Proceedings Paper:

Liu, B, Siu, YL orcid.org/0000-0003-3585-5861, Mitchell, GN orcid.org/0000-0003-0093-4519 et al. (1 more author) (2012) Multi-Hazard Risk Assessment: A Comparative Evaluation of Alternative Approaches. In: IDRiM. From surprise to rationality: Managing unprecedented large-scale disasters. Third Conference of the International Society for Integrated Disaster Risk Management (IDRiM), 07-09 Sep 2012, Beijing Normal University, Beijing, China,. . (Unpublished)

Multi-Hazard Risk Assessment: A Comparative Evaluation of Alternative Approaches

Baoyin Liu[1], Yim Ling Siu[1], Gordon Mitchell[2,] Wei Xu[3,4]

1. School of Earth and Environment, Leeds University, Leeds, LS2 9JT, UK
2. School of Geography and water@leeds, Leeds University, Leeds, LS2 9JT, UK
3. State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, Beijing 100875, China
4. Academy of Disaster Reduction and Emergency Management, Ministry of Civil Affairs and Ministry of Education, Beijing 100875, China

Abstract: Natural hazard risk assessments predominantly focus on individual rather than multiple hazards. Recent years have seen greater attention given to the theory and methods of multi-hazard risk assessment (MHRA), but there is no widely agreed definition of MHRA and no clear routes for overcoming the problems associated with existing multi-hazard risk assessment approaches. We begin to address these knowledge gaps by comparing two frequently used but very different MHRA methods – risk index and mathematical statistics methods. The risk index method computes MH risk from risk factors (hazard, vulnerability, exposure), while the mathematical statistics method integrates historical time-series data to calculate MH risk. These methods were applied within the context of China's Yangtze River Delta Region, comprising 85 million people in 140 administrative units. The analysis illustrates the inconsistency of existing MHRA methods. For example, the Zhabei and Hongkou districts rank 2nd and 4th respectively, in terms of MH risk, according to the risk index method, but 132nd and 131st using the mathematical statistics method. In addition, neither method is able to account for interaction between different hazards, such as those observed in the 2011 Tohoku earthquake in Japan, and the subsequent tsunami and nuclear power station meltdown at Fukushima Daiichi. A refined MHRA model based on scenario simulation is therefore proposed and its relative merits discussed.

Keywords: Multi-hazard risk assessment; risk index; mathematical statistics; scenario simulation

1. Introduction

The impacts of one hazardous event are often exacerbated by interaction with other hazards (e.g. the 2011 Tohoku earthquake which led to a tsunami and subsequently the Fukushima Daiichi nuclear disaster), whilst some hazards occur one after another in quick succession without an evident common cause, for example in China's Yangtze River Delta flooding may be caused by a typhoon, and by monsoonal (i.e. non-typhoon) rainfall from June to August each year. The short time period between events may reduce disaster resilience and recovery, and hence is indicative of greater risk than when events are considered individually. The problem is that by investigating single hazards in isolation to each other, the overall natural risks for these areas may be underestimated. To avoid this pitfall, more attention should be paid to multi-hazard risk assessment (MHRA).

Many studies have been carried out examining the theory and methods of MHRA (Armonia, 2006; Di Mauro et al., 2006; Marzocchi et al., 2009). Generally speaking, MHRA is based on single-hazard risk assessment; the main advantage of MHRA is that it puts different types of hazards into a single system for a joint evaluation. In principle, it takes into account the characteristics of each hazardous event (e.g. probability, frequency, intensity/magnitude), and their mutual interactions and interrelations. The aim of MHRA is to have a holistic view of the total effects or impacts by assessing and mapping the expected loss, due to the occurrence of various natural hazards, on the social, environmental and economic settings in a given area (Dilley et al., 2005; Armonia, 2006).

Broadly speaking, two main approaches to MHRA have been developed. These are: 1) a focus on multiple hazards which affect a given area through the development of a synthetic indicator; and 2) assessment of the integrated losses for a given period of time using statistical methods. MHRA methods are thus an extension of existing methods applied in assessment of single hazards. There are no MHRA studies that compare analysis of risk using these two approaches for the same area. Therefore, a comparison between these two methods is conducted to gain insights into the utility of the MHRA methods and their relative advantages and limitations.

This paper compares the risk index and mathematical statistics methods (definition and methodology), and then applies them to the Yangtze River Delta to analyze differences, including data needs and results. After discussing possible reasons for differences in results, the relative merits of these two methods are summarized, and a refined MRHA model is proposed.

2. Definition and formula of risk

In risk index method, risk is defined as the probability of loss caused by the interaction between the vulnerability of exposure and the hazard. The risk expression mostly quotes the indexes of hazard, exposure and vulnerability (ISDR, 2004):

$$\text{Risk} = \text{Hazard x Exposure x Vulnerability} \qquad (1)$$

In equation 1, hazard means potentially damaging physical events which could occur in a study area; exposure means elements (e.g. people, crops, infrastructure) which expose to that hazard; vulnerability means the intrinsic characteristics of those elements that makes them more or less susceptible to adverse impact.

The mathematical statistics method describes risk according to the probability of occurrence of an event and the severity it has toward human life, property and the environment, which could be expressed by the cross product of the probability and the probable consequence (IUGS, 1997):

$$\text{Risk} = \text{Probability x Consequence} \qquad (2)$$

In equation 2, probability represents the probability of occurrence of hazard; consequence represents the magnitude of impact caused on realization of the hazard. Hence, the risk index method helps to understand the disaster formation mechanism and the contribution of hazard, vulnerability and exposure to overall risk (which is often referred to “risk formation approach” in the risk literature); while the statistics method expresses risk as probabilistic loss, and can be used to predict and evaluate future disaster losses.

3. Methodology

3.1 Risk index method

This method calculates a risk index with reference to the disaster formation approach (equation 1). Selection of component indicators for hazard, vulnerability and exposure, and calculation of associated weights are key steps in the risk index approach. The process is similar to that for an individual hazard, but in MHRA all single hazard risks are aggregated in a unified risk index. Some methods (Category 1 below) first aggregate all the single hazards in a multi-hazard index and then calculate multi-hazard risk considering vulnerability and exposure. Others (Category 2 below) calculate single hazard risk considering exposure and vulnerability for all hazards and then aggregate these risks to determine multi-hazard risk.

Category 1: This approach analyzes the hazard, vulnerability and exposure to obtain the respective multi-hazard, vulnerability and exposure indices. The multi-hazard risk index is then calculated by summation (Munich Re 2003; Schmidt-Thomé et al. 2003; Fleischhauer et al. 2005; Schmidt-Thomé 2006a; Schmidt-Thomé 2006b; SCEMDOAG 2006). It can be expressed as:

$$R = f\left(\sum_{i=1}^{n} H_i, \sum_{i=1}^{n} V_i, \sum_{i=1}^{n} E_i\right) \tag{3}$$

Where: R is Multi-hazard risk; H_i is Hazard; V_i is Vulnerability and E_i is Exposure.

The Calculation of the Total Place Vulnerability Index in the State of South Carolina, USA (SCEMDOAG, 2006) used this method to calculate a multi-hazard index, aggregating all hazards with equal weight. An urban multi-hazard risk analysis using Geographic Information System (GIS) and remote sensing for Kohima Town, India (Khatsu and Van Westen, 2005) used ArcGIS software[1] to overlay equal weighted, single hazard maps to generate a multi-hazard map. These methods do not fully reflect the spatial variability in various impacts of different hazards in an area. The Natural Hazard Index for Mega-cities (Munich Re, 2003) used average annual losses and probable maximum loss as indicators for hazard analysis (in a ratio of 80:20 for each relevant hazard), but the key problem here is that the probable maximum loss for very infrequent catastrophes is unknown. The ESPON multi-hazard approach (Schmidt-Thomé et al., 2003; Fleischhauer et al., 2005; Schmidt-Thomé, 2006a; Schmidt-Thomé, 2006b) used the Delphi method to decide weights for each hazard. Delphi analysis draws on collective wisdom and absorbs useful ideas, which is assumed to make the result more accurate, but the process is relatively complicated and protracted, which makes it difficult to apply widely. Furthermore, results obtained by Delphi analysis may vary according to experience of participants involved (i.e. familiarity bias), and are sensitive to any events that occur during the deliberative process (availability bias).

Category 2: In this approach, each hazard risk index is first assessed individually for a given area.

---

[1] ArcGIS is proprietary software produced by Esri. It is a computer suite consisting of a group of geographic information system (GIS) software for working with geographic information and maps. For details, see the Esri website (http:// http://www.esri.com/software/arcgis).

Weights are then assigned to each individual hazard risk and summation is used to derive the multi-hazard risk index (Wood et al. 2003; JRC 2004; Bell and Glade 2004; Dilley et al. 2005; Arnold et al. 2006; Sales et al. 2007; Wang et al. 2008; Wipulanusat et al. 2009). This approach is depicted as:

$$R = \sum_{i=1}^{n} f\,(H_i, V_i, E_i) \tag{4}$$

Where: R is Multi-hazard risk; H_i is Hazard; V_i is Vulnerability and E_i is Exposure.

Most applications in this category calculate multi-hazard risk by aggregating single hazard risk using ArcGis or other GIS software. Examples include the European Commission's Joint Research Centre (JRC)[2]–Multi-risk Approach (Wood et al., 2003; JRC, 2004; Sales et al., 2007), a Multi-Hazard Analysis in the village of Bíldudalur, Iceland (Bell and Glade, 2004), the World Bank's methodology for Natural Disaster Hotspot analysis (Dilley et al., 2005; Arnold et al., 2006), the DDRM multi-risk approach (Fleischhauer, 2005; Armonia, 2006), and a Multi-hazard risk assessment using GIS and remote sensing in the Pak Phanang Basin, Thailand (Wipulanusat et al., 2009). These methods suffer the same drawback of the Category 1 methods, in that the multi-hazard risk index is calculated by aggregating all single hazard risks with equal weight, which does not adequately reflect the various impacts of different hazards present in the same area.

Whilst both categories of methods have helped to develop the practice of MHRA and can be used to better compare the *relative* degree of danger between different areas, most applications utilize hazard, vulnerability and exposure to assess the final multi-hazard risk without considering probabilities and exceedence probabilities, and thus these methods cannot reflect the real risk situation in the study areas. Although the tools are useful in a relative sense for synthetic indicator, they are less helpful in an absolute sense for determining integrated losses.

3.2 Mathematical statistics method

The mathematical statistics method is based upon analysis of past natural disasters. Through analysis of the relationship between the probability of an event, and the magnitude of the consequences of that event, an exceedence probability-loss curve can be built. Such curves are used to predict and evaluate future disaster risk.

The basic model for the mathematical statistics method is shown in equation 2 above, and the associated loss curve in Figure 1. Loss here is the loss (damage) associated with the disaster, EP(L) is the exceedence probability for the corresponding loss. Both parametric and nonparametric methods are used to derive probabilities.

Figure 1. Exceedence probability-loss curve

---

[2] The European Commission's Joint Research Centre comprises seven scientific institutes in which the Institute for Environment and Sustainability (IES) has developed harmonized EU-wide methodologies and information systems for the prevention and prediction of weather-driven natural hazards in order to optimize the support and exchange expertise on risk reduction and management.

Parametric method: The mathematical theory in this method supposes that disaster losses follow a known distribution function. Data on historical losses are used to estimate the distribution function parameters, and then the probability distribution can be calculated using these parameters. In this distribution curve, occurrence sequences of disaster can be depicted as $F(X, u_1, u_2, u_3)$, with u_1, u_2, u_3 being the distribution parameters. Through random sampling $X_1, X_2, X_3 \dots X_n$ in the X with n sample, distribution parameters $u_i = R(X_1, X_2, X_3 \dots X_n)$ can be calculated, and then the probability of different disaster losses can be calculated by the distribution curve. Grünthal et al. (2006) built exceedence probability-mean wind speed curves for windstorm risk assessment using Schmidt and Gumbel distributions (Gumbel, 1958). Stedinger et al. (1992) estimated the parameters by the method of moments for Gumbel type Ⅰ, Pearson type Ⅲ, Weibull and Lognormal, and Grünthal et al. (2006) used these distributions to build exceedence probability-discharge curves for flood risk assessment.

Because the factors that contribute to natural disasters are complex, there is sometimes a lack of historical data, and sample size is too small. These make it difficult to assume a probability distribution function that reflects the real situation for parameter estimation, and hence an alternative method is needed.

Nonparametric method: The nonparametric method mainly includes histogram density estimation, kernel density estimation and information diffusion to derive probability estimates. Histogram density estimation first draws a histogram and curve according to varying degrees of disaster, then based on the curve type, adopts a moving average (using exponential smoothing or other methods) to analyze historical loss data. A mathematical statistics model can then be built to reflect the functional relationship between disaster degree and frequency. However, the results obtained with this method are crude and are influenced greatly by the interval choice. In order to overcome the disadvantages of histogram density estimation, Rosenblatt (1956) and Parzen (1962) proposed the use of kernel density estimation, which can be used to estimate the probability density function of arbitrary shapes. Kernel density estimates are closely related to histograms, but can be endowed with properties such as smoothness or continuity by using a suitable kernel. Let $(x_1, x_2, \dots, x_n)$ be a sample drawn from some distribution with an unknown density f. Its kernel density estimator is depicted as:

$$\tilde{f}_h(\mathrm{x}) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{x - x_i}{h}\right) \tag{5}$$

Where $K(\bullet)$ is the kernel function, and $h > 0$ is a smoothing parameter called the bandwidth. However, the key problem of how to choose an appropriate smoothing parameter still remains. The information diffusion method was introduced by Huang (1997) to overcome this problem, and using this method can improve the accuracy of natural disaster risk assessment. Let losses $(u_1, u_2, \dots, u_n)$ be a sample, T_i is the real losses in each disaster, the probability distribution can be calculated as:

$$f_i(u_j) = \frac{1}{h\sqrt{2\pi}}\exp\left[-\frac{(T_i - u_j)^2}{2h^2}\right] \quad (i = 1, 2 \cdots m;\ j = 1, 2 \cdots n) \tag{6}$$

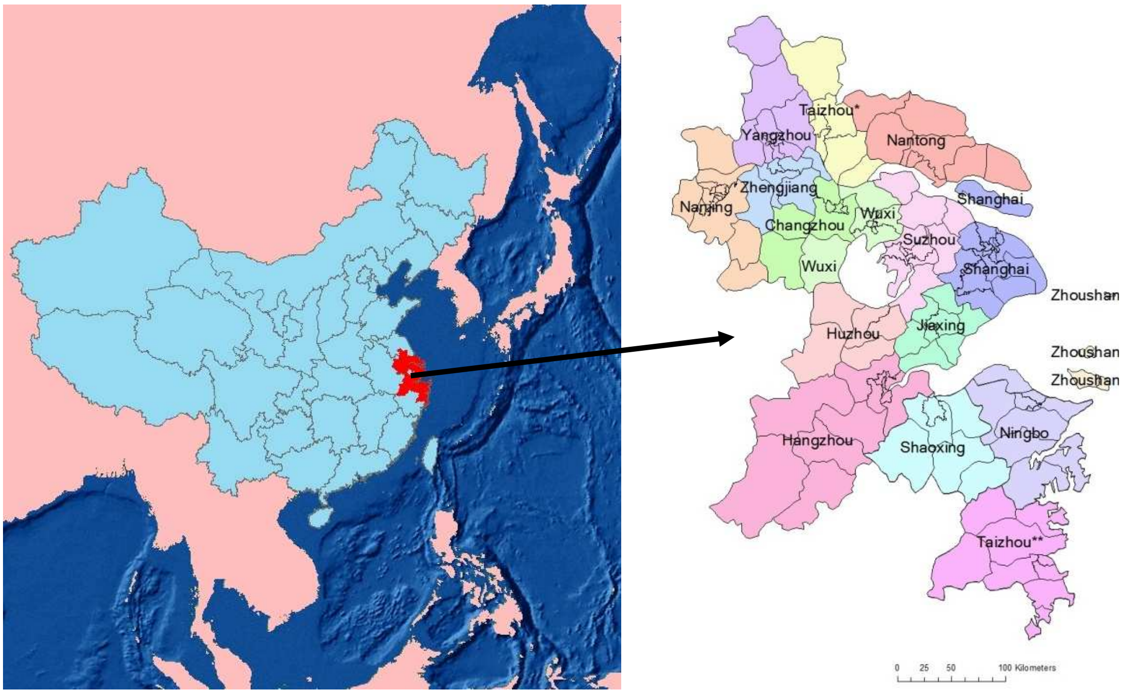
h is the diffusion coefficient，which can be decided by maximum b, minimum a of the samples and sample number m. Information diffusion method can use sample data to assess natural disaster risk. Huang (2000) showed that this method is about 28% more efficient than histogram density estimation.

The mathematical statistics method using historical data biasing the calculation towards expected loss, and gives more consideration on the probability of occurrence, but exposure and vulnerability are neglected to some extent.

4. Case study of the Yangtze River Delta

4.1 Case study region

The Yangtze River Delta (Figure 2), located in the central part of the eastern coastal area of China, comprises 140 counties including those in the southern Jiangsu and northern Zhejiang provinces, and includes 16 major cities, of which the largest is Shanghai. With an area of 99,600 km^2 (1% of the country area) and a population of about 85 million (6.5% of the country population), the area contributes 17.8% of Gross Domestic Product (GDP), 22% of financial revenue, and 34.8% of export trade, making it one of the country’s main economic regions. According to historical data, in China, 16% of all typhoons that occurred between 1950 and 2010 made landfall in this region, and nearly 30% influenced the region. The region was hit by catastrophic floods in 1991 and 1999, which cause direct economic losses of 11 and 14.1 billion Yuan respectively.



(Taizhou is in Jiangsu Province, Taizhou** is in Zhejiang province.)*

Figure 1. The Yangtze River Delta

With both population density and economic activity growing, this already vulnerable region is becoming increasingly susceptible to natural disasters. This growing vulnerability, combined with occurrence of several different natural hazards, makes the area a suitable region in which to research multi-hazard risk appraisal.

4.2 Research data and methods

4.2.1 Data

The comparative analysis of the two HRA approaches is conducted for the Yangtze River Delta region, using the data shown in Table 1. Historical disaster data is needed by both methods, whilst the risk index method requires more detailed socioeconomic data, which has been available only since 2006.

Table 1. Data for MHRA in the Yangtze River Delta

Method	Data	Index	Statistical unit	Time interval	Source
Risk index method	Socioeconomic data	Population size, gender ratio, age structure, traffic condition, telecommunication facilities and medical condition	County level	2006	Statistical Yearbook

	Historical disaster data	Number of disaster	County level	1950-2000	Meteorological Department and Civil Administration Department
		Deaths caused by disaster	Total area	1950-2000	
Mathematical statistics method	Socioeconomic data	Population size	City level	1950-2010	Statistical Yearbook
	Historical disaster data	Deaths caused by disaster	City level	1950-2010	Meteorological Department and Civil Administration Department
		Population affected by disaster[3]	County level	1990-2010	

4.2.2 Methods

Risk index method: The multi-hazard index was the sum of each hazard value multiplied by its weight, which was calculated according to the average historical death toll caused by this hazard. Gender ratio, age structure, traffic condition, telecommunication facilities and medical condition were selected to calculate the vulnerability index with the help of the entropy method. The exposure index was represented by the population density. Multi-hazard risk index to human life was then calculated by aggregating the multi-hazard index, the vulnerability index and the exposure index. Finally, the multi-hazard risk index map of human life was developed (Liu and Xu, 2012).

Mathematical statistics method: The multi-hazard risk on human life was assessed based on information diffusion. The probability distribution of single-hazard loss was calculated based on historical loss data (1950-2010). These single-hazard losses were aggregated to integrated losses, and the exceedence probability calculated based on the probability distribution of a single-hazard. Finally, exceedence probability-loss curve and maps of multi-hazard risk on human life with different exceeding probability were developed with the help of ArcGIS software (Liu, 2011).

These two methods both can be expanded to evaluate the risk of more than two hazards and exposures. Compared to the mathematical statistics method, the risk index method is simple and easy to apply. Though mathematical statistics method requires less data than the risk index method, updating the required data is more difficult than the risk index method, as the exceedence probability-loss curve must be rebuilt with each update.

4.3 Results

The multi-hazard risk index map (Figure 3) shows that high-risk index areas are mainly found in Minhang, Putuo, Zhabei, Huangpu, Yangpu, Hongkou, Baoshan, Changning in Shanghai city and Wenling in Taizhou** city. Minhang, Putuo, Zhabei, Huangpu, Yangpu, Hongkou, Baoshan, Changning rank as high risk areas due to a high exposure index value (high population density) and high hazard index value (mainly flood hazard). The risk index value of Wenling is also large due to high typhoon hazard and vulnerability index values though the exposure index value is very small. Low-risk index

---

[3] Multi-hazard risk was assessed at city level in 2011. In this research, deaths in each county were calculated through dividing the deaths in the city level with a certain weight, which is decided by population affected by flood and typhoon in each county from 2001 to 2010

areas are mainly found in the north-western part of the region and some counties in Hangzhou southwest.

In the map of multi-hazard risk to human life, with 10 year, 20 year and 50 year return periods, the death level distribution are basically identical (Liu, 2011), so here a risk map using a 20 years return period was chosen for comparison. Because the results of integrated losses are expressed as deaths per million people, the population size of each county in 2006 were input into to calculate the possible deaths in this year caused by multi-hazard with 20 years return period (Figure 4). Note that in this map, Ninghai, Cixi and Jinzhou in Ningbo, Fuyang in Hangzhou, Baoying in Changzhou are at high risk level and counties in Shanghai are at a low level.

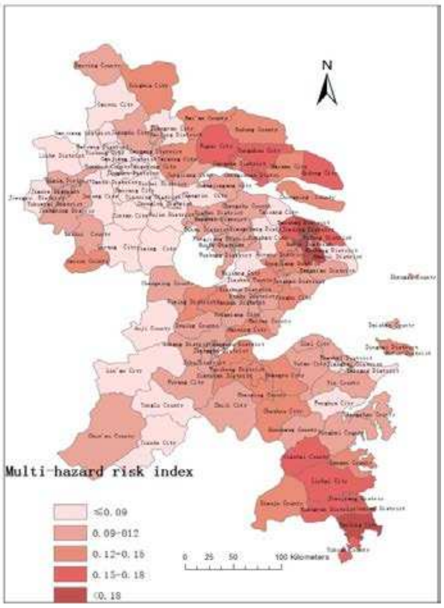


Figure 3. Multi-hazard risk index

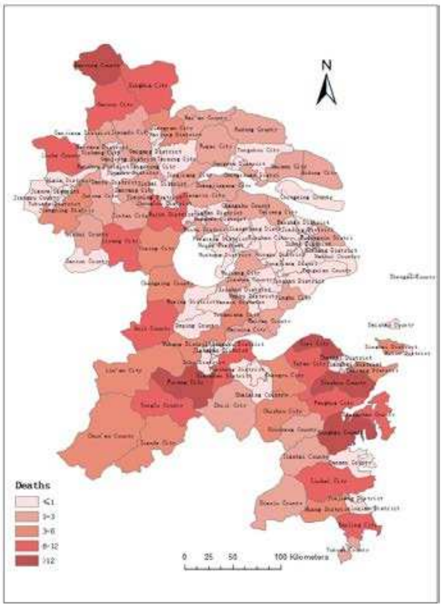


Figure 4. Multi-hazard risk with 20 years return period in 2006

Because the results obtained in the risk index method are a synthetic indicator (unit less index), and in the mathematical statistics method results are integrated losses (deaths), they cannot be compare directly. Therefore, spearman correlation was used to calculate the rank-order correlation of counties for the two multi-hazard risk approaches.

As shown in Tables 2 and 3, the top 10 and bottom 10 countries in synthetic indicator and integrated losses are totally different. For example, the Zhabei and Hongkou rank 2nd and 4th respectively in the synthetic indicator risk index method, but 132nd and 131st in integrated losses using the mathematical statistics method. Spearman rank correlation coefficient is -0.14, so there is no correlation between them.

Table 2. Highest MH risk counties

Rank	Synthetic indicator	Integrated losses
1	Yangpu	Ninghai
2	**Zhabei**	Fuyang
3	Huangpu	Cixi
4	**Hongkou**	Jinzhou
5	**Putuo**	Baoying
6	Minhang	Fenghua
7	**Changning**	Xiaoshan
8	Wenling	Yuyao
9	Baoshan	Linhai
10	Yuhuan	Wenling

Table 3. Lowest MH risk counties

Rank	Synthetic indicator	Integrated losses
131	Pukou	**Hongkou**
132	Linan	**Zhabei**
133	Anji	**Changning**
134	Dantu	Luwan
135	Jingkou	Jingan
136	Danyang	**Putuo**
137	Jiangyan	Tongzhou
138	Runzhou	Pingjiang
139	Kunshan	Qinhuai
140	Yizheng	Jinqu

5. Discussion

5.1 Comparative performance

The results obtained by these two methods are totally different and have no correlation. The possible reasons for the difference are:

1) In multi-hazard risk index assessment, the vulnerability and exposure indexes were built with data for 2006 only, so results may not reflect the danger degree in exposure and vulnerability. Integrated loss assessment used historical loss data from 1950-2010, but it cannot consider the vulnerability situation. Exposure value and vulnerability change every year as the population grows and the economy develops. A high vulnerability value in 2006 can make a county rank high in the synthetic indicator, but in other years this county may have a low vulnerability, which make it have few disaster loss records, lead to a low rank in integrated losses.

2) In the multi-hazard risk index assessment, risk is calculated as a product of hazard, vulnerability and exposure. The great difference in population density (exposure index) leads to results only on the basis of exposure index, e.g. population density in Huangpu is 48 501 people per km^2, which is nearly 500 times bigger than Chunan with 102 people per km^2. .

3) Mathematical statistics method on loss assessment ignores the influence of extreme events (where return periods are significantly greater than the time period represented in the sample of observed data). Including more extreme events in the sample can make probability of exceedence higher and influence the shape of the probability distribution curve, e.g. counties in Ningbo are at high risk in the 20 year return period map, because the Ningbo region experienced a particularly devastating typhoon in 1956, causing many deaths, and this rare event is included in the generative data.

5.2 Relative merits of the two methods

Despite the results being very different, it cannot be concluded that one method is wrong or that neither is correct, because they have a different focus. The advantages and disadvantages of these two methods are summarized in Table 4. The synthetic indicator mainly uses the risk index method, which analyzes risk considering the disaster formation mechanism, and emphasizes relative risk by considering more fully the exposure and vulnerability; however it ignores risk probability, with results obtained used to compare the relative danger between different areas, but with no reflection of the real risk situation in these areas. Integrated losses in a given time mainly relies on the mathematical statistics method to calculate possible losses (e.g. economic loss, mortality) caused by multiple natural hazards in a given region and time period. Mathematical statistics bias the calculation towards the expected loss and the corresponding probability, but exposure and vulnerability is neglected to some extent. Thus, there is a need for developing a method which can combine the advantages of these two methods.

Table 4. Advantages and disadvantages of risk index and mathematical statistical methods

	Risk index method	Mathematical statistical method
Advantages	• Considers the disaster formation mechanism. • Helps to understand the contribution of hazard, vulnerability and exposure to overall risk. • Better compares the relative danger between different areas • Simple to operate	• Calculates the possible loss • Calculates exceedence probability for risk
Disadvantages	• Cannot calculate probability of the risk • Weight problem is not resolved • Neglects interaction between different hazards	• Neglects vulnerability and exposure • Potentially biased by extreme events • Data update is complex • Neglects interaction between different hazards

5.3 Scenario simulation

Disaster scenarios can be simulated using a MH risk model built to take advantage of the merits of both the risk index and mathematical statistics methods. The risk index helps to analyze the disaster formation process, and the mathematical statistics method to estimate the possibility of loss. Using these two methods, after making clearly how natural hazards influence an area, simulation models can be built which simulate scenarios about some hazardous events of different magnitude and probability of hazard occur to assess overall risk.

The basic framework of scenario simulation models is: 1) identify the exposure distribution in the study area; 2) identify the influence range of some hazards with different magnitude; 3) simulate scenarios about how these hazards influence the study area and identify the affected exposures; and 4) calculate losses in different scenarios combing with the vulnerability of exposures.

Scenario simulation has become a common approach in natural disaster risk assessment. GIS and multi-agent, neural network, cellular automata and other complex system simulation modeling have been used within scenario simulation to simulate the disaster development process under human disturbance, and to assess disaster risk dynamically with risk visualization. FEMA (2004) input national baseline data, inventory data, hazard maps and expert adjustment analysis parameters into their HAZUS-MH software, and then used scenario simulation to analyze various impacts (e.g. physical damage, economic loss, social impact) of flood, earthquake, hurricane. Riskcity, a GIS-based training package, developed by United Nations University – ITC School (UNU-ITC) uses GIS software to analyze different types of hazards, create an exposures database, assess vulnerability, and estimate annual loss for earthquakes, landslides, floods, and technological hazards (Van Westen, 2008). RiskScape, a software model developed by the Research Organizations GNS Science and the National Institute of Water and Atmospheric Research Ltd. (NIWA) in New Zealand can be used to calculate damage ratio and absolute loss from different natural hazards and for various exposures based on GIS (Schmidt et al. 2011).

Such models greatly enhance disaster risk analysis precision and offer an important basis to reveal the cause of disasters, assist emergency rescue, simulate and formulate emergency control plan. However, though FEMA, Riskcity and RiskScape are named multi-hazard risk, they only calculate loss caused by a single-hazard without aggregation to integrated loss. In addition, they all neglect the interactions and interrelations between different hazards, e.g. one hazard may occur repeatedly in time; different hazards may independently occur in same place; different (or same) hazards may occur dependently in same place. There is therefore a need to develop an improved model of integrated loss for use in MHRA simulation.

5.4 A conceptual model for MRHA

Although existing scenario simulation models could take advantage of the merits of both risk index and mathematical statistics methods, in practice, they neglect the interaction between different hazards. In order to address this problem, we propose a conceptual model which can address the possible loss caused by multiple hazards, with an explicit consideration of interaction between different hazards. Its basic framework is shown in Figure 5. The key steps of this approach are as follows:

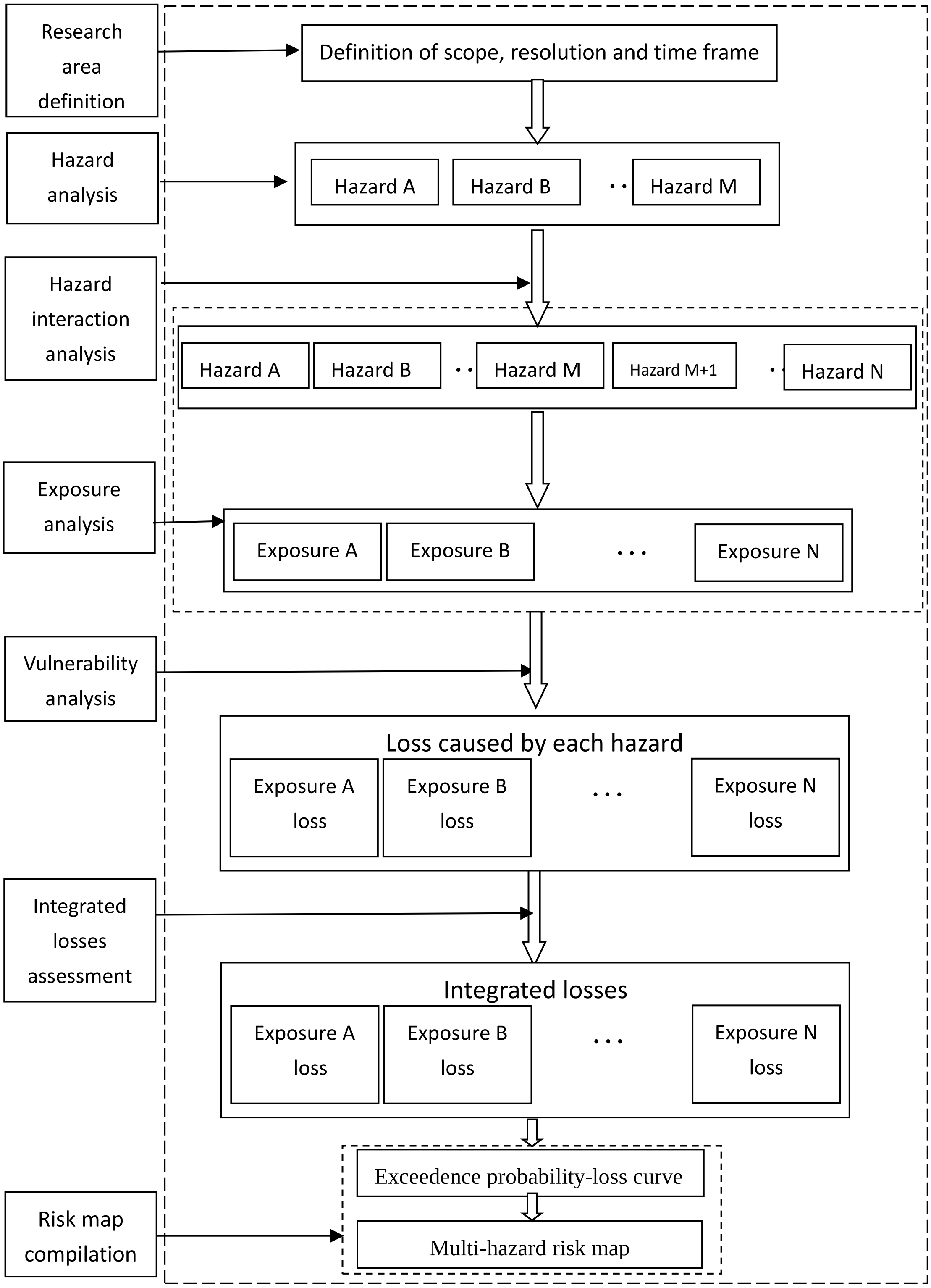


Fig 5. A conceptual model for MHRA

1) Define the assessment spatial scope (e.g. world, district, local), resolution (e.g. grids, administrative district) and time frame (e.g. year, month, season) according to the request of stakeholders.

2) Multiple hazards will be assumed to occur during the research time frame. Identify the spatio-temporal extent of these hazards in the study region, and analyze the relationship between intensity and probability of occurrence for each hazard.

3) Based on hazard interaction analysis, e.g. event tree analysis (Marzocchi et al., 2009), and 'disaster chain' analysis (Shi, 1991), identify what derivatives hazards can be induced by these assumed hazards and calculate the probability of occurrence for each derivatives hazard.

4) Identify and analyze the spatial and temporal distribution of exposures which affected by these hazards in research area.

5) Input all hazard data and affected exposure data into this part. The exposure loss caused by each hazard can be calculated through vulnerability analysis, e.g. vulnerability curve (Penning-Rowsell and Chatterton, 1977).

6) Aggregate all losses caused by single hazard together to calculate the integrated losses. The aggregation process needs to consider the ‘exacerbation function’ (e.g. damage caused by one disaster can be made worse than expected due to a lack of recovery from a prior event), and avoid repetitive computation (e.g. some exposures have been totally destroyed by one disaster, but the exposure database cannot update immediately, so these totally destroyed exposures are still used to calculate loss caused by other disasters).

7) Simulate all possible scenarios and calculate the corresponding losses. Then the exceedence probability-loss curve and multi-hazard risk maps with different multi-hazard return period can be drawn with the probability of multiple hazards occurrence and the corresponding integrated losses.

Compared to existing methods, this model will not only calculate the exceedence probability of multi-hazard risk, but also analyze the relevant relationships between different hazards.

6. Conclusion

MHRA is used to assess the excepted loss caused by multiple hazards in a given area. It takes into account the characteristics of each hazardous event, and their mutual interactions and interrelations. The risk index and mathematical statistics methods both have certain drawbacks in MHRA. The synthetic indicator of multiple hazards affecting a given area mainly uses the risk index method, which analyzes risk considering the disaster formation mechanism, and emphasizes relative risk by considering more fully the exposure and vulnerability, but it ignores risk probability. The results obtained are used to compare the relative danger between different areas, but do not reflect the real risk situation. Integrated losses in a given time mainly relies on the mathematical statistic method to calculate possible losses (e.g. economic loss, mortality) caused by multiple nature hazards in a given region and time period. Methods using mathematical statistics bias the calculation towards the expected loss, and give more consideration on the probability of occurrence, but exposure and vulnerability is largely neglected.

Scenario simulation, used digital technology tools, can simulate different disaster scenarios, including the disaster formation process, so as to assess possible loss. Simulation can take advantage of the merits of both risk index and probabilistic methods, so is considered a more comprehensive method to analyze multi-hazard risk. However, existing scenario simulation models do not consider interaction between different hazards.

A relatively comprehensive MHRA conceptual model is therefore proposed. MHRA of natural hazards is focused on scenario simulation, with explicit consideration of the relationship between different hazards. This model can take advantage of the merits of both risk index and mathematical statistics methods; it not only analyzes risk considering the disaster formation mechanism from hazard, vulnerability and exposure, but also calculates the possible loss and corresponding probability in different scenarios. The relationship between different hazards will be considered in model construction, so hazard interaction must also be analyzed. How best to build these modules (e.g. hazard interaction analysis, vulnerability analysis) is the subject of ongoing research.

7. References

Armonia Project–Applied Multi-Risk Mapping of Natural Hazards for Impact Assessment, 2006. *Applied multi-risk mapping of natural hazards for impact assessment, Report on new methodology for multi-risk assessment and the harmonisation of different natural risk maps.* Genova (Italy): Armonia, European Community.

Arnold, M., et al., 2006. *Natural disaster hotspots case studies.* Washington, D.C.: World Bank.

Bell, R. and Glade, T., 2004. Multi-hazard analysis in natural risk assessments. In: Brebbia CA editor. *Proccedings of the 4th international conference on computer simulation in risk analysis and hazard mitigation*. Rhodes, Greece 26-29 September 2004. Southampton (UK): WIT Press.

Dilley, M., et al., 2005. *Natural disaster hotspots, a global risk analysis.* Washington, D.C.: World Bank.

Di Mauro, C., et al., 2006. Definition of multi-risk maps at regional level as management tool: experience gained by civil protection authorities of Piemonte region. In: *5th conference on risk assessment and management in the civil and industrial settlements.* Pisa, Italy 17-19 October 2006. Pisa (Italy): University of Pisa.

FEMA, 2004. *Using HAZUS-MH for Risk assessment.* [online] Available at: <http://www.fema.gov/plan/prevent/hazus/index.shtm.> [Accessed 10 October 2004].

Fleischhauer, M., 2005. *ARMONIA scientific colloquium: risk assessment and spatial planning in France.* Dortmund, Germany 4 April 2005.

Fleischhauer, M., et al., 2005. Multi-risk assessment of spatially relevant hazards in Europe. In: *International ESMG (European Safety Management Group) symposium 2005.* Nürnberg, Germany 11- 13 October 2005. Hamm (Germany): ESMG.

Grünthal. G., et al., 2006. Comparative risk assessment for the city of Cologne-storms, floods, earthquake. *Natural Hazards,* 38, pp.21-44.

Gumbel, E. J., 1958. *Statistics of Extremes.* New York: Columbia University Press.

Huang, C.F., 1997. Principle of information diffusion. *Fuzzy Sets and Systems,* 91 (1), pp.69-90.

Huang, C.F., 2000. Demonstration of benefit of information distribution for probability estimation. *Signal Process,* 80 (6), pp.1037-48.

ISDR (Intentional Strategy for Disaster Reduction), 2004. *Living with risk. A global review of disaster reduction initiatives.* Geneva: United Nations publication.

IUGS, 1997. Quantitative risk assessment for slopes and landslides—the state of the art. In: D.M. Cruden and R. Fell, eds., 1997. *Landslide risk assessment.* Rotterdam (Netherlands): Balkema.

JRC (Joint Research Centre), 2004. *European commission: annual report 2003.* Brussels: European Communities.

Khatsu, P. and Van Westen, C.J., 2005. Urban multi-hazard risk analysis using GIS and Remote Sensing: A case study from Kohima Town, Nagaland, India. In: *ACRS 2005: proceedings of the 26th Asian conference on remote sensing.* Hanoi, Vietnam 7-11 November 2005. New York: Curran Associates.

Liu, B.Y., 2011. *Multi-hazard risk assessment in the Yangtze River delta region: a case study on human life* (in Chinese). Unpublished master dissertation. Beijing Normal University.

Liu, B.Y. and Xu, W., 2012. Comprehensive multi-risk assessment of natural hazards to human life in the Yangzte River Delta region (in Chinese). *Journal of Natural Disasters*, 21(3), pp.56-63.

Marzocchi, W., et al., 2009. *Principles of multi-risk assessment. Interaction amongst natural and man-induced risks.* Brussels: European Communities.

Munich Reinsurance Company, 2003. *Topics—annual review: natural catastrophes 2002.* Munich: Munich Re Group, 2003.

Parzen, E., 1962. On estimation of a probability density function and mode. *The Annals of Mathematical Statistics*, 33(3), pp.1065-76.

Penning-Rowsell, E.C. and Chatterton, J.B., 1977. T*he benefits of flood alleviation: A manual of assessment techniques.* Hampshire (UK): Gower, Aldershot.

Rosenblatt, M., 1956. Remarks on some nonparametric estimates of a density function. *The Annals of Mathematical Statistics,* 27(3), pp.832-37.

Sales, J., Wood, M. and Jelínek, R., 2007. *Risk mapping of industrial hazards in new member states.* Ispra (Italy): European Commission, Joint Research Centre.

SCEMDOAG (South Carolina Emergency Management Division Office of the Adjutant General), 2006. *State of South Carolina hazards assessment 2005*. South Carolina (US): University of South Carolina, Hazards Research Lab, Department of Geography.

Schmidt, J., et al., 2011. Quantitative multi-risk analysis for natural hazards: a framework for multi-risk modelling. *Natural Hazards,* 58, pp.1169-92.

Schmidt-Thomé, P., et al., 2003. Development of natural hazard maps for European regions. In: *EU-MEDIN forum on disaster research "The Road to Harmonisation"*. Thessaloniki, Greece 26–27 May 2003.

Schmidt-Thomé, P. ed., 2006a.*The spatial effects and management of natural and technological hazards in Europe.* Luxembourg: European Spatial Planning and Observation Network (ESPON) project

1.3.1, Geological Survey of Finland, 2006.

Schmidt-Thomé, P. ed., 2006b. *Natural and technological hazards and risks affecting the spatial development of European regions.* Espoo (Finland): Geological Survey of Finland.

Shi, P.J., 1991. On the theory of disaster research and its practice (in Chinese). *Jounal of Nanjing University,* 11, pp.37-42.

Stedinger, J. R., Vogel, R. M., and Foufoula-Georgiou, E., 1992. Frequency analysis of extreme events. In: D. R. Maidment ed., 1992. *Handbook of Hydrology.* New York: McGraw-Hill Inc.

Van Westen, C.J., 2008. RiskCity: a training package on the use of GIS for urban multi - hazard risk assessment. In: Sassa, D. and Canuti, P. eds., *Proceedings of the First World Landslide Forum.* Tokyo, Japan 18-21 November 2008. Tokyo: United Nations University Press, pp.665-68.

Wang, J.A., et al., 2008. The regionalization of urban natural disasters in China. *Natural Hazards,* 44, pp.169-79.

Wipulanusat, W., Nakrod, S. and Prabnarong, P., 2009. Multi-hazard risk assessment using Gis and RS applications: a case study of Pak Phanang basin. *Walailak Journal of Science and Technology,* 6(1), pp.109-25.

Wood, M., Arellano, A.L.V. and Mushtaq, F., 2003. *Management of natural and technological hazards in Central and Eastern European countries (PECO), Fifth Framework Programme of Research and Technological Development.* Ispra (Italy): Joint Research Centre, European Commission.