Hazard interaction analysis for multi-hazard risk assessment: a systematic classification based on hazard-forming environment

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Abstract

This paper develops a systematic hazard interaction classification based on the geophysical environment that natural hazards arise from – the hazard-forming environment. According to their contribution to natural hazards, geophysical environmental factors in the hazard-forming environment were categorized into two types. The first are relatively stable factors which construct the precondition for the occurrence of natural hazards, whilst the second are trigger factors, which determine the frequency and magnitude of hazards. Different combinations of geophysical environmental factors induce different hazards. Based on these geophysical environmental factors for some major hazards, the stable factors are used to identify which kinds of natural hazards influence a given area, and trigger factors are used to classify the relationships between these hazards into four types: independent, mutex, parallel and series relationships. This classification helps to ensure all possible hazard interactions among different hazards are considered in multi-hazard risk assessment. This can effectively fill the gap in current multi-hazard risk assessment methods which to date only consider domino effects. In addition, based on this classification, the probability and magnitude of multiple interacting natural hazards occurring together can be calculated. Hence, the developed hazard interaction classification provides a useful tool to facilitate improved multi-hazard risk assessment.

1 Introduction

Many world regions are subject to multiple natural hazards. In these areas, the impacts of one hazardous event are often exacerbated by interaction with other hazards (Marzocchi et al., 2009). The mechanism by which these interactions occur varies, and may be a product of one event triggering another, or ‘crowding’, where events occur independently without evident common cause, but in close proximity, spatially, temporally, or both (Tarvainen et al., 2006; Carpignano et al., 2009; Marzocchi et al., 2012). Close proximity between events may reduce resilience and recovery, and hence is indicative of greater risk than for events considered in isolation. Multi-Hazard Risk Assessment (MHRA) has developed to combat the limitations of single hazard appraisal, with MHRA approaches building on those developed for single-hazard risk assessment, but additionally considering hazard interaction (Armonia, 2006; Marzocchi et al., 2009; Di Mauro et al., 2006). The existing research on hazard interaction in

MHRA mainly focuses on the domino (cascade) effect, whereby one hazardous event triggers another (e.g. a landslide induced by an earthquake, a flood induced by a storm) (Marzocchi et al., 2012; Frolova et al., 2012). Such studies analyze hazard interaction beginning with given information about the primary hazard, which triggers another or increases the probability of others occurring. Hazard matrix or event tree are the commonly used methods. For example, Kappes et al. (2010) proposed a matrix to identify the possible triggering effect within seven hazards in an alpine region, whilst Gill and Malamud (2014) analyzed 21 hazards using a hazard matrix which focuses on hazard interactions where one hazard triggers another or increases the probability of others occurring. Marzocchi et al. (2009, 2012) employed an event tree to analyze multi-hazard risk due to triggering effects in Italy; Frolova et al. (2012) identified technological accidents (fires, explosions, release of chemical materials) triggered by earthquakes according to the distribution of shaking intensity in Russia; whilst the MATRIX (New Multi-HAzard and MulTi-RIsK Assessment MethodS for Europe) project (Garcia-Aristizabal and Marzocchi, 2013) adopted event-tree and fault-tree strategies to identify the domino effects scenarios in Naples (volcanic earthquakes and seismic swarms triggered by volcanic activity), Guadeloupe (rainfall-and earthquake-triggered landslides), and Cologne (earthquake-triggered embankment/flood defense dyke failures). Eshrati et al. (2015) also proposed elaboration of event trees as a useful method to analyze the potential consequences of domino effects in more detail by simulating the possible chain of triggering events. However, the interaction between different hazards is complex and dynamic, and the domino effect is not able to cover all situations. For example, two hazards may occur independently without evident common cause, but in close proximity, spatially, temporally, or both. Hence, interaction between different natural hazards needs a systematic and comprehensive analysis to facilitate improved MHRA.

This paper therefore aims to develop a systematic hazard interaction classification based on the geophysical environment that gives rise to natural hazards. Based on this classification, all possible interactions among different hazards can be considered, and the probability and magnitude of multiple interacting natural hazards occurring together can be calculated in MHRA. Section 2 introduces a basic definition of hazard-forming environment and its contribution to natural hazard. Section 3 presents a systematic classification of hazard interactions based on hazard-forming environment analysis. Section 4 applies this classification within MHRA to test its utility, and sect. 5 introduces a case study in China's

Yangtze River Delta. Further discussion, including limitations of the approach, is presented in sect.6 before drawing a final conclusion in sect. 7.

2 Hazard-forming environment

Natural hazards are a product of geophysical processes and therefore arise from a specific geophysical environment, which includes environmental factors in the atmosphere, hydrosphere, biosphere and lithosphere. These factors are the basic conditions for the occurrence of hazards (Park, 1994; Shi, 1996; McGuire et al., 2002). Natural hazards are also extreme natural events (McGuire et al., 2002; Smith and Petley, 2009). Here, "extreme" means natural hazards are extraordinary compared to the normal natural event. The "extreme" is always caused by one or more environmental factors' substantial departure in either the positive or the negative direction from their mean value, thus flood can be induced when precipitation is above the normal level, and drought occur when it is below the normal level.

According to their contribution to natural hazard, geophysical environmental factors can be categorized into two types. Factors in the first type form the background for the occurrence of natural hazards. Here, these factors can be considered as stable factors, which are the preconditions to hazards. These factors never change or change very little over a long time (hundreds or thousands of years), e.g. tectonic plates or landform. Compared to the stable factors, factors in the second type are constantly changing, e.g. daily precipitation and temperature. Substantial changes in these factors give rise to hazard. Therefore, they can be taken as trigger factors for natural hazards and are the factors that determine the frequency and magnitude of hazards. The fundamental characteristics of natural hazards are decided by these geophysical environmental factors. Hence, geophysical environmental factors are the determining factors for natural hazards, and the geophysical environment which consists of these factors can be defined as the "hazard-forming environment". Different combinations of these geophysical environmental factors can induce different hazards. Hence hazard-forming environment analysis is useful in both hazard identification and hazard interaction analysis.

For illustrative purpose, Table 1 lists the relationship between some specific major hazards and their hazard-forming environments. These then are the geophysical environmental (stable and trigger) factors for the most common major natural hazards. They provide a basis for analyzing interactions among hazards, which we discuss next.

3 Hazard-forming environment for hazard interaction analysis

The geophysical environmental factors in the hazard-forming environment were categorized into two types, stable factors and trigger factors (discussed above). In this section, stable factors are used to identify which kinds of natural hazards influence a given area, and then a systematic classification of hazards interaction is developed to calculate the probability and magnitude of multiple interacting hazards occurring together based on trigger factors.

3.1 Stable factors for hazard identification

Hazard identification is used to identify which kinds of natural hazards influence a given area, and hence also the spatial distribution of that hazard. Stable factors act as a precondition for major natural hazards (see above) and according to their characteristics, the type of hazards influencing a given area can be deduced. For example, if a coastal city is located in a tectonically stable platform with low, flat terrain and numerous rivers, then these environmental factors determinate that slow riverine floods, coastal floods and pluvial floods could influence this city, but strong earthquakes, volcanic eruptions, landslides and avalanche are unlikely.

The susceptibility of each (geographical) assessment unit to each hazard can be calculated based on these stable factors. The relationship between stable factors and major natural hazards can be expressed as:

$$S(H_k) = f(SF_1, SF_2 \cdots SF_j)(j = 1, 2 \cdots n) \quad (1)$$

Thus, the susceptibility of each assessment unit to each hazard can be calculated as:

$$S_i(H_k) = \sum_{j=1}^{n} w_j \, Nor\left(SF_j\right)_i \quad (2)$$

Where, for any given assessment unit i:

S is susceptibility,

H is hazard,

SF is stable factors,

$S_i(H_k)$ is susceptibility to hazard k, given stable factors SF_j,

$Nor(SF_j)_i$ is the normalization of stable factor j in assessment unit i, and

w_j is the weight for stable factor j.

w_j can be calculated by one of several methods, including Principal Component Analysis

(PCA) (Cutter et al., 2000), Analytic Hierarchy Method (AHP) (Thirumalaivasan et al., 2003), and fuzzy comprehensive evaluation (Dixon, 2005).

Having calculated the susceptibility of each assessment unit to each hazard, maps can be drawn to show the spatial distribution of individual hazards, then the spatial distribution of multiple hazards obtained through aggregation.

3.2 Trigger factors for hazard analysis

Substantial changes in trigger factors are the main reason that hazards are induced, thus trigger factors can be used to estimate both the frequency and magnitude of hazards. The degree of change in trigger factors represents hazard magnitude, and the probability of change in trigger factors represents hazard probability. The relationship between trigger factors and natural hazards can thus be expressed as:

$$f(p_{ti}) = p(h_j) \tag{3}$$

Where, one trigger factor induces one hazard,

$$f(p_{ti}) = p(h_1, h_2 \cdots h_j) \tag{4}$$

Where, one trigger factor induces multiple hazards,

$$f(p_{t1}, p_{t2} \cdots p_{ti}) = p(h_j) \tag{5}$$

Where, multiple trigger factors induce one hazard, and

$$f(p_{t1}, p_{t2} \cdots p_{ti}) = p(h_1, h_2 \cdots h_j) \tag{6}$$

Where, multiple trigger factors induce multiple hazards. In these cases:

$p(h_j)$ *is* the probability of hazard j, and
p_{ti} is the probability of the change in trigger factor i.

p_{ti} can be calculated by the mathematical statistics approach to define a function to determine event magnitude and frequency. For example, Grünthal et al. (2006) calculated exceedance probability-mean wind speed curves for windstorm magnitude assessment using Schmidt and Gumbel distributions (Gumbel, 1958).

3.3 A systematic classification of hazard interactions

Hazard interaction analysis is used to calculate the probability and magnitude of multiple hazards occurring together, given different types of possible relationships. According to the trigger factors for each hazard, the relationships between different natural hazards are categorized into four types.

3.3.1 Independent relationship

In the independent relationship, the changes in trigger factors which induce hazard A are independent of that which induce hazard B. The occurrences of these two hazards are independent, e.g., the trigger factors for typhoon and earthquake are unrelated.

The relationship between these trigger factors and hazards can be expressed as:

$$f(p_{t1}, p_{t2} \cdots p_{ti}) = p(h_A) \tag{7}$$

$$f(p_{ti+1}, p_{ti+2} \cdots p_{tn}) = p(h_B) \tag{8}$$

Where, p_{ti} is the probability of the change in trigger factor *i*, and

$p(h_j)$ *is* the probability of hazard *j* occurrence.

The changes in trigger factors $t_1, t_2 \ldots t_i$ are independent of changes in trigger factors $t_{i+1}, t_{i+2} \ldots t_n$. If the changes in these trigger factors occur together, then hazard A and hazard B happen together. Hence, the probability of these two hazards occurring together can be calculated as:

$$P(A \cap B) = p(h_A) \times p(h_B) = f(p_{t1}, p_{t2} \cdots p_{ti}) \times f(p_{ti+1}, p_{ti+2} \cdots p_{tn}) \tag{9}$$

Where, p_{ti} is the probability of the change in trigger factor *i*, and

$p(h_j)$ *is* the probability of hazard *j* occurrence.

3.3.2 Mutex relationship

Here, the changes in trigger factors which induce hazard A and which induce hazard B are mutually exclusive (mutex). Thus hazard A and hazard B cannot occur together. The changes in trigger factors for these hazards can be expressed as:

$$f(p_{ti+}) = p(h_A) \tag{10}$$

$$f(p_{ti-}) = p(h_B) \tag{11}$$

Where, $_{ti+}$ represents the trigger factor *i* departure in a positive direction from its mean value,

$_{ti-}$ represents the trigger factor *i* departure in a negative direction from its mean value,

p_{ti} is the probability of the change in trigger factor *i*, and

$p(h_j)$ *is* the probability of hazard *j* occurrence.

One trigger factor cannot move in two directions simultaneously, hence, the probability of these two hazards occurring together can be expressed as:

$$P(A \cap B) = 0 \tag{12}$$

3.3.3 Parallel relationship

The changes in one or some trigger factors have the chance to induce more than one hazard A_1, $A_2 \ldots A_n$ at the same time. The relationship of hazards A_1, $A_2 \ldots A_n$ is parallel. For example, fast riverine flood and landside induced by heavy rainfall can be taken as a parallel relationship. This relationship between trigger factors and these hazards can be expressed as:

$$\begin{gathered} f(p_{t1}, p_{t2} \cdots p_{ti}) = p(h_{A_1}) \\ f(p_{t1}, p_{t2} \cdots p_{ti}) = p(h_{A_2}) \\ \cdots \\ f(p_{t1}, p_{t2} \cdots p_{ti}) = p(h_{A_n}) \end{gathered} \tag{13}$$

Where, p_{ti} is the probability of the change in trigger factor i, and

$p(h_j)$ *is* the probability of hazard j occurrence.

Hazards A_1, $A_2 \ldots\ldots A_n$ constitute a hazard group, with all hazards in the group induced by the same trigger factor(s). Hence, the frequency and magnitude of this hazard group are determined by the changes in these trigger factors. The probability of this hazard group (hazards A_1, $A_2 \ldots\ldots A_n$) occurring can be expressed as:

$$P(A_1 \cap A_2 \cdots \cap A_n) = f(p_{t1}, p_{t2} \cdots p_{ti}) \tag{14}$$

Where, p_{ti} is the probability of the change in trigger factor i, and

$p(h_j)$ *is* the probability of hazard j occurrence.

3.3.4 Series relationship

In the Series relationship, hazard A induces changes in some trigger factors, and then the changes in these trigger factors induce hazard B. This can be expressed as:

$$f(p_{t1}, p_{t2} \cdots p_{ti}) = p(h_A) \rightarrow f(p_{ti+1}, p_{ti+2} \cdots p_{tn}) = p(h_B) \tag{15}$$

Where, p_{ti} is the probability of the change of trigger factor i, and

$p(h_j)$ *is* the probability of hazard j occurrence.

The changes of trigger factors $t_1, t_2 \ldots t_i$ induce the hazard A, then hazard A causes the changes in trigger factors $t_{i+1}, t_{i+2} \ldots t_n$. The changes in trigger factors $t_{i+1}, t_{i+2} \ldots t_n$ induce hazard B.

Hence, the probability of hazard A and B occurring together can be expressed as:

$$P(A \cap B) = p(h_A) \times p(h_B) = f(p_{t1}, p_{t2} \cdots p_{ti}) \times f(p_{ti+1}, p_{ti+2} \cdots p_{tn} | h_A) = f(p_{t1}, p_{t2} \cdots p_{ti}) \times f(p_{ti+1}, p_{ti+2} \cdots p_{tn} | p_{t1}, p_{t2} \cdots p_{ti}) \quad (16)$$

Where, p_{ti} is the probability of the change of trigger factor i,

$p(h_j)$ *is* the probability of hazard j, and

$p_{tn}|h_A$ is the probability of the change of trigger factor n given the magnitude of hazard A occurrence.

This classification is useful as it helps to ensure that all possible relationships among different hazards are considered. It can effectively fill a gap in current multi-hazard methods which to date only consider domino effects. In addition, the probability and magnitude of multiple hazards with these relationships occurring together also can be calculated based on substantial changes in trigger factors, with the change of degree in them representing the magnitude of hazards, and the probability of changes in them representing the probability of hazards. In the next section, this classification is applied within multi-hazard risk assessment (MHRA) to demonstrate its utility.

4 Application in multi-hazard risk assessment

Generally, MHRA is based on single-hazard risk assessment. The main advance of MHRA is that it puts different types of hazards into a single system for joint evaluation (Armonia, 2006; Di Mauro et al., 2006; Marzocchi et al., 2009; Carpignano et al., 2009). The aim of MHRA is to have a holistic view of the total effects or impacts by assessing and mapping expected loss, due to the occurrence of various natural hazards, in the social, environmental and economic assets of a given area. In principle, it takes into account the characteristics of each hazardous event (probability, frequency, magnitude), and their mutual interactions and interrelations (e.g. one hazard may occur repeatedly in time; different hazards may occur independently in the same place; different hazards may occur dependently in the same place) (Kappes et al., 2012; Marzocchi et al., 2012). Figure 1 lists a basic framework of MHRA (Bell and Glade, 2004; Di Mauro et al., 2006; Marzocchi et al., 2009; Carpignano et al., 2009; Schmidt et al., 2011). There are five main components: 1) hazard identification: identify which natural hazards influence a given area; 2) hazard interaction analysis: calculate the probability and magnitude of multiple hazards occurring together; 3) exposure analysis: identify the elements exposed to these hazards; 4) vulnerability analysis: calculate the possible loss for the exposure, under conditions caused by multiples hazards of varying magnitude; and 5) Multi-hazard risk curve/map: draw a curve/map based on the probability of multiple hazards and the corresponding loss.

Magnitude refers to the strength or force of the hazard event, with magnitude measured using different units, depending on the hazard. This make it is hard to directly compare the magnitude of different hazards, therefore, in vulnerability analysis, most MHRA approaches calculate the loss in each hazard individually, with the same vulnerability, and these losses are summed to obtain the total loss. However, in reality, vulnerability may vary according to prior events. Hence, the final results obtained in these approaches cannot reflect the real loss situation.

In the proposed classification scheme, four types of interaction are identified: independent, mutex, parallel and series relationships. All possible hazard interactions can be considered in this classification scheme, and the frequency and magnitude of these multiple interacting hazards occurring together can be measured using the relevant trigger factors (Fig. 2). (Mutex is not shown, as by definition, these hazards cannot occur together).

In Fig. 2a, hazard A and hazard B are an independent relationship. The changes in trigger factors $t_1, t_2... t_i$ which induce hazard A are independent of the changes in trigger factors $t_{i+1}, t_{i+2}... t_n$ which induce hazard B. These trigger factors can be taken as a trigger factor group ($t_1, t_2... t_i, t_{i+1}, t_{i+2}... t_n$) to measure the frequency and magnitude of hazard A and B occurring together.

In Fig. 2b, hazards A_1, A_2…A_n represent a parallel relationship. Hazards A_1, A_2…A_n are all induced by the changes in the same trigger factors $t_1, t_2... t_i$. The frequency and magnitude of this hazard group (A_1, A_2…A_n) are determined by the changes in these trigger factors. Hence, the trigger factor group ($t_1, t_2... t_i$) is chosen to measure the frequency and magnitude of hazard group (A_1, A_2…A_n).

In Fig. 2c, hazard A and hazard B represent the series relationship. The changes in trigger factors $t_1, t_2... t_i$ induce hazard A, then the hazard A induces the changes in trigger factors $t_{i+1},t_{i+2}... t_n$. The changes in trigger factors $t_{i+1}, t_{i+2}... t_n$ induce hazard B. Here, the trigger factor group ($t_1, t_2... t_i$) is chosen to represent the magnitude of hazard A, and the trigger factor group ($t_{i+1}, t_{i+2}... t_n$) is chosen to represent the magnitude of hazard B. The probability and degree of the changes in the trigger factor group ($t_{i+1}, t_{i+2}... t_n$) are determined by the magnitude of hazard A, that is, the changes in the trigger factor group ($t_1, t_2 \ldots t_i$). Hence, these two trigger factor groups combine in a new trigger factor group ($t_1, t_2 \ldots t_i, t_{i+1}, t_{i+2} \ldots t_n | t_1, t_2 \ldots t_i$) to measure the frequency and magnitude of hazard A and B occurring together.

As shown in Fig. 2, the frequency and magnitude of multiple hazards occurring together can be measured by the relevant trigger factor group in the hazard interaction analysis. Therefore, in vulnerability analysis, the multiple interacting hazards can be treated as a multiple hazards group with the change of degree in the relevant trigger factor group representing the magnitude, and the relevant vulnerability corresponding to this whole group rather than the component single hazards. In this way, the results obtained are more reliable. In next section, we apply this classification scheme within a MHRA model to estimate potential loss caused by multiple hazards in China's Yangtze River Delta (YRD).

5 A case study in China's Yangtze River Delta

5.1 Hazard identification

The Yangtze River Delta (YRD), facing the Pacific to the east, is a major floodplain characterised by low, flat terrain and numerous rivers, lakes and canals. It is highly prone to a range of natural hazards. Due to the abundant rainfall and high channel density, the whole YRD is liable to frequent riverine floods. The YRD is coastal and an oceanic landform between Eurasia and the Pacific, so the coastal areas are also susceptible to typhoons and coastal floods. The northern plain areas, below an average altitude of 200 metres, are vulnerable to pluvial floods, whilst the southern hilly areas are subject to landslides and fast riverine floods. The YRD is located in a relatively stable geological platform, so highly destructive earthquakes (over magnitude 6) are unlikely. Given these characteristics, our case study focuses on typhoon, flood (slow riverine flood, fast riverine flood, coastal flood and pluvial flood) and landslide.

Given the stable factors shown in Table 1, the susceptibility of each county (the geographical unit of analysis within the YRD) to each hazard can be calculated based on Eq. (2). According to the types of hazards in each county, the whole YRD area is divided into four zones (Fig. 3). Counties in zone I are susceptible to three kinds of hazards, typhoon, slow riverine flood and pluvial flood. Counties in zone II are susceptible to four kinds of hazards, typhoon, slow riverine flood, pluvial flood and coastal flood. Counties in zone III are susceptible to five kinds of hazards, typhoon, slow riverine flood, fast riverine flood, pluvial flood and landslide. Counties in zone IV are susceptible to all six natural hazards (as zone III plus coastal flood), typhoon, slow riverine flood, fast riverine flood, pluvial flood, coastal flood and landslide. This regionalization is helpful in identifying the multi-hazard situation in each county, and thus is the basis for hazard interaction analysis.

5.2 Hazard interaction analysis

Hazard interaction is analysed for each of these four zones. According to the trigger factors for YRD hazards, the relationships among multiple hazards in the YRD can then be shown (Fig. 4). Take zone I: Trigger - typhoon rainfall as an example: here, typhoon is viewed as the trigger factor, with changes of wind speed and rainfall, which induce slow riverine flood, pluvial flood and strong wind. These three hazards are in a parallel relationship and constitute a hazard group with each hazard induced by common trigger factors (wind speed and rainfall). Hence, the frequency and magnitude of this hazard group are determined by the changes in wind speed and rainfall. The exceedance probability of this hazard group (slow riverine flood, pluvial flood and strong wind) occurring with different magnitudes can be expressed as:

$$EP(Hs \cap Hp \cap Hw) = EP(wind\ speed, rainfall) \tag{17}$$

Where, H_s is slow riverine flood,

H_p is pluvial flood,

H_w is strong wind, and

EP(wind speed, rainfall) is the exceedance probability of the corresponding maximum daily rainfall and maximum daily wind speed sets, which can be calculated based on the mathematical statistics approach with maximum daily rainfall and maximum wind speed during each historical typhoon.

In the same way, the exceedance probabilities of multiple hazards in other zones also can be calculated. Thus for :

Zone I: Trigger - non-typhoon rainfall.

$$EP(Hs \cap Hp) = EP(non - typhoon\ rainfall) \tag{18}$$

Zone II: Trigger - typhoon rainfall.

$$EP(Hs \cap Hp \cap Hc \cap Hw) = EP(wind\ speed, rainfall) \tag{19}$$

Zone II: Non-typhoon rainfall as trigger factor.

$$EP(Hs \cap Hp \cap Hc) = EP(non - typhoon\ rainfall) \quad (20)$$

Zone III: Trigger - typhoon rainfall.

$$EP(Hs \cap Hp \cap Hf \cap Hl \cap Hw) = EP(wind\ speed, rainfall) \quad (21)$$

Zone III: Trigger - non-typhoon rainfall.

$$EP(Hs \cap Hp \cap Hf \cap Hl) = EP(non - typhoon\ rainfall) \quad (22)$$

Zone IV: Trigger - typhoon rainfall.

$$EP(Hs \cap Hp \cap Hc \cap Hf \cap Hl \cap Hw) = EP(wind\ speed, rainfall) \quad (23)$$

Zone IV: Trigger - non-typhoon rainfall.

$$EP(Hs \cap Hp \cap Hc \cap Hf \cap Hl) = EP(non - typhoon\ rainfall) \quad (24)$$

Where, H_s is slow riverine flood,

H_p is pluvial flood,

H_w is strong wind,

H_f is fast riverine flood,

H_c is coastal flood,

H_l is landslide,

EP(non-typhoon rainfall) is the exceedance probability of the corresponding maximum non-typhoon daily rainfall, which can be calculated based on the mathematical statistics approach with maximum daily rainfall during each historical non-typhoon rainfall, and

EP(wind speed, rainfall) is the exceedance probability of the corresponding maximum daily rainfall and maximum daily wind speed sets, which can be calculated based on the mathematical statistics approach with maximum daily rainfall and maximum wind speed during each historical typhoon.

Taking typhoon as an example, the results, as distribution of maximum daily rainfall and maximum wind speed with different exceedance probabilities, are shown in Fig. 5.

5.3 Multi-hazard risk assessment

The hazard interaction analysis is then applied within the MHRA. Here, the YRD being struck by two consecutive typhoons (the most common multi-hazard scenario in the YRD) is taken as an example of this risk assessment. Maximum daily rainfall and maximum daily wind speed in each typhoon are selected as trigger factors to construct the set of hazard-related indicators which represent the magnitudes of multiple hazards. The first and second typhoons have an independent relationship, so based on the hazard interaction analysis in section 5.2, the MHRA framework in the four zones of the YRD can be constructed as shown in Fig.6.

With respect to losses, this case study takes the economic loss as an example, with GDP in 2013 selected as the exposure indicator. The vulnerability-related indicators selected were: the number of mobile phone users per 10,000 people, doctors per 10,000 people, population density, GDP per km^2, number of medical institutions per km^2, percentage of population age >15 and < 65, percentage of male residents, and percentage employed (Cutter et al., 2000; Liu, 2015). Based on the historical loss data form 1980 to 2012, the loss distribution influenced by typhoons with different exceedance probabilities is then calculated, with results shown in Fig. 7.

6 Discussion

6.1 Contribution to multi-hazard risk assessment

In this research, a comprehensive approach to classify hazard interactions based on analysis of the hazard-forming environment has been developed. The proposed hazard interaction classification provides a useful tool to facilitate improved MHRA. We now discuss the importance of such hazard-forming environment analysis within the wider MHRA process.

For hazard identification, historical data analysis is a commonly used method (Munich Re, 2003; UNDP, 2004). However, this method relies on extensive historical data (at least 20 years) which is often unavailable for some areas. Additionally, because hazard occurrence is a random event, historical data may not contain all the possible hazard situations, especially as some hazards have a long return period (e.g. volcanic eruption). In this research, analysis of stable factors is used, identifying hazard from environmental factors rather than past observations of hazard, and so all possible hazard situations can be considered, even if some hazards have long return periods. Thus, stable factor analysis helps to fill a significant gap in existing hazard identification as hazard records may not reflect all possible hazard situations due to their long return period. In addition, compared to historical hazard data, most data for stable factors are easy to collect, e.g. river basins, landform. Hence, stable factors for hazard identification also can be used to solve the data problems of existing methods.

In hazard interaction, relationships among hazards were systematized for the first time in the MHRA research field, based on trigger factors analysis. A four class hazard interaction categorization was developed: independent, mutex, parallel and series relationships. The application of this categorization ensures that all possible relationships among different hazards are considered in the MHRA. Thus, trigger factors analysis can effectively fill the gap in existing methods which to date only consider domino effects.

With respect to vulnerability analysis, we know that some hazards may hit a given area consecutively over a short period. A short interval between such hazards means that recovery is constrained, and hence that vulnerability is not constant for each new event. However, existing MHRA methods calculate loss for each hazard individually, assuming equal vulnerability, before then summing to obtain the final loss. Thus, the final results cannot reflect the real loss situation, where vulnerability varies according to prior events. With our approach, the frequency and magnitude of hazards occurring together can be calculated by trigger factors in the hazard interaction analysis. Therefore, in the vulnerability analysis, hazards can be treated as a multiple hazards group, with the relevant vulnerability corresponding to this group rather than the component single hazards. In this way, the results obtained are more reliable.

6.2 Limitations in hazard-forming environment analysis

Hazard-forming environment analysis provides a useful tool for MHRA. However, as the formation of some hazards is not fully understood, there are some limitations to hazard-forming environment analysis.

Firstly, according to the contribution to natural hazard, environmental factors in hazard-forming environment were categorized into two types. Factors in the first type are stable factors which form the background to the occurrence of natural hazards. These stable factors were used to identify which kinds of hazards could influence a given area and deduce the spatial distribution of these hazards. However, the occurrences of some natural hazards, such as thunderstorm or tornado, have no obvious environment characteristic. These hazards could probably happen anywhere, thus existing knowledge about the hazard-forming environment is insufficient to identify the spatial distribution of these hazards.

A second problem lies with the trigger factors. Substantial changes in trigger factors are the main reason that hazards are induced. According to the trigger factors for each hazard, the relationships between different natural hazards can be categorized, and the probability of these relationships occurring can be calculated. However, knowledge of trigger factors is incomplete, and there may still be some unknown trigger factors which could induce new relationships between natural hazards that we have not considered above.

7 Conclusion

This study has developed a systematic hazard interaction classification based on characteristics of the hazard-forming environment. According to the contribution to natural hazards, the geophysical environmental factors in the hazard-forming environment were categorized into two types, stable factors and trigger factors. Based on these geophysical environmental factors for notable major hazards, the stable factors were used to identify which types of natural hazards influence a given area, and trigger factors are used to classify the relationships between these hazards into four types: independent, mutex, parallel and series relationships.

We applied this classification within MHRA. This classification is useful as it helps to ensure all possible relationships among different hazards are considered. It can effectively fill a gap in current MHRA methods which to date only consider domino effects. In addition, based on this classification, the frequency and magnitude of multiple interacting hazards occurring together can be calculated with the change in trigger factors. Therefore, in MHRA, these multiple interacting hazards can be treated as a multiple hazards group, with the change of degree in the relevant trigger factors representing the magnitude, and the probability of changes in them representing the probability of this group. In this way, the results obtained are more reliable. Hence, the developed hazard interaction classification based on hazard-forming environment provides a useful tool to facilitate improved MHRA.

MHRA is performed primarily for the purpose of providing information and insight to those who make decisions about how natural hazard risk should be managed. The hazard interaction classification developed in this research helps MHRA provide more reliable results, which can help public planners and decision-makers make optimal investment in disaster avoidance and mitigation. The classification also helps public planners and decision-makers understand the possible interactions among different hazards, so they can take appropriate and more targeted mitigation measures. Public planners and decision-makers can also use hazard-forming environment analysis to help residents, businesses and other organizations to better understand the natural hazards they are exposed to, and their susceptibility to these hazards, thus enhancing public risk awareness and informing local risk management.

Acknowledgements: We are grateful to NHESS editor Prof. Thomas Glade for the editorial handling. We would like to thank Dr. Martin Mergili and one anonymous reviewer for their insightful comments and suggestions.

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Table 1 The relationship between some specific major hazards and their hazard-forming environments.

Hazard	Definition	Stable factor	Trigger factor
Earthquake	A sudden and violent shaking of the ground caused by the sudden breaking and movement of tectonic plates of the earth's crust (Alexander, 1993).	Crustal plate boundary (Nishenko and Buland, 1987; Pacheco et al., 1993).	Movement of the earth’s crust (Nishenko and Buland, 1987; Pacheco et al., 1993).
Volcanic eruption	A volcanic eruption occurs when magma and the dissolved gases it contains are discharged from a volcanic vent (Blong, 1984).	Crustal plate boundary (Blong, 1984; Alexander, 1993).	The buoyancy of the magma, the pressure from the exsolved gases in the magma, and the injection of a new batch of magma into an already filled magma chamber (Kilinc, 1999).
Tropical cyclone (Hurricane, Tropical storm, Typhoon)	Storms with swirling atmospheric disturbance occurring in tropical or subtropical maritime regions (McGuire et al., 2002; IFRC, 2013).	Point of origin: 1) Five degrees of latitude away from the Equator; 2) Vast and warm ocean (Gray, 1979; Henderson-Sellers et al., 1998; McGuire et al., 2002).	Point of origin: 1) Water temperature at least 26.5 ℃ down to a depth of at least 50 m; 2) Low amounts of weak vertical wind shear; 3) A pre-existing system of disturbed weather; and 4) High humidity (Gray, 1979; Henderson-Sellers et al., 1998; McGuire et al., 2002).
		Track: The distance to the origin (Smith, 2013).	Track: The movement of tropical cyclones is accompanied by strong winds and heavy rain, and a series of hazards induced by the changes of winds and rainfall are the reasons that damage occurs in the cyclone track (Smith, 2013). Thus, tropical cyclone is viewed as the changes of wind speed and rainfall, and these changes can be used as trigger factors to measure the magnitude of other hazards in the track.
Slow riverine	Slow riverine flood occurs in relatively	1) Flat and low-lying terrain; 2) River	The most common is heavy rainfall. Other factors

flood	flat areas, and land may stay covered with shallow, slow-moving floodwater for days or weeks (Kron, 2005).	basins; and 3) Land surface with poor water infiltration capacity (Kron, 2005).	include melting snow and ice, and high tides (Barredo, 2007).
Fast riverine flood	Fast riverine flood occurs in hilly and mountainous areas, and are characterized by a rapid rise in water, with high velocities that occur in an existing river channel over a short period (Alexander, 1993).	1) Hilly or mountainous terrain; 2) River basins; and 3) Land surface with poor water infiltration capacity (Alexander, 1993; Kron, 2005).	The most common is heavy rainfall. Other factors include melting snow and ice, and high tides (Barredo, 2007).
Coastal flood	A normally dry coastal area is inundated by sea water (McGuire et al., 2002).	1) Flat and low-lying terrain; 2) Coastal area; and 3) Land surface with poor water infiltration capacity (McGuire et al., 2002; Barredo, 2007).	Coastal flood can be induced by several trigger factors including storm surges induced by tropical cyclones, tidal waves and tsunamis (McGuire et al., 2002; Barredo, 2007).
Pluvial flood	The phenomenon where surface water accumulates as input exceeds infiltration. It is common in low-lying areas with poor water absorption ability (Falconer et al., 2009; Zhou et al., 2012).	1) Flat and low-lying terrain; and 2) Land surface with poor water infiltration capacity (a common attribute of urban areas) (Falconer et al., 2009; Zhou et al., 2012).	The principal trigger factor for pluvial flood is heavy rainfall (Maksimović et al., 2009).
Landslide	A geological phenomenon which includes a wide range of ground movements with rock and soil over a sloping surface (Varnes, 1958).	1) Hilly or mountainous terrain; and 2) Slope material with poor water absorption capacity (Varnes, 1984; Guzzetti et al., 1999).	1) Heavy rainfall which increases the pressure of material on the slope; and 2) Earthquake which reduces the resisting (shear) forces of the slope (Varnes, 1984; Kuriakose et al., 2009).
Avalanche	A rapid flow of snow down a sloping surface (McClung and Schaerer, 2006; Smith, 2013).	1) Hilly or mountainous terrain; and 2) Slope with snowpack (McClung and Schaerer, 2006;	1) Heavy snowfall or rainfall which increases the pressure of snowpack on the slope; 2) Metamorphic changes in the snowpack

		Smith, 2013).	such as melting due to solar radiation; and 3) Earthquake which reduces the resisting (shear) forces of the slope (McClung and Schaerer, 2006; Smith, 2013).
Drought	A condition of abnormal weather resulting in a shortage of water (Dracup et al., 1980; Wilhite and Glantz, 1985; McKee et al., 1993).	1) Low annual average precipitation; 2) High annual average temperature; 3) Low drainage density; and 4) Land surface with poor water absorption capacity (Alexander, 1993; Smith and Petley, 2009).	Lack of rainfall (Smith and Petley, 2009).

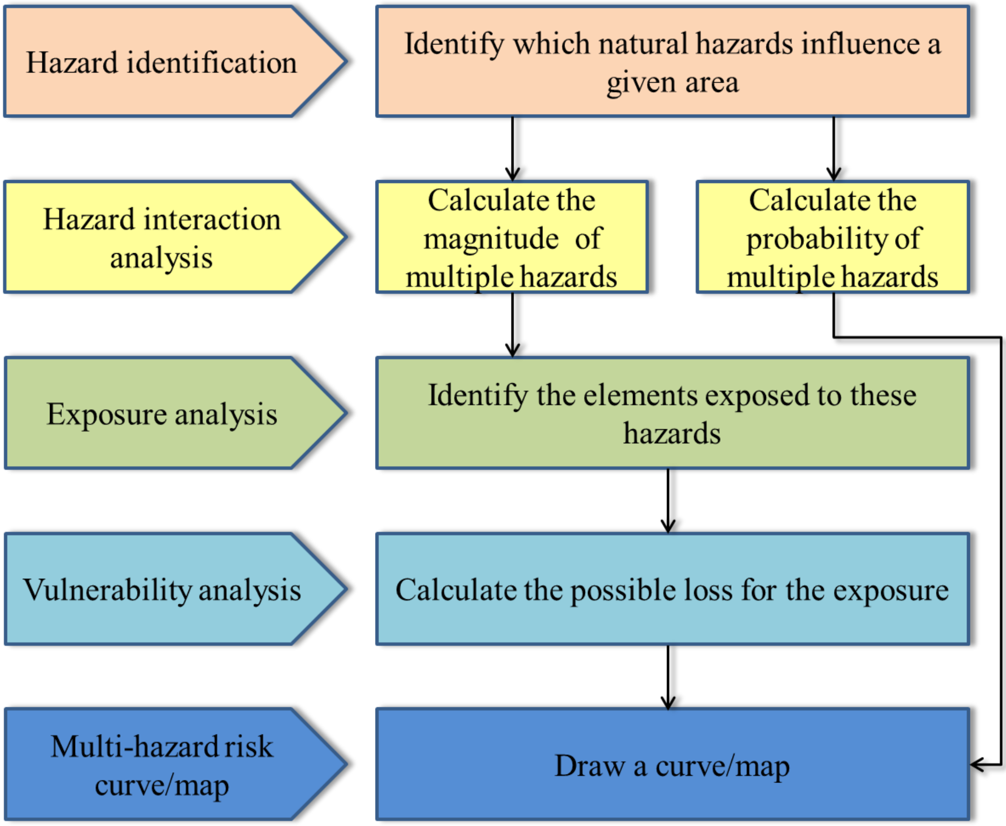
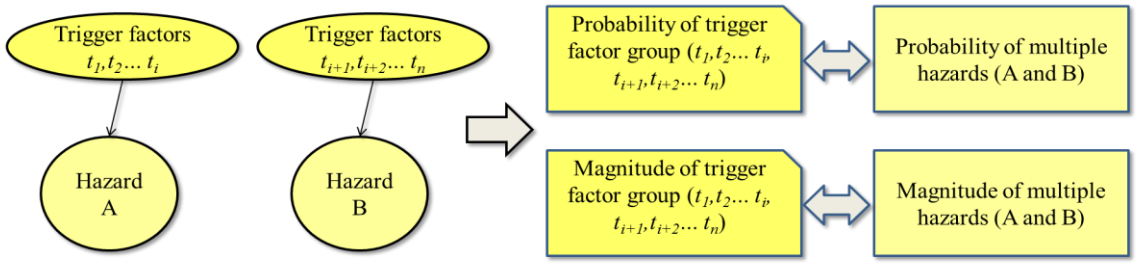
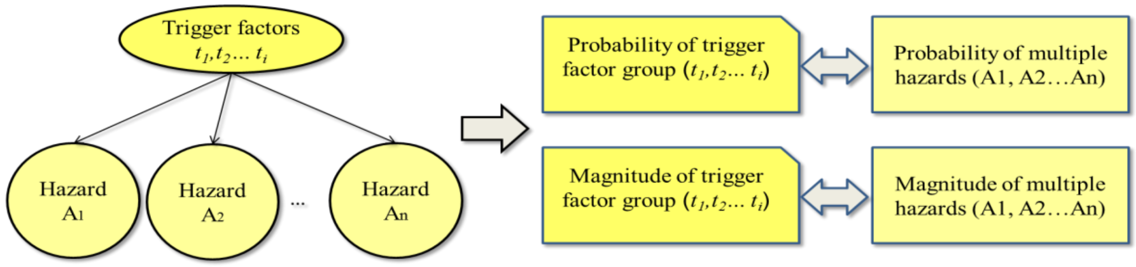


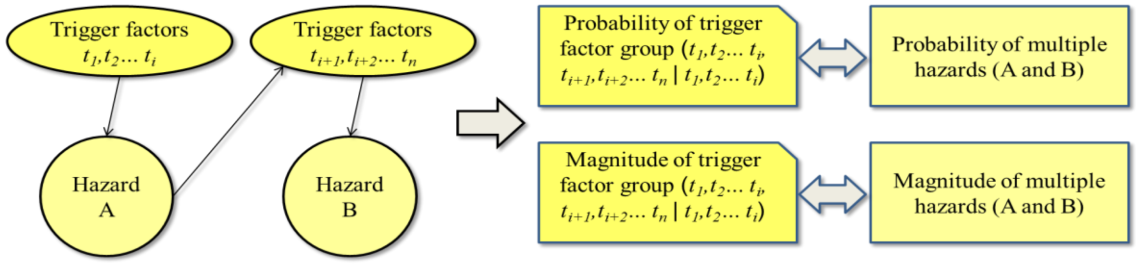
Figure 1. Basic framework of multi-hazard risk assessment



(a) Independent relationship



(b) Parallel relationship



(c) Series relationship

Figure 2. Hazard interaction analysis for hazards with different relationships

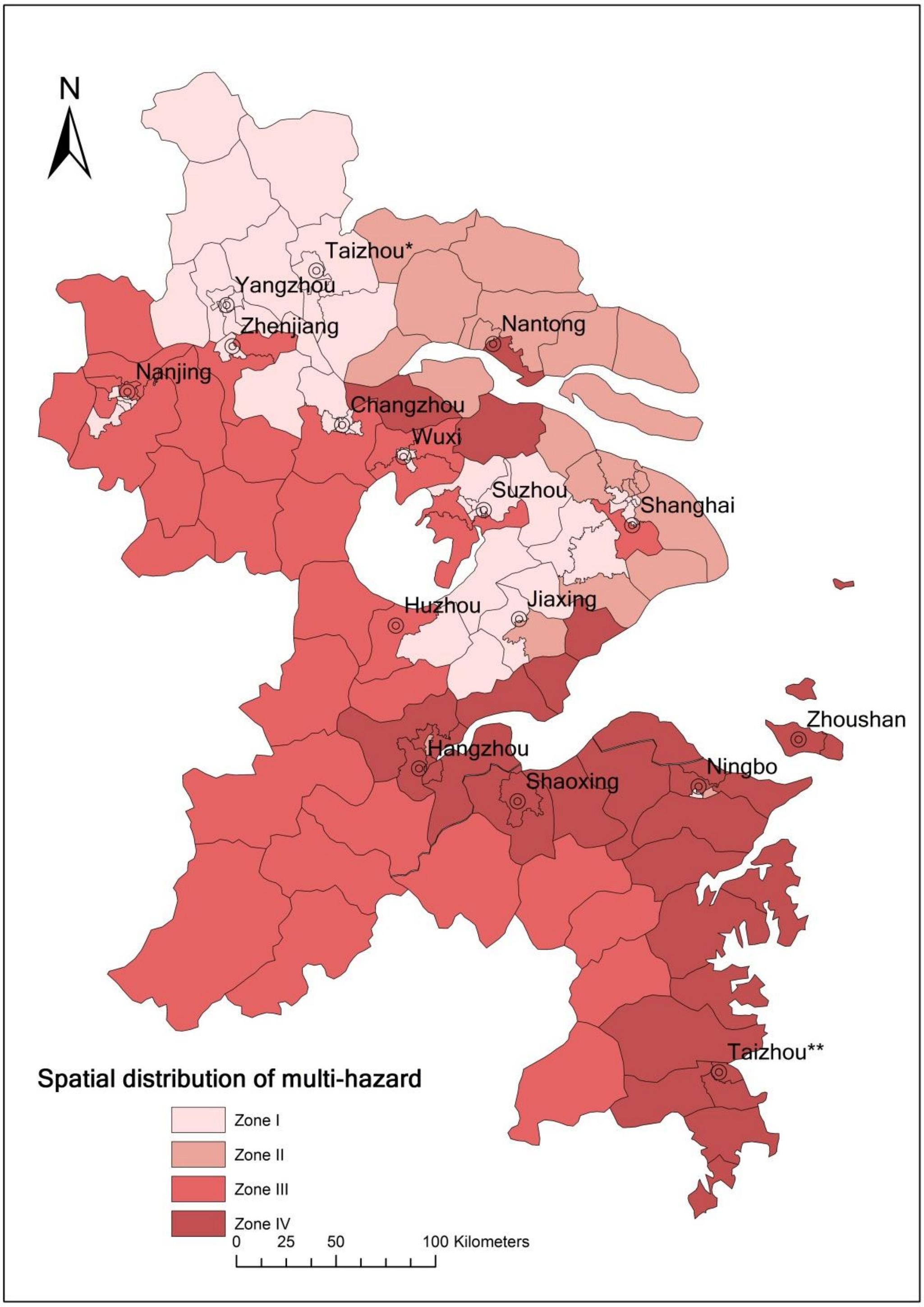


Figure 3. Spatial distribution of multi-hazard in the Yangtze River Delta *(Note that Taizhou* is in Jiangsu Province and Taizhou** is in Zhejiang Province)*

Zone I: typhoon, slow kinds riverine flood, pluvial flood. Zone II: typhoon, slow kinds riverine flood, pluvial flood and coastal flood. Zone III: typhoon, slow kinds riverine flood, fast kinds riverine flood, pluvial flood and landslide Zone IV: typhoon, slow kinds riverine flood, fast kinds riverine flood, pluvial flood, coastal flood and landslide.

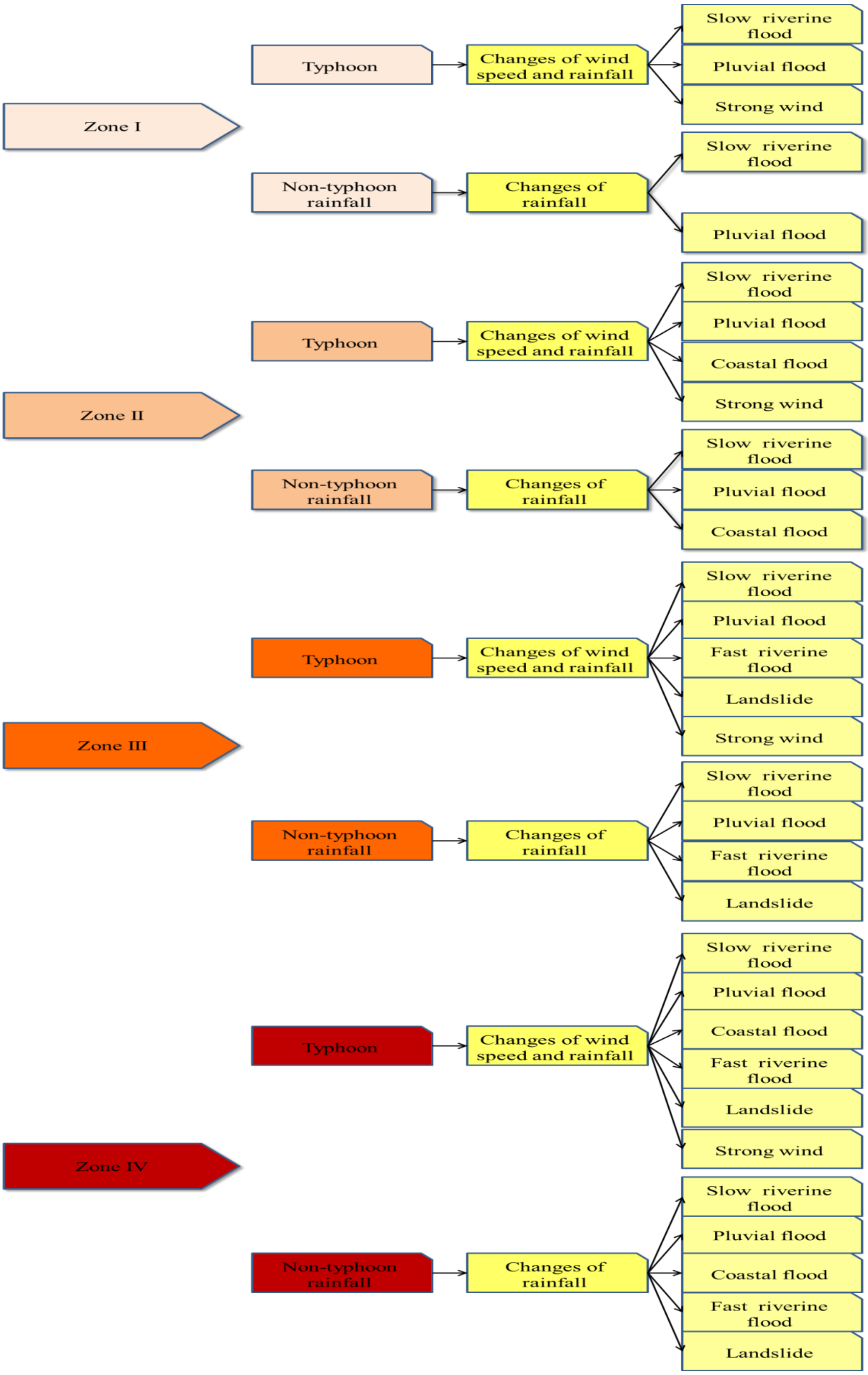
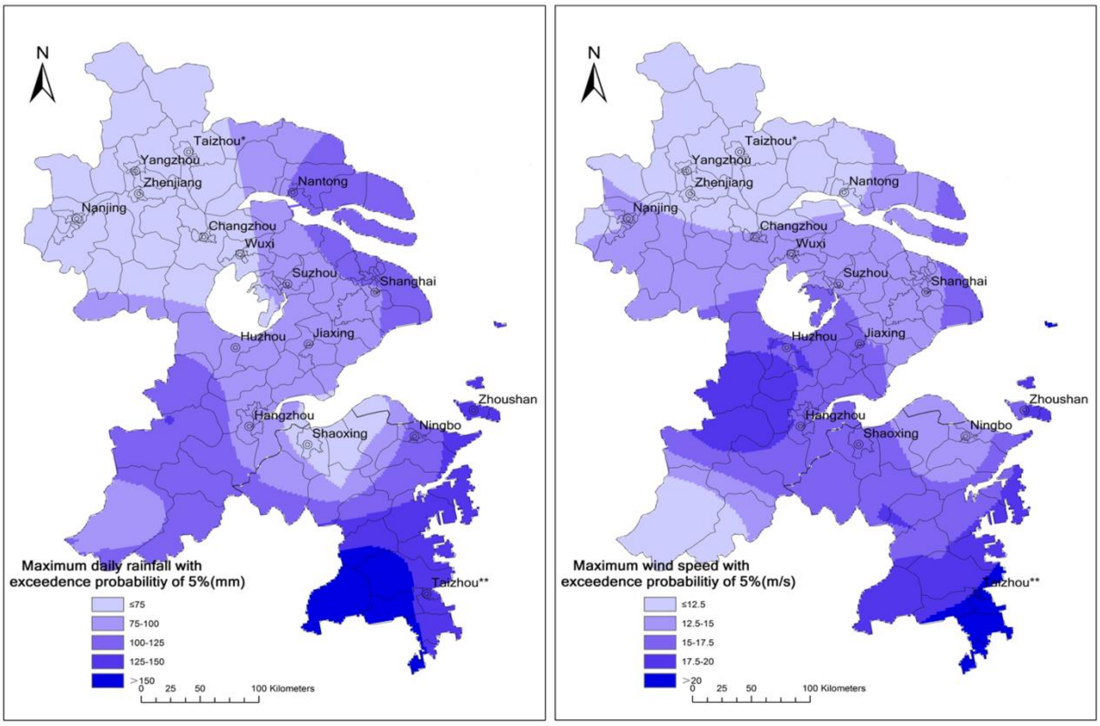
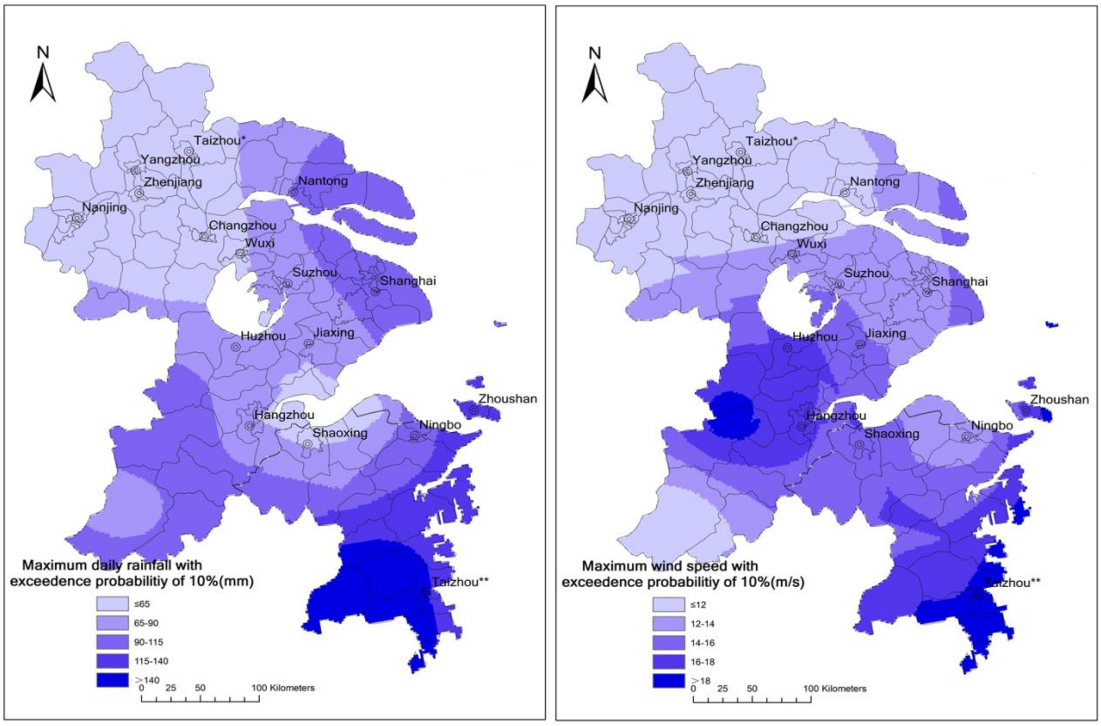


Figure 4. The relationships among multiple hazards in the Yangtze River Delta



(a) Maximum daily rainfall distribution with exceedance probability of 5%

(b) Maximum wind speed distribution with exceedance probability of 5%



(c) Maximum daily rainfall distribution with exceedance probability of 10%

(d) Maximum wind speed distribution with exceedance probability of 10%

Figure 5. Distribution of maximum daily rainfall and maximum wind speed during typhoon with different exceedance probabilities

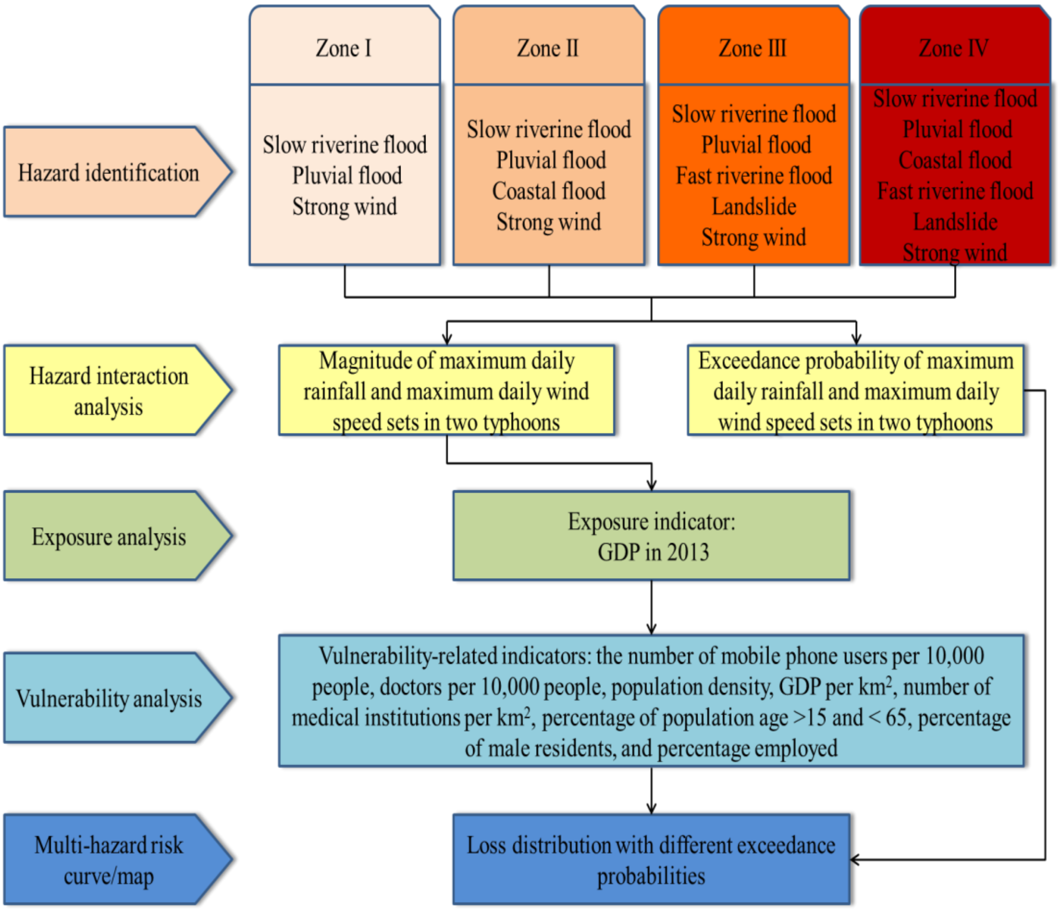
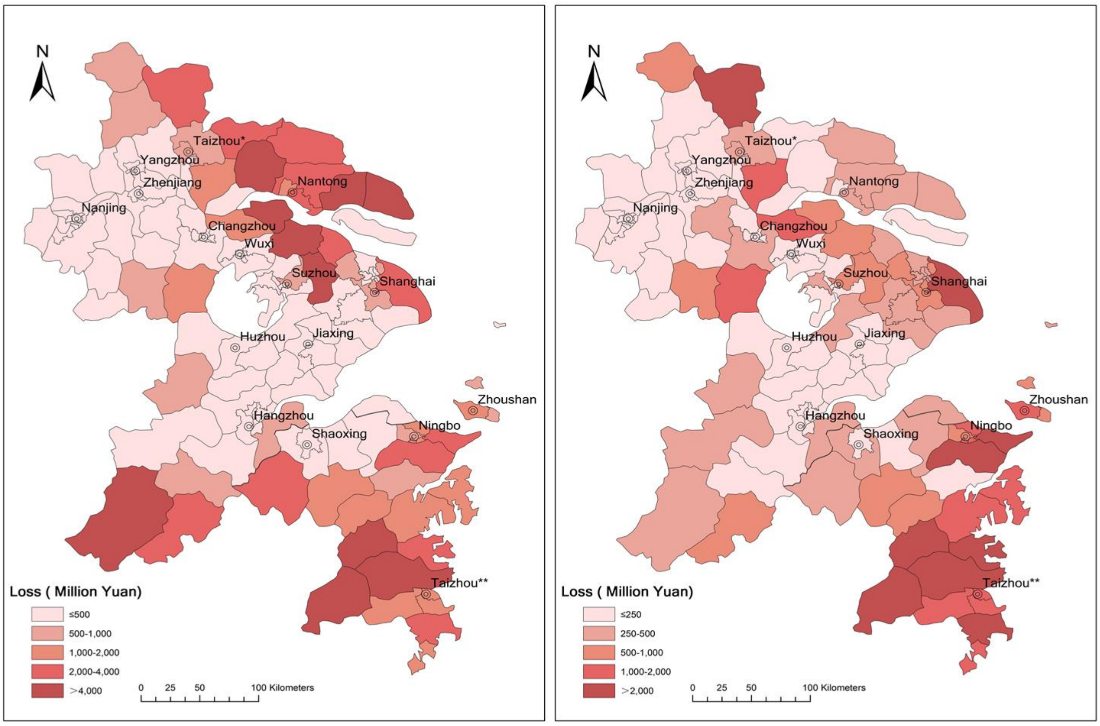
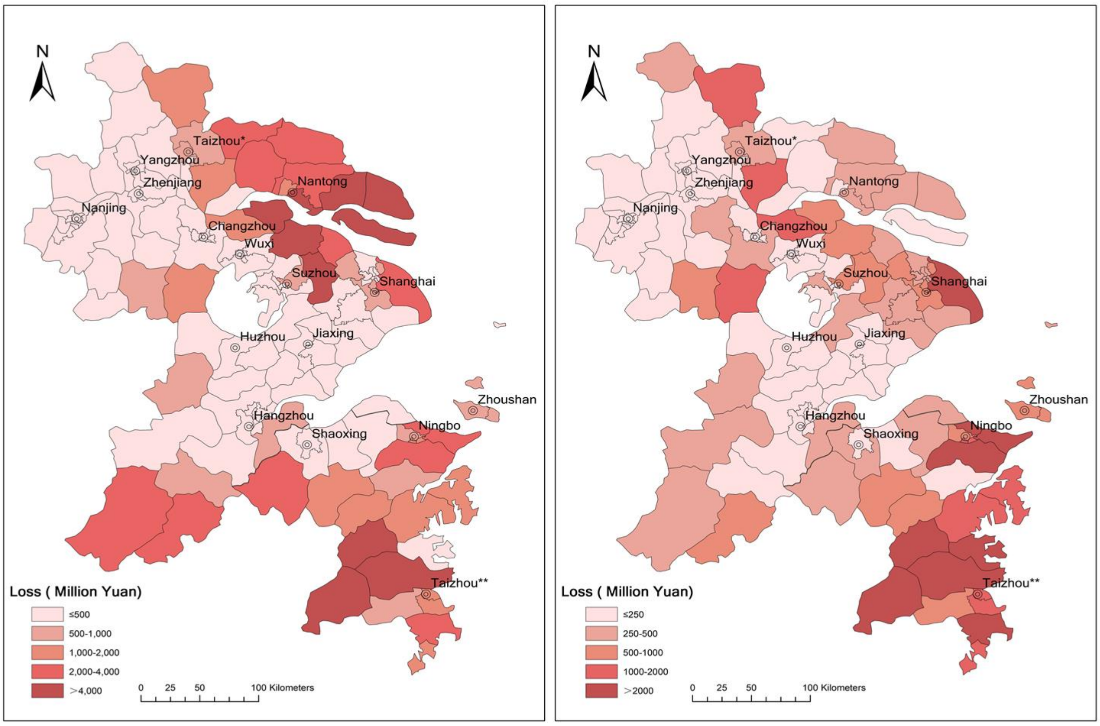


Figure 6. Basic framework of multi-hazard risk assessment for two consecutive typhoons in the Yangtze River Delta



(a) Loss distribution influenced by two typhoons with exceedance probability of 1% and exceedance probability of 10%

(b) Loss distribution influenced by two typhoons with exceedance probability of 5% and exceedance probability of 10%



(c) Loss distribution influenced by two typhoons with exceedance probability of 10% and exceedance probability of 1%

(d) Loss distribution influenced by two typhoons with exceedance probability of 10% and exceedance probability of 5%

Figure 7. Loss distribution influenced by two consecutive typhoons with different exceedance probabilities