_{submergence}(T_j) - 6520.402 \tag{13}$$

where the $L(T_j)$ denotes the direct economic loss in the storm-driven flood of return period j (unit: ten thousand CNY); $I_{rainfall}(T_j)$ denotes the strongest daily rainfall in the storm-driven flood of return period j (unit: mm); and $A_{submergence}(T_j)$ denotes the disaster area in the storm-driven flood of return period j (unit: ten thousand square metre).

4.2.2. Assessment and Distribution of the Urban Multi-Hazards Risk of Xiamen

Assuming the abovementioned annual probabilities of occurrence and values of direct loss estimated in three earthquakes and three storm-driven floods, we may then measure the multi-hazards risk in each evaluation unit, presented as the sum of all annual expected values of loss in different disasters in a one-year period (see Equation (6)). We proceed to use the natural fracture (Jenks) method to reclassify all the evaluation results of multi-hazards risk in the 93 evaluation units of Xiamen and visualise them with ArcGIS software (Figure 3).

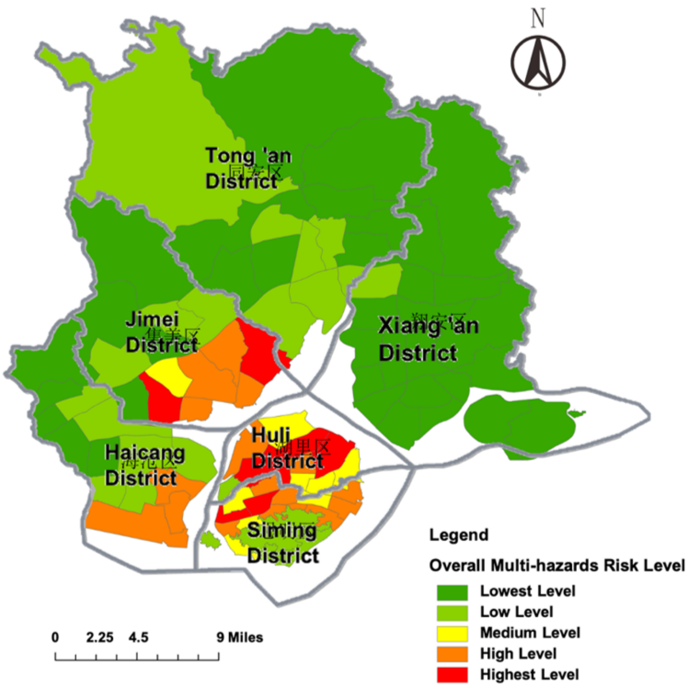

Figure 3. The multi-hazards risk distribution of Xiamen.

4.2.3. Assessment Result and Distribution of the Urban Anti-Disaster Capacity of Xiamen

The indicators in the assessment index system for urban anti-disaster capacity (Table 1) proposed in Section 3.3 are all positive indicators, meaning that the larger the index value, the larger the secondary index value, and the greater the urban anti-disaster capacity we measured. Ten experts in risk management and urban planning fields were invited to participate in our questionnaire-based survey and their scoring on the comparative importance among all the indicators was collected. After the consistency test, the scoring data of importance judgment matrix of all the experts were processed through AHP in yaahp statistical software to obtain the weights for these three subsystems and the weights for indicators in each subsystem (Figure 4).

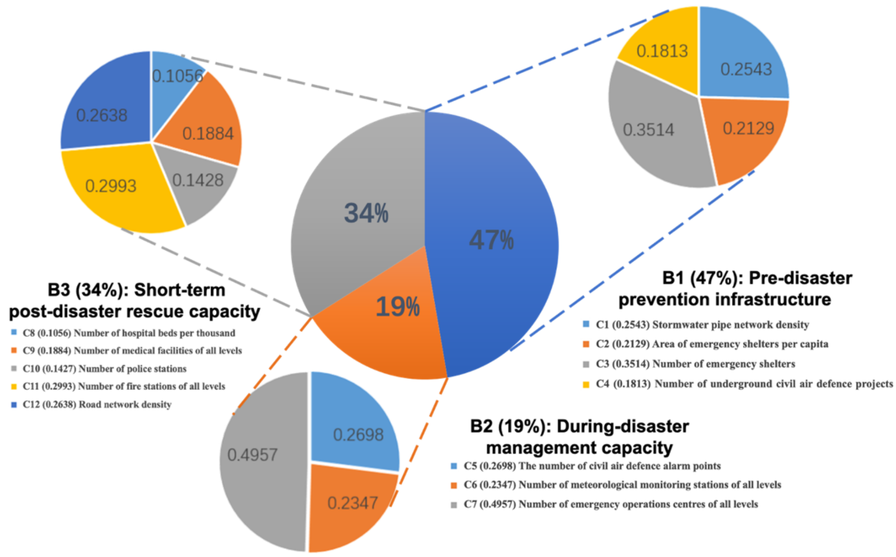

Figure 4. Diagram of weight values for subsystems and indicators in the assessment index system for urban anti-disaster capacity status.

After assessment of all 93 evaluation units in Xiamen using Equation (8), we use the natural fracture (Jenks) method to reclassify all the results of the three subsystems and visualise them with ArcGIS software (Figure 5). After assessment of all 93 evaluation units in Xiamen Equation (9), we use the natural fracture (Jenks) method to reclassify the results and visualise them with ArcGIS software (Figure 6) to illustrate the distribution status of urban anti-disaster capacity in Xiamen.

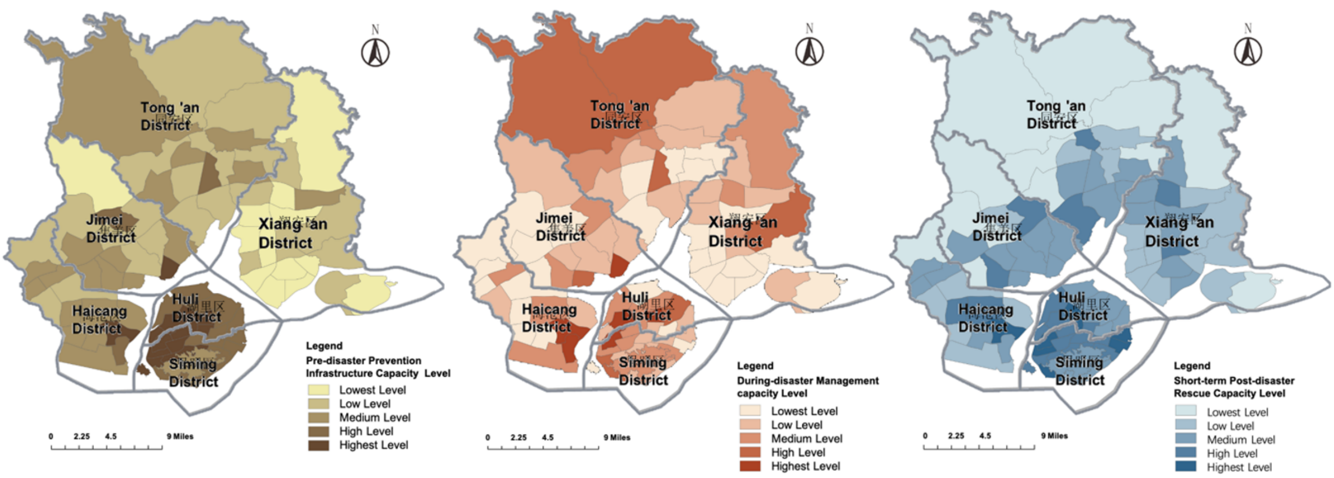

Figure 5. The evaluation results of three subsystems of urban anti-disaster capacity in Xiamen.

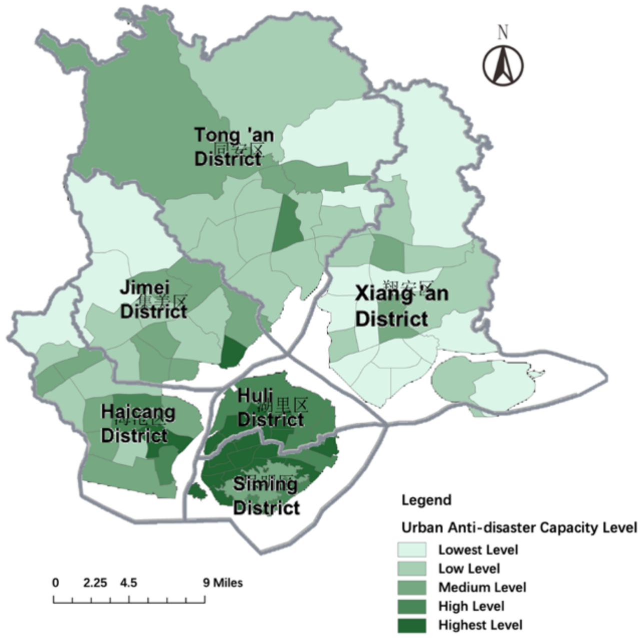

Figure 6. The evaluation results of urban anti-disaster capacity in Xiamen.

4.2.4. The Analysis of the Relative Composite Risk Index in Xiamen

Based on the above results, the relative composite risk index is calculated for all the 93 evaluation units in Xiamen through Equations (10)–(12). We then use the natural fracture (Jenks) method to reclassify the results and visualise them with ArcGIS software (Figure 7) to illustrate the distribution status of relative composite risk index in Xiamen.

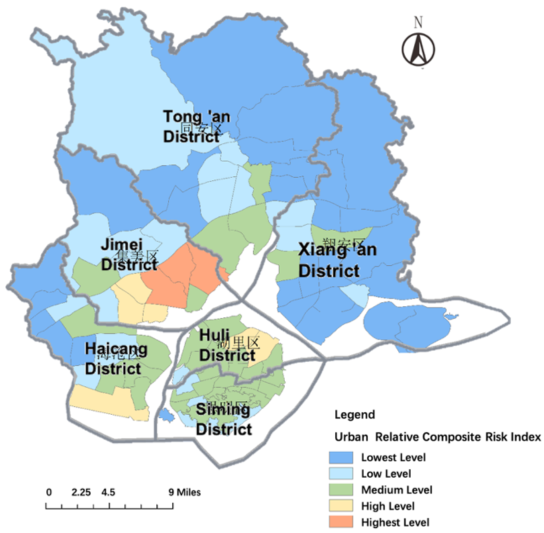

Figure 7. The evaluation results of urban relative composite risk index in Xiamen.

4.3. Planning Strategies for Disaster Risk Prevention and Mitigation

According to the above assessment results and statistics through our UMRAF (Table 3), about 1/3 of the evaluation units are in a medium relative composite risk status, which indicates a relative balance between its multi-hazards risk and its local anti-disaster capacity. Figure 7 shows most of the "safe" units of Xiamen in our assessment are in Tong'an and Xiang'an Districts, the mid- and southern parts of the main island, and the northern parts of Jimei and Haicang Districts. All three "unsafe" units are in Jimei District, and six evaluation units with high-level urban relative composite risk are in Haicang, Jimei, and Huli Districts.

Table 3. The numbers of evaluation units of urban relative composite risk at each level.

Level	Description of the Relative Composite Risk Status	Number	Percentage
Lowest	Safe, but excessive anti-disaster facilities and resources	31	33.3%
Low	Safe and comparatively adequate facilities and resources	22	23.7%
Medium	Safe, with a relative balance between multi-hazards risk and local anti-disaster capacity	31	33.3%
High	Less safe, and comparatively inadequate anti-disaster facilities and resources	6	6.5%
Highest	Unsafe with serious inadequate anti-disaster capacity	3	3.2%

The UMRAF provides results of urban multi-hazards risk analysis and anti-disaster capacity assessments as important foundations of risk management and disaster prevention and mitigation planning. Based on the comparative review of our assessment results above, we formed a strategic plan for urban comprehensive disaster-resilience improvements (Figure 8) in prioritising risk management and planning actions in the face of multi-hazards risk in specific parts of the city. This highlighted one priority comprehensive improvement area, two secondary comprehensive improvement areas, and two third-level improvement areas. In addition, our assessment results from the UMRAF platform also targeted a list of key locations for the prevention and mitigation of specific urban hazards. Detailed strategies were suggested, respectively, according to their risks and specific shortages in anti-disaster facilities and resources. The plan supports the formation and updates of the Masterplan of Xiamen (2017–2035) and the Urban Comprehensive Disaster Prevention Plan (2017–2035) for Xiamen.

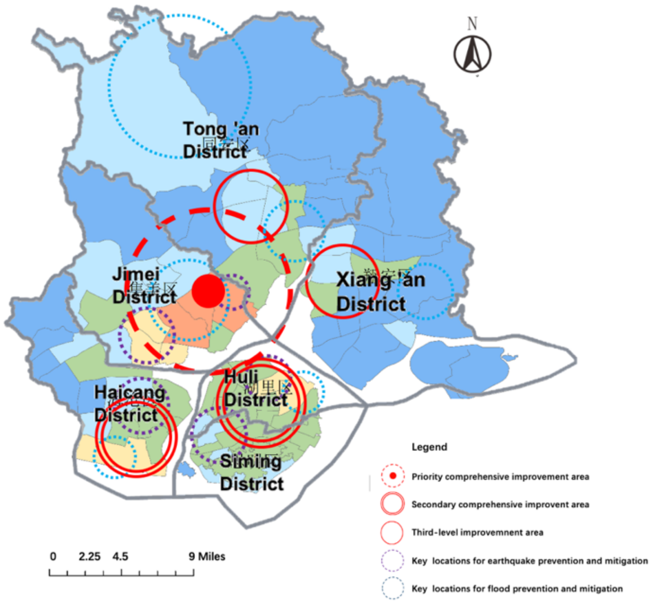

Figure 8. The strategic plan for urban comprehensive disaster-resilience improvements in Xiamen.

The whole assessment process was based on the working platform of the UMRAF in ArcGIS software, using the community unit of Xiamen as the basic management unit. We combined the dataset in our empirical research and all the evaluation results to form the urban comprehensive disaster database of Xiamen to help facilitate the tailoring of measures that can reduce risk at a local level. At a future stage, with the inclusion of more local hazard factors and the collection of more diversified data related to urban anti-disaster capacity, the contents of this database can be expanded and updated to further support the continuous examination of improvement projects and dynamic monitoring of the implementation process of Urban Comprehensive Disaster Prevention Plans.

5. Discussion

The aim of our research is to evaluate urban disaster risk according to basic components of risk. The proposed UMRAF comprehensively considers both the occurrence frequencies of disasters and their consequences (direct economic loss and loss of life) as well as the local risk response capabilities in a single assessment. It echoes the idea of Huang's theoretical model of comprehensive risk assessment of natural disasters [6] and theoretically involves the differences in frequencies and consequences between diverse hazards, as well as the impacts of local anti-disaster capabilities and facilities. Compared with previous multi-hazard risk assessment studies [30–44], our perspective of annual expected direct loss attempts to avoid the disadvantage of being unable to consider the differences in frequency and consequences of disasters when evaluating different disasters in one region at the same time. Relative to traditional disaster risk assessment models [27,28] and frameworks [45–48], our approaches are more adaptive for urban planning purposes with spatial characteristics of facilities.

The case study in Xiamen has verified the feasibility of the proposed approaches in the UMRAF. As an alternative and comprehensive approach to the assessment of urban multi-hazards disaster risk, the UMRAF has the following key features:

1. It provides new place-based model for risk evaluation with a very legible structure to conceptualise urban disaster risk from an economic point of view. It is derived from the basic component of risk, which is the probability of consequences. Calculating the annual expected direct loss makes it easier to measure and compare levels of risks. The use of annual expected direct loss is applicable in all kinds of evaluation units, ranging from regional scales to municipal and community. Although in theory this multi-hazards risk can reasonably represent all disaster risks, it still follows the laws of "the greater the intensity, the lower the probability of occurrence", without bias or underestimation of any single disaster.
2. It offers cross-disciplinary risk evaluation model that involves assessments of not only the vulnerability of urban populations, properties, and infrastructures, but also the consideration of local anti-disaster capability. It further recognises that loss of life is as important as economic disaster loss in the disaster risk assessment. More kinds of consequences are involved from the perspective of disaster loss than from the disaster system. Several professional theories and proven methods in environmental economics, engineering, and disaster science are integrated into and applied in our study.
3. It presents comprehensive risk assessment that provides effective planning and improvement guidance for urban disaster prevention and mitigation facilities and emergency management resources. The UMRAF is a dynamic framework adaptive for comprehensive urban disaster risk management. The amount and types of urban disasters and the selection of urban anti-disaster capability are both flexible to suit local needs and data availability. The construction of a local disaster database will provide continuous monitoring and long-term guidance for local disaster prevention and mitigation.

Given the uncertain occurrence of natural disasters, the higher the urban anti-disaster capacity of a city, the better the sustainability and resilience. Assessment of disaster risk itself cannot reduce the threat from disasters, but the comprehensive consideration and pre-assessment of multi-hazards risk and local anti-disaster capability are able to provide a scientific basis for governments to formulate relief policies, to make disaster prevention and mitigation plans, and to implement insurance policies and other risk management strategies. However, the economic and social costs of supporting facilities and services should not be ignored in order to unilaterally pursue excessive protection infrastructure, perfect preparation, and quick response to disasters. It is necessary to determine a proper balance between the multi-hazards risk and anti-disaster capacity status of a place at the planning and decision making stage. Therefore, the proposed UMRAF makes sense in looking for the weak points of disaster prevention works, optimising the anti-disaster facilities and resources in specific areas and aiming for a proper balance between local disaster risk and risk response.

When the values of urban overall disaster risk and urban anti-disaster capacity for a place are at the same level at a location, it is recognised that there is neither shortage nor surplus of local anti-disaster resources. Our examination of the proper balance between them (relative composite risk index analysis) is helpful in identifying and monitoring the actual urban risk distribution across the city. In practical terms, it is more feasible to involve only two or three local common disasters using our UMRAF. Based on the measurements of single-disaster risks, overall disaster risk, anti-disaster capability, and relative composite risk index, a local basic database for disaster prevention and mitigation can be constructed to provide a long-term normalised management and dynamic monitoring platform for the future spatial optimisation of urban disaster prevention and risk management strategies.

6. Conclusions

This paper studies the developments in urban disaster risk assessment, and in particular reviews the relevant theories and literature. Standing at the intersection of risk management and disaster system theory and at the forefront of the interdisciplinary field of catastrophology, economics, and urban infrastructure planning, our proposed framework expands the coverage of comprehensive urban disaster risk assessment. It is a cross-disciplinary study of risk assessment that broadens the disaster risk literature and provides a place-based model for measuring urban multi-hazards risk from an economic point of view by drawing on relevant definitions and methods in the literature on risk management, property evaluation, value of statistical life, and disaster system theory.

The proposed UMRAF attempts to provide an alternative approach to the understanding, measurement, and presentation of comprehensive urban disaster risk, i.e., different from methods in traditional disaster system theory. The UMRAF includes a place-based model for measuring urban multi-hazards risk, an indicator-system-based method for urban anti-disaster capacity examination, and following analysis of a local relative composite risk index. Similar to traditional urban disaster risk assessment methods, this framework helps determine possible scopes and degrees of negative consequences. The major differences are that both consequences and probabilities of occurrences of different disasters and disaster intensities are incorporated in our assessment. It also innovatively contains the loss of value of life resulting from disasters in the city within the annual expected direct loss assessment.

Our empirical study in Xiamen verifies the feasibility of proposed approaches in the UMRAF and shows that the UMRAF has the potential to provide city planners and policy makers with visual guidance in prioritising risk management and planning actions in the face of multi-hazards risk in specific parts of the city. Importantly, the UMRAF integrates existing methods of urban natural disaster loss measurement and risk analysis. As for its mechanism such a new approach is applied to place-based urban disaster risk analysis and management. In summary, it provides a reference quantitative research model for practical urban multi-hazards risk, supporting urban disaster prevention and response strategies.

We note certain limitations of this framework: (1) although disaster impacts are often long-lasting, our assessment does not include the value loss of indirect and long-term impacts of disasters in our assessment due to their complex composition, and (2) the provided urban anti-disaster capacity assessment index system is still not perfect, so it may be adjusted or supplemented in accordance with local situations in other practices. Future studies will focus on involving the long-term local impacts of disasters and the capability of public health security systems in the assessment framework. In addition, we are attempting to incorporate more technologies to analyse the expected direct loss of different disasters, especially common urban disasters, and some studies will include a case study to enrich our framework with more empirical evidence to improve the assessment index system for urban anti-disaster capacity.

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References

1. Johnson, K.; Depietri, Y.; Breil, M. Multi-hazard risk assessment of two Hong Kong districts. *Int. J. Disaster Risk Reduct.* **2016**, *19*, 311–323. [CrossRef]
2. Varnes, D.J. Landslide hazard zonation: A review of principles and practice. *Nat. Hazards* **1984**, *3*, 63. [CrossRef]
3. Riddell, G.A.; Delden, H.V.; Maier, H.R.; Zecchin, A.C. Exploratory scenario analysis for disaster risk reduction: Considering alternative pathways in disaster risk assessment. *Int. J. Disaster Risk Reduct.* **2019**, *39*, 101230. [CrossRef]
4. Marin, G.; Modica, M.; Paleari, S.; Zoboli, R. Assessing disaster risk by integrating natural and socio-economic dimensions: A decision-support tool. *Socio-Econ. Plan. Sci.* **2021**, *77*, 101032. [CrossRef]
5. Kappes, M.S.; Keiler, M.; Elverfeldt, K.V.; Glade, T. Challenges of dealing with multi-hazard risk: A review. *Nat. Hazards* **2012**, *64*, 1925–1958. [CrossRef]
6. Huang, C. A basic model of comprehensive risk assessment. *J. Appl. Basic Sci. Eng.* **2008**, *16*, 371–381.
7. Wu, L.; He, D.; Hong, W.; Ji, Z.; You, W.; Zhao, L. Research progress on risk assessment and vulnerability of natural disasters. *J. Catastrophology* **2014**, *29*, 129–135.
8. Liu, Y.; Lu, C.; Yang, X.; Wang, Z.; Liu, B. Fine-scale coastal storm surge disaster vulnerability and risk assessment model: A case study of Laizhou Bay, China. *Remote Sens.* **2020**, *12*, 1301. [CrossRef]
9. Mileti, D. *Disasters by Design: A Reassessment of Natural Hazards in the United States*; Joseph Henry Press: Washington, DC, USA, 1999. [CrossRef]
10. Okada, N.; Tatano, H.; Hagihara, Y. *Integrated Research on Methological Development of Urban Diagnosis for Risk and its Applications*; Annual Report of the Disaster Prevention Research Institute; Kyoto University: Kyoto, Japan, 2003; pp. 1–8.
11. Merz, B.; Kreibich, H.; Thieken, A.; Schmidtke, R. Estimation uncertainty of direct monetary flood damage to buildings. *Nat. Hazards Earth Syst. Sci.* **2004**, *4*, 153–163. [CrossRef]
12. Ge, Q.; Zou, M.; Zheng, J. *Preliminary Study on Comprehensive Assessment of Natural Disaster Risk in China*; Science Press: Beijing, China, 2008.
13. Yin, Z.; Xu, S.; Yin, J.; Wang, J. Small-scale urban rainstorm waterlogging disaster scenario simulation and risk assessment. *Acta Geogr. Sin.* **2010**, *65*, 553–562.
14. Kazmierczak, A.; Cavan, G. Surface water flooding risk to urban communities: Analysis of vulnerability, hazard and exposure. *Landsc. Urban Plan.* **2011**, *103*, 185–197. [CrossRef]
15. IPCC. *Climate Change: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2014.
16. Pagliacci, F.; Russo, M. Multi-hazard, exposure and vulnerability in Italian municipalities. In *Resilience and Urban Disasters*; Borsekova, K., Nijkamp, P., Eds.; Edward Elgar Publishing: Cheltenham, UK, 2019; pp. 175–198.
17. Davidson, R.A.; Shah, H.C. *An Urban Earthquake Disaster Risk Index*; The John A. Blume Earthquake Engineering Center, Department of Civil and Environmental Engineering Stanford University: Stanford, CA, USA, 1997.
18. Bollin, C.; Cárdenas, C.; Hahn, H.; Vatsa, K.S. *Disaster Risk Management by Communities and Local Governments*; IDB Publications: Washington, DC, USA, 2003.
19. Ntajal, J.; Lamptey, B.L.; Mahamadou, I.B.; Nyarko, B.K. Flood disaster risk mapping in the lower mono river basin in togo, West Africa. *Int. J. Disaster Risk Reduct.* **2017**, *23*, 93–103. [CrossRef]
20. Zhang, J.; Okada, K.; Dona, Y. Integrated natural disaster risk management. *Urban Disaster Reduct.* **2005**, *2*, 2–5.
21. Cutter, S.L.; Ash, K.D.; Emrich, C.T. The geographies of community disaster resilience. *Glob. Environ. Chang.* **2014**, *29*, 65–77. [CrossRef]

22. Guo, E.; Zhang, J.; Ren, X.; Zhang, Q.; Sun, Z. Integrated risk assessment of flood disaster based on improved set pair analysis and the variable fuzzy set theory in central Liaoning Province, China. *Nat. Hazards* **2014**, *74*, 947–965. [CrossRef]
23. Tanaka, Y. Psychological dimensions of risk assessment: Risk perception and risk communication. *Prog. Nucl. Energy* **1997**, *32*, 243–253. [CrossRef]
24. Yang, Y.; Zhang, L.; Huang, B.; Li, M. The evaluation index system of city disaster emergency capability since and its empirical study. *Urban Dev. Res.* **2010**, *17*, 118–124.
25. Kellens, W. *Analysis, Perception and Communication of Coastal Flood Risks: Examining Objective and Subjective risk Assessment = Analyse, Perceptie en Communicatie van Overstromingsrisico's in Kustgebieden: Onderzoek naar Objectieve en Subjectieve Risicobeoordeling*; Ghent University, Faculty of Sciences: Ghent, Belgium, 2011.
26. Salman, A.M.; Li, Y. Flood risk assessment, future trend modeling, and risk communication: A review of ongoing research. *Nat. Hazards Rev.* **2018**, *19*, 04018011.1–04018011.21. [CrossRef]
27. Feng, H.; Zhang, F.; Dai, S. Research on the method system of disaster risk assessment for comprehensive disaster prevention planning. *Mod. Urban Res.* **2017**, *32*, 93–98.
28. Yan, Q.; Meng, J.; Kang, Y. Research progress on risk analysis and assessment of urban natural disasters based on disaster prevention planning. *Geogr. Geogr. Inf. Sci.* **2011**, *27*, 78–83.
29. Barría, P.; Cruzat, M.L.; Cienfuegos, R.; Gironás, J.; Escauriaza, C.; Bonilla, C.; Moris, R.; Ledezma, C.; Guerra, M.; Rodríguez, R.; et al. From Multi-Risk Evaluation to Resilience Planning: The Case of Central Chilean Coastal Cities. *Water* **2019**, *11*, 572. [CrossRef]
30. Dilley, M.; Mundial, B. *Natural Disaster Hotspots: A Global Risk Analysis*; World Bank, Hazard Management Unit: Washington, DC, USA, 2005.
31. Gai, C.; Weng, W.; Yuan, H. Multi-disaster coupled comprehensive risk assessment based on GIS. *J. Tsinghua Univ. Nat. Sci.* **2011**, *51*, 627–631.
32. Wang, H.Y.; Xue, H. Compilation of county level comprehensive risk zoning Map of natural disasters: A case study of Luanxian County. *J. Nat. Disasters* **2013**, *3*, 84–90.
33. Bernal, G.A.; Salgado-Gálvez, M.A.; Zuloaga, D.; Tristancho, J.; González, D.; Cardona, O. Integration of Probabilistic and Multi-Hazard Risk Assessment within Urban Development Planning and Emergency Preparedness and Response: Application to Manizales, Colombia. *Int. J. Disaster Risk Sci.* **2017**, *8*, 270–283. [CrossRef]
34. Carreño, M.L.; Cardona, O.; Barbat, A.H.; Suarez, D.C.; Perez, M.D.P.; Narvaez, L. Holistic Disaster Risk Evaluation for the Urban Risk Management Plan of Manizales, Colombia. *Int. J. Disaster Risk Sci.* **2017**, *8*, 258–269. [CrossRef]
35. Xue, Y.; Chen, B.; Huang, C.; Yan, J. Soft hierarchical model for multi-disaster comprehensive risk assessment. *Prog. Geogr.* **2012**, *31*, 353–360.
36. Yang, J.; Wang, L.; Xu, G. Fuzzy comprehensive evaluation of comprehensive disaster risk in Chongqing. *Earth Environ.* **2014**, *42*, 252–259.
37. Westen, C.V.; Kappes, M.S.; Luna, B.Q. *Medium-Scale Multi-Hazard Risk Assessment of Gravitational Processes*; Springer: Dordrecht, The Netherlands, 2014.
38. Araya-Munoz, D.; Metzger, M.J.; Stuart, N.; Wilson, A.M.W.; Carvajal, D. A spatial fuzzy logic approach to urban multi-hazard impact assessment in conception, Chile. *Sci. Total Environ.* **2017**, *576*, 508–519. [CrossRef]
39. Shome, P.; Afroj, S. Local Level multi-hazards mapping for natural and manmade hazards: A case study of Chittagong Division. *J. Environ. Eng. Its Scope* **2019**, *2*, 1–9. [CrossRef]
40. Li, S.; Yang, S.; Liu, X. Multi-disaster spatial-temporal network modeling for non-process: A case study of drought-heatwave coupling in Beijing-Tianjin-Hebei region. *Geogr. Res.* **2017**, *8*, 1415–1427.
41. Wang, W.; Zhang, K.; Chen, Y. Multi-disaster coupled comprehensive risk assessment in Shennongjia forest area based on GIS. *Hubei Agric. Sci.* **2018**, *57*, 49–54.
42. Lu, Y. Apreliminary study on coupled risk assessment of multiple disasters in coastal cities. *J. Catastrophol.* **2015**, *30*, 211–216.
43. Kappes, M.S.; Keiler, M.; Glade, T. From Single- to Multi-Hazard Risk analyses: A concept addressing emerging challenges. In *Mountains Risks: Bringing Science to Society (International Conference)*; Malet, J., Glade, T., Casagli, N., Eds.; CERG Editions: Strassbourg, Germany, 2010; pp. 351–356.
44. Liu, A.; Wu, C. Research on disaster chain risk assessment method based on complex network. *Syst. Eng. Theory Pract.* **2015**, *35*, 7–13.
45. FEMA; NIBS. *Earthquake Loss Estimation Methodology-HAZUS97, Technical Manual*; Federal Emergency Management Agency: Washington, DC, USA, 1997.
46. Schneider, P.J.; Schauer, B.A. HAZUS—Its Development and Its Future. *Nat. Hazards Rev.* **2007**, *7*, 40–44. [CrossRef]
47. Jaiswal, K.S.; Wald, D.J.; Earle, P.S.; Porter, K.A.; Hearne, M. *Earthquake Casualty Models within the USGS Prompt Assessment of Global Earthquakes for Response (PAGER) System*; Springer: Dordrecht, The Netherlands, 2011.
48. Chen, H.F. HAZ-China Earthquake Disaster Loss Evaluation System Design and Preliminary Implementation. Doctoral Dissertation, Institute of Engineering Mechanics, Beijing, China, 2012.
49. Charles, F. The Value of Life. *Harv. Law Rev.* **1969**, *82*, 1415–1437.
50. Schelling, T.C. The Life You Save May Be Your Own. In *Problems in Public Expenditure and Analysis*; Chase, S.B., Ed.; Brookings Institution: Washington, DC, USA, 1968.

51. Aldy, V.J.E. The value of a statistical life: A critical review of market estimates throughout the world. *J. Risk Uncertain.* **2003**, *27*, 5–76.
52. Zhou, S.; Zhai, G.; Shi, Y.; Lu, Y. Urban Seismic Risk Assessment by Integrating Direct Economic Loss and Loss of Statistical Life: An Empirical Study in Xiamen, China. *Int. J. Environ. Res. Public Health* **2020**, *17*, 8154. [CrossRef]
53. UNDRO. *Mitigating Natural Disaster Phenomenal Effecys and Options: A Manual for Policy Makers and Planners*; UN Publications: New York, NY, USA, 1991.
54. Cornell, C.A. Engineering seismic risk analysis. *Bull. Seismol. Soc. Am.* **1968**, *58*, 1583–1606. [CrossRef]
55. Gao, M. Probability model of earthquake intensity based on Poisson distribution. *China Earthq.* **1996**, *2*, 91–97.
56. *GB18306-2015*; Seismic Ground Motion Parameter Zonation Map of China. Standards Press of China: Beijing, China, 2015.
57. *GB/T24335-2009*; Chinese Code of Classification of Earthquake Damage to Buildings. Standards Press of China: Beijing, China, 2009.
58. *GB/T18208.4-2011*; Post-Earthquake Field Works-Part 4: Assessment of Direct Seismological Loss. Standards Press of China: Beijing, China, 2011.
59. Mishra, S.K.; Singh, V.P. Soil conservation service curve number (scs-cn) methodology. *Water Sci. Technol. Libr.* **2007**, *22*, 355–362.
60. Liu, X.; Li, J. Application of SCS model in estimation of runoff from small watershed in loess plateau of China. *Chin. Geogr. Sci.* **2008**, *18*, 7. [CrossRef]
61. Turner, B.; Kasperson, R.E.; Matson, P.A.; Mccarthy, J.J.; Schiller, A. A framework for vulnerability analysis in sustainability science. *Proc. Natl. Acad. Sci. USA* **2003**, *100*, 8074–8079. [CrossRef] [PubMed]
62. Zhou, B.; Zhou, J.; Zhou, X.; Yang, Y. Quantitative Analysis of Comprehensive Ability of Urban Disaster Prevention and Mitigation. *J. Disaster Prev. Sci. Technol. Inst.* **2010**, *9*, 104–112.
63. Duzgun, H.; Yucemen, M.S.; Kalaycioglu, H.S.; Celik, K.; Kemec, S.; Ertugay, K. An integrated earthquake vulnerability assessment framework for urban areas. *Nat. Hazards* **2011**, *59*, 917–947. [CrossRef]
64. Weis, S.W.M.; Agostini, V.N.; Roth, L.M.; Gilmer, B.; Schill, S.R.; Knowles, J.E. Assessing vulnerability: An integrated approach for mapping adaptive capacity, sensitivity, and exposure. *Clim. Chang.* **2016**, *136*, 615–629. [CrossRef]
65. *GB50011-2010*; Chinese Code for Seismic Design of Buildings. China Academy of Building Research. Standards Press of China: Beijing, China, 2010.