Nat. Hazards Earth Syst. Sci. Discuss., 3, 7203–7229, 2015
www.nat-hazards-earth-syst-sci-discuss.net/3/7203/2015/
doi:10.5194/nhessd-3-7203-2015

Natural Hazards and Earth System Sciences
Discussions
Open Access

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

B. Liu[1], Y. L. Siu[1], and G. Mitchell[2]

[1]School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK
[2]School of Geography, University of Leeds, Leeds, LS2 9JT, UK

Received: 10 November 2015 – Accepted: 14 November 2015 – Published: 1 December 2015

Correspondence to: Y. L. Siu (y.l.siu@leeds.ac.uk)

Published by Copernicus Publications on behalf of the European Geosciences Union.

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 Project, 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 discusses the relationship between some specific major hazards and their hazard-forming environments. Section 4 presents a systematic classification of hazard interactions based on hazard-forming environment analysis, and Sect. 5 applies this classification within MHRA to test its utility. 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. Next, we illustrate the hazard-forming environment concept with reference to some major hazards.

3 Hazard-forming environment for major natural hazards

For illustrative purpose, this section discusses the relationship between some specific major hazards and their hazard-forming environments.

3.1 Earthquake

Earthquake is one of the most destructive natural hazards. An earthquake is 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). Earthquakes are caused mostly by tectonic movements in the earth's crust, thus the distribution of earthquake tends to follow crustal plate boundaries (Nishenko and Buland, 1987; Pacheco et al., 1993). The plate boundary can therefore be used as the precondition (stable factor) to earthquake, with movement of the earth's crust treated as the trigger factor.

3.2 Volcanic eruption

A volcanic eruption occurs when magma and the dissolved gases it contains are discharged from a volcanic vent (Blong, 1984). Volcanoes are distributed mostly at the margins of the tectonic plates (Alexander, 1993; Blong, 1984), hence the plate boundary also can be used as the precondition (stable factor) to volcanic eruption. Several factors can trigger a volcanic eruption. The most common are: 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).

3.3 Tropical cyclone

Tropical cyclone is the generic name for storms with swirling atmospheric disturbance occurring in tropical or subtropical maritime regions (McGuire et al., 2002). Cyclones are called by other names in different parts of the world, with common terms including "Hurricane" in the Caribbean and the Atlantic Ocean, "Tropical storm" in the Indo-Pacific region, and "Typhoon" in the north-west Pacific (IFRC, 2013). The formation of tropical cyclones is a topic of extensive ongoing research and is not fully understood, but a series of factors are necessary including: (1) five degrees of latitude away from the Equator, (2) vast and warm ocean, (3) water temperature at least 26.5 °C down to a depth of at least 50 m, (4) low amounts of weak vertical wind shear, (5) a pre-existing system of disturbed weather; and (6) high humidity (Gray, 1979; Henderson-Sellers et al., 1998; McGuire et al., 2002). Of these factors, the first two are stable factors (preconditions) and the others are trigger factors in the hazard-forming environment.

In contrast to other hazards, tropical cyclones can move thousands of kilometers (Smith, 2013), hence, in an inland area, the distance to the origin of tropical cyclones can be used as the precondition (stable factor) for tropical cyclone identification.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀◀ ▶▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

The movement of tropical cyclones is accompanied by strong winds and heavy rain, and a series of hazards (e.g. strong winds, floods) 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, which are determined by the hazard-forming environment in the track.

3.4 Flood

As the most common of all natural hazards, flood can be defined as a temporary inundation of land area by water from any source (Alexander, 1993; Kron, 2005; CEC, 2006). There are several classification schemes for floods in the relevant literature, e.g. Berz et al. (2001) and Kron (2005) classified floods in three main types: river flood, flash flood and storm surge; Jonkman (2005) divided floods into six types: coastal floods, flash floods, river floods, drainage problems, tsunamis and tidal waves. However these classification schemes are not well suited to differentiating flood hazard factors in the hazard-forming environment. Therefore, a flood classification based on the hazard forming environment is proposed, with four types of floods: slow riverine flood, fast riverine flood, coastal flood and pluvial flood. The definitions of these four types of floods are further discussed below.

Riverine (fluvial) flooding is where water overtops the banks of a river to take it outside its regular boundaries (Jonkman, 2005). The dynamics of riverine flooding vary with terrain. Slow riverine flood occurs in relatively flat areas, and land may stay covered with shallow, slow-moving floodwater for days or weeks (Kron, 2005). Fast riverine floods occur 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). An important feature of riverine flood is that the ground becomes fully saturated, thus the soil's capacity to store water is exceeded, and there is consequently an increase in overland flow and runoff to rivers (Kron, 2005). Hence, the preconditions (stable factors) to slow riverine flood can be summarized as: (1) flat and low-lying terrain, (2) river basins; and (3) land surface with poor water infiltration capacity, and the preconditions to fast riverine flood are: (1) hilly or mountainous terrain, (2) river basins; and (3) land surface with poor water infiltration capacity. Surplus water beyond the capacity of a river is the only reason for riverine flood, hence the trigger factors to these two kinds of river flood are basically the same. Several trigger factors can cause a river flood, of which the most common is heavy rainfall. Other factors include melting snow and ice, and high tides (Barredo, 2007).

Coastal flood occurs when a normally dry coastal area is inundated by sea water (McGuire et al., 2002). Hence, coastal floods occur mainly in low-lying coasts. The preconditions (stable factors) to coastal flood include: (1) flat and low-lying terrain, (2) coastal area; and (3) land surface with poor water infiltration capacity. 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 (ponding) is 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). The preconditions (stable factors) to pluvial flood are mainly: (1) flat and low-lying terrain; and (2) land surface with poor water infiltration capacity (a common attribute of urban areas). The principal trigger factor for pluvial flood is heavy rainfall (Maksimović et al., 2009).

3.5 Landslide

Landslide is the most common hazard in many mountainous and hilly areas. It can be defined as a geological phenomenon which includes a wide range of ground movements with rock and soil over a sloping surface (Varnes, 1958). Landslides mainly occur in hilly areas where the land surface has poor water absorption ability (Varnes, 1984; Guzzetti et al., 1999). The preconditions (stable factors) to landslide are: (1) hilly or mountainous terrain; and (2) slope material with poor water absorption capacity. Landslides occur when the stability of the slope changes from a stable to an unstable condition. Trigger factors which can change the stability of the slope mainly include:

(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).

3.6 Avalanche

An avalanche (snowslide) is a rapid flow of snow down a sloping surface (McClung and Schaerer, 2006; Smith, 2013). As a mountain-slope hazard, it is similar with landslide, only with snow instead of rock and soil. Hence, the preconditions (stable factors) to avalanche are: (1) hilly or mountainous terrain; and (2) slope with snowpack. Avalanches are typically triggered when the forces on the snow exceed its strength. Trigger factors for avalanche mainly include: (1) heavy snowfall or rainfall which increases the pressure of snowpack on the slope, (2) metamorphic changes in the snowpack 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).

3.7 Drought

Drought is markedly different to tropical cyclone, flood and the other natural hazards described above as it develops slowly and has a prolonged existence, and may persist for several years (Alexander, 1993; Smith, 2000). Drought can be simply defined as a condition of abnormal weather resulting in a shortage of water (Dracup et al., 1980; Wilhite and Glantz, 1985; McKee et al., 1993). It is common to divide drought in three main types: meteorological drought (a prolonged period with less than average precipitation), agricultural drought (droughts that affect crop production) and hydrological drought (water reserves such as aquifers, lakes and reservoirs fall below the statistical average) (Hisdal and Tallaksen, 2000; Smith and Petley, 2009). Drought results in a shortage of water, and meteorological drought usually precedes the other kinds of drought (Hisdal and Tallaksen, 2000).

Lack of rainfall within a given period is taken as the direct physical processes leading to drought (Smith and Petley, 2009), hence, lack of rainfall can be treated as the main trigger factor. Droughts easily occur in areas with low annual average precipitation and high annual average temperature (Alexander, 1993). Water reserves such as aquifers, lakes and reservoirs, can help to reduce the susceptibility to drought. Therefore, the preconditions (stable factors) to drought are: (1) low annual average precipitation, (2) high annual average temperature, (3) low drainage density; and (4) land surface with poor water absorption capacity.

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.

4 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.

4.1 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

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀◀ ▶▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

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:

$$S(H_k) = f(\mathrm{SF}_1, \mathrm{SF}_2 \ldots \mathrm{SF}_j)(j = 1, 2 \ldots n). \tag{1}$$

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

$$S_i(H_k) = \sum_{j=1}^{n} w_j \mathrm{Nor}(\mathrm{SF}_j)_i \tag{2}$$

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, $\mathrm{Nor}(\mathrm{SF}_j)_i$ 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.

4.2 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 be expressed as:

$$f(p_{\mathrm{t}i}) = p(h_j) \tag{3}$$

where, one trigger factor induces one hazard,

$$f(p_{\mathrm{t}i}) = p(h_1, h_2 \ldots h_j) \tag{4}$$

where, one trigger factor induces multiple hazards,

$$f(p_{\mathrm{t}1}, p_{\mathrm{t}2} \ldots p_{\mathrm{t}i}) = p(h_j) \tag{5}$$

where, multiple trigger factors induce one hazard, and

$$f(p_{\mathrm{t}1}, p_{\mathrm{t}2} \ldots p_{\mathrm{t}i}) = p(h_1, h_2 \ldots h_j) \tag{6}$$

where, multiple trigger factors induce multiple hazards. In these cases: $p(h_j)$ is the probability of hazard j, and $p_{\mathrm{t}i}$ is the probability of the change in trigger factor i. $p_{\mathrm{t}i}$ 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).

4.3 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.

4.3.1 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:

$$f(p_{\mathrm{t}1}, p_{\mathrm{t}2} \ldots p_{\mathrm{t}i}) = p(h_A) \tag{7}$$

$$f(p_{\mathrm{t}i+1}, p_{\mathrm{t}i+2} \ldots p_{\mathrm{t}n}) = p(h_B) \tag{8}$$

where, $p_{\mathrm{t}i}$ 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:

$$P\left(A \bigcap B\right) = p(h_A) \times p(h_B) = f(p_{\mathrm{t}1}, p_{\mathrm{t}2} \ldots p_{\mathrm{t}i}) \times f(p_{\mathrm{t}i+1}, p_{\mathrm{t}i+2} \ldots p_{\mathrm{t}n}) \tag{9}$$

where, $p_{\mathrm{t}i}$ is the probability of the change in trigger factor i, and $p(h_j)$ is the probability of hazard j occurrence.

4.3.2 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, e.g. drought and slow riverine flood cannot happen at the same time. The changes in trigger factors for these hazards can be expressed as:

$$f(p_{\mathrm{t}i+}) = p(h_A) \tag{10}$$

$$f(p_{\mathrm{t}i-}) = p(h_B) \tag{11}$$

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:

$$P\left(A \bigcap B\right) = 0. \tag{12}$$

4.3.3 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:

$$\begin{aligned} &f(p_{t1}, p_{t2} \ldots p_{ti}) = p\left(h_{A_1}\right) \\ &f(p_{t1}, p_{t2} \ldots p_{ti}) = p\left(h_{A_2}\right) \\ &\ldots \\ &f(p_{t1}, p_{t2} \ldots p_{ti}) = p\left(h_{A_n}\right) \end{aligned} \tag{13}$$

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:

$$P\left(A_1 \bigcap A_2 \ldots \bigcap A_n\right) = f(p_{t1}, p_{t2} \ldots p_{ti}) \tag{14}$$

where, $p_{\mathrm{t}i}$ is the probability of the change in trigger factor i, and $p(h_j)$ is the probability of hazard j occurrence.

4.3.4 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:

$$f(p_{\mathrm{t}1}, p_{\mathrm{t}2} \ldots p_{\mathrm{t}i}) = p(h_A) \longrightarrow f(p_{\mathrm{t}i+1}, p_{\mathrm{t}i+2} \ldots p_{\mathrm{t}n}) = p(h_B) \tag{15}$$

where, $p_{\mathrm{t}i}$ 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 thus be expressed as:

$$\begin{aligned} P\left(A \bigcap B\right) &= p(h_A) \times p(h_B) = f(p_{\mathrm{t}1}, p_{\mathrm{t}2} \ldots p_{\mathrm{t}i}) \times f(p_{\mathrm{t}i+1}, p_{\mathrm{t}i+2} \ldots p_{\mathrm{t}n} | h_A) \\ &= f(p_{\mathrm{t}1}, p_{\mathrm{t}2} \ldots p_{\mathrm{t}i}) \times f(p_{\mathrm{t}i+1}, p_{\mathrm{t}i+2} \ldots p_{\mathrm{t}n} | p_{\mathrm{t}1}, p_{\mathrm{t}2} \ldots p_{\mathrm{t}i}) \end{aligned} \tag{16}$$

where, $p_{\mathrm{t}i}$ is the probability of the change of trigger factor i, $p(h_j)$ is the probability of hazard j, and $p_{\mathrm{t}n} | h_A$ 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.

5 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. Different types of hazards use different units to measure their magnitude. 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 $t_1, t_2 \ldots t_i$ which induce hazard A are independent of the changes in trigger factors $t_{i+1}, t_{i+2} \ldots t_n$ which induce hazard B. These trigger factors can be taken as a trigger factor group $(t_1, t_2 \ldots t_i, t_{i+1}, t_{i+2} \ldots t_n)$ to measure the frequency and magnitude of hazard A and B occurring together.

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

In Fig. 2c, hazard A and hazard B represent the series relationship. The changes in trigger factors $t_1, t_2 \ldots t_i$ induce hazard A, then the hazard A induces 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. Here, the trigger factor group $(t_1, t_2 \ldots t_i)$ is chosen to represent the magnitude of hazard A, and the trigger factor group $(t_{i+1}, t_{i+2} \ldots t_n)$ is chosen to represent the magnitude of hazard B. The probability and degree of the changes in the trigger factor group $(t_{i+1}, t_{i+2} \ldots t_n)$ 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 $(t_1, t_2 \ldots t_i, t_{i+1}, t_{i+2} \ldots t_n \mid t_1, t_2 \ldots t_i)$ 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 addition, we applied this classification scheme into a MHRA model to estimate potential loss caused by multiple hazards in China's Yangtze River Delta (Liu, 2015). The calculated results were used to compare with the observed data in a model validation exercise. The validation results demonstrate that this model can more effectively represent the real world, and that the outputs, possible loss caused by multiple hazards, obtained with the model are reliable (Liu, 2015).

6 Discussion

6.1 Contribution to multi-hazard risk assessment

In this research, we developed a comprehensive approach to classify hazard interactions based on analysis of the hazard-forming environment. 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 the occurrence of hazard 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). Analysis of the stable factors in this research identifies hazard from environmental factors rather than past observations of hazard, and so can consider all possible hazard situations even if some hazards have long return periods. Thus, stable factor analysis helps to fill a significant gap in existing hazard identification as observed hazard events may not reflect all possible hazard situations due to their long return period.

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 development of this categorization basically 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

In this study, we 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 that 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 Thomas Glade for the editorial handling. We would like to thank the anonymous reviewers for their insightful comments and suggestions.

References

Alexander, D.: Natural Disasters, UCL Press, London, 1993.

Armonia – Applied Multi-Risk Mapping of Natural Hazards for Impact Assessment: 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, Armonia, European Community, Brussels, 85 pp., 2006.

Barredo, J. I.: Major Flood Disasters in Europe: 1950–2005, Nat. Hazards, 42, 125–148, 2007.

Bell, R. and Glade, T.: Quantitative risk analysis for landslides – examples from Bíldudalur, NW-Iceland, Nat. Hazards Earth Syst. Sci., 4, 117–131, doi:10.5194/nhess-4-117-2004, 2004.

Berz, G., Kron, W., Loster, T., Rauch, E., Schimetschek, J., Schmieder, J., Siebert, A., Smolka, A., and Wirtz, A.: World map of natural hazards – a global view of the distribution and intensity of significant exposures, Nat. Hazards, 23, 443–465, 2001.

Blong, R. J.: Volcanic hazards: a sourcebook on the effects of eruptions, Academic Press, Sydney, 1984.

Carpignano, A., Golia, E., Di Mauro, C., Bouchon, S., and Nordvik, J.: A methodological approach for the definition of multi-risk maps at regional level: first application, J. Risk Res., 12, 513–534, 2009.

CEC – Commission of the European Communities: Proposal for a Directive on the Assessment and Management of Floods (COM (2006)15 final), Commission of the European Communities, Brussels, 21 pp., 2006.

Cutter, S. L., Mitchell, J. T., and Scott, M. S.: Revealing vulnerability of people and place: a case study of Geogretown county, South Carolina, Ann. Assoc. Am. Geogr., 90, 713–737, 2000.

Di Mauro, C., Bouchon, S., Carpignana, A., Golia, E., and Peressin, S.: 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, 17–19 October 2006, University of Pisa, Italy, 2006.

Dixon, B.: Groundwater vulnerability mapping: a GIS and fuzzy rule based integrated tool, Appl. Geogr., 25, 327–347, 2005.

Dracup, J. A., Lee, K. S., and Paulson, E. G,: On the definition of droughts, Water Resour. Res., 16, 297–302, 1980.

Eshrati, L., Mahmoudzadeh, A., and Taghvaei, M.: Multi hazards risk assessment, a new methodology, Int. J. Health Syst. Disaster Manage., 3, 79–88, 2015.

Falconer, R. H., Cobby, D., Smyth, P., Astle, G., Dent, J., and Golding, B.: Pluvial flooding: new approaches in flood warning, mapping and risk management, J. Flood Risk Manage., 2, 198–208, 2009.

Frolova, N. I., Larionov, V. I., Sushchev, S. P., and Bonnin, J.: Seismic and integrated risk assessment and management with information technology application, in: 15th World Conference on Earthquake Engineering, 24–28 September 2012, Lisbon, Portugal, 2012.

Garcia-Aristizabal, A. and Marzocchi, W.: Scenarios of Cascade Events, ENV.2010.6.1.3.4, New Methodologies for Multi-Hazard and Multi-Risk Assessment, European Commission, Brussels, 82 pp., 2013.

Gill, J. C. and Malamud, B. D.: Reviewing and visualizing the interactions of natural hazards, Rev. Geophys., 52, 680–722, 2014.

Gray, W. M.: Hurricanes: their formation, structure and likely role in the tropical circulation, Meteorol. Trop. Oceans, 77, 155–218, 1979.

Grünthal, G., Thieken, A. H., Schwarz, J., Radtke, K. S., Smolka, A., and Merz, B.: Comparative risk assessment for the city of Cologne-storms, floods, earthquake, Nat. Hazards, 38, 21–44, 2006.

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

Guzzetti, F., Carrara, A., Cardinali, M., and Reichenbach, P.: Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, Central Italy, Geomorphology, 31, 181–216, 1999.

Henderson-Sellers, A., Zhang, H., Berz, G., Emanuel, K., Gray, W., Landsea, C., Holland, G., Lighthill, J., Shieh, S.-L., Webster, P., and McGuffie, K.: Tropical cyclones and global climate change: a post-IPCC assessment, B. Am. Meteorol. Soc., 79, 19–38, 1998.

Hisdal, H. and Tallaksen, L. M. (Eds.): Drought Event Definition, Assessment of the Regional Impact of Droughts in Europe, Technical Report No. 6, Department of Geophysics, University of Oslo, Oslo, 41 pp., 2000.

IFRC – International Federation of Red Cross and Red Crescent Societies: Meteorological Hazards: Tropical Storms, Hurricanes, Cyclones and Typhoons, available at: https://www.ifrc.org/en/what-we-do/disaster-management/about-disasters/definition-of-hazard/tropical-storms-hurricanes-typhoons-and-cyclones (last access: 1 October 2015), 2013.

Jonkman, S. N.: Global perspectives on loss of human life caused by floods, Nat. Hazards, 34, 151–175, 2005.

Kappes, M. S., Keiler, M., and Glade, T.: From single- to multi-hazard risk analyses: a concept addressing emerging challenges, in: Mountain Risks: Bringing Science to Society, edited by: Malet, J. P., Glade, T., and Casagli, N., CERG Editions, Strasbourg, France, 351–356, 2010.

Kappes, M. S., Keiler, M., von Elverfeldt, K., and Glade, T.: Challenges of analyzing multi-hazard risk: a review, Nat. Hazards, 64, 1925–1958, 2012.

Kilinc, A.: What Causes a Volcano to Erupt and How Do Scientists Predict Eruptions, Scientific American, available at: http://www.scientificamerican.com/article/what-causes-a-volcano-to/ (last access: 1 October 2015), 1999.

Kron, W.: Flood risk = hazard · values · vulnerability, Water Int., 30, 58–68, 2005.

Kuriakose, S. L., Sankar, G., and Muraleedharan, C.: History of landslide susceptibility and a chorology of landslide-prone areas in the Western Ghats of Kerala, India, Environ. Geol., 57, 1553–1568, 2009.

Liu, B.: Modelling multi-hazard risk assessment: a case study in the Yangtze River Delta, China, PhD thesis, School of Earth and Environment, The University of Leeds, Leeds, UK, 201 pp., 2015.

Maksimović, Č., Prodanović, D., Boonya-Aroonnet, S., Leitao, J. P., Djordjević, S., and Allitt, R.: Overland flow and pathway analysis for modelling of urban pluvial flooding, J. Hydraul. Res., 47, 512–523, 2009.

Marzocchi, W., Mastellone, M., Di Ruocco, A., Novelli, P., Romeo, E., and Gasparini, P.: Principles of Multi-Risk Assessment: Interactions Amongst Natural and Man-Induced Risks, European Commission, Directorate-General for Research, Environment Directorate, Luxembourg, 72 pp., 2009.

Marzocchi, W., Garcia-Aristizabal, A., Gasparini, P., Mastellone, M., and Di Ruocco, A.: Basic principles of multi-risk assessment: a case study in Italy, Nat. Hazards, 62, 551–573, 2012.

McClung, D. and Schaerer, P. A.: The Avalanche Handbook, The Mountaineers Books, Seattle, 2006.

McGuire, B., Mason, I., and Kilburn, C.: Natural Hazards and Environmental Change, Arnold, London, 2002.

McKee, T. B., Doesken, N. J., and Kleist, J.: The relationship of drought frequency and duration to time scales, in: 8th Conference on Applied Climatology, 17–22 January 1993, Anaheim, California, 1993.

Munich Re – Munich Reinsurance Company: Topics – Annual Review: Natural Catastrophes 2002, Munich Re Group, Munich, 2003.

Nishenko, S. P. and Buland, R.: A generic recurrence interval distribution for earthquake forecasting, B. Seismol. Soc. Am., 77, 1382–1399, 1987.

Pacheco, J. F., Sykes, L. R., and Scholz, C. H.: Nature of seismic coupling along simple plate boundaries of the subduction type, J. Geophys. Res.-Sol. Ea., 98, 14133–14159, 1993.

Park, C.: Environment issues, Prog. Phys. Geogr., 18, 411–424, 1994.

Schmidt, J., Matcham, I., Reese, S., King, A., Bell, R., Henderson, R., Smart, G., Cousins, J., Smith, W., and Heron, D.: Quantitative multi-risk analysis for natural hazards: a framework for multi-risk modelling, Nat. Hazards, 58, 1169–1192, 2011.

Shi, P. J.: Theory and practice of disaster study, J. Nat. Disaster, 5, 6–17, 1996.

Smith, K.: Environmental Hazards: Assessing Risk and Reducing Disaster, 3rd Edn., Routledge, New York, 2000.

Smith, K.: Environmental Hazards: Assessing Risk and Reducing Disaster, 6th Edn., Routledge, New York, 2013.

Smith, K. and Petley, D. N.: Environmental Hazards: Assessing Risk and Reducing Disaster, 5th Edn., Routledge, New York, 2009.

Tarvainen, T., Jarva, J., and Greiving, S.: Spatial pattern of hazards and hazard interactions in Europe, in: Natural and Technological Hazards and Risks Affecting the Spatial Development of European Regions, vol. 42, edited by: Schmidt-Thomé, P., Geological Survey Of Finland, Espoo, Finland, 83–91, 2006.

Thirumalaivasan, D., Karmegam, M., and Venugopal, K.: AHP-DRASTIC: software for specific aquifer vulnerability assessment using DRASTIC model and GIS, Environ. Model. Softw., 18, 645–656, 2003.

UNDP – United Nations Development Programme: Reducing Disaster Risk: a Challenge for Development, United Nations Development Programme, Bureau for Crisis Prevention and Recovery, New York, 146 pp., 2004.

Varnes, D. J.: Landslide types and processes, Highway Res. Board Spec. Rep., 29, 20–47, 1958.

Varnes, D. J.: Landslide Hazard Zonation: a Review of Principles and Practice, UNESCO – The United Nations Educational, Scientific and Cultural Organization, Paris, 63 pp., 1984.

Wilhite, D. A. and Glantz, M. H.: Understanding: the drought phenomenon: the role of definitions, Water Int., 10, 111–120, 1985.

Zhou, Q., Mikkelsen, P. S., Halsnæs, K., and Arnbjerg-Nielsen, K.: Framework for economic pluvial flood risk assessment considering climate change effects and adaptation benefits, J. Hydrol., 414, 539–549, 2012.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

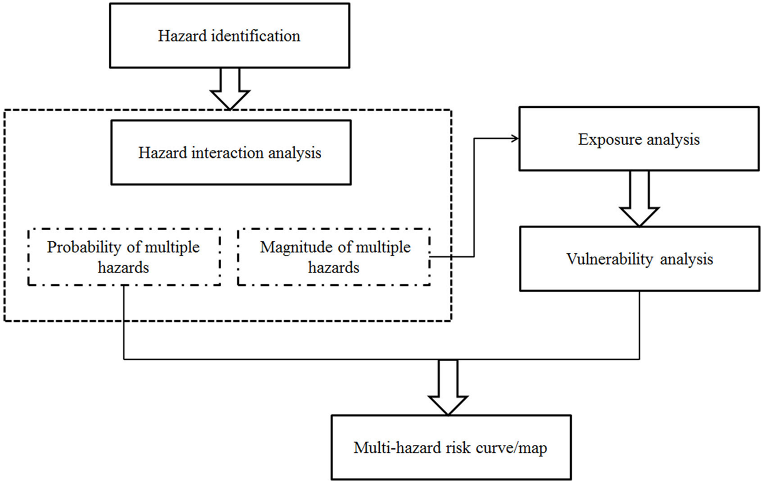

Figure 1. Basic framework of multi-hazard risk assessment.

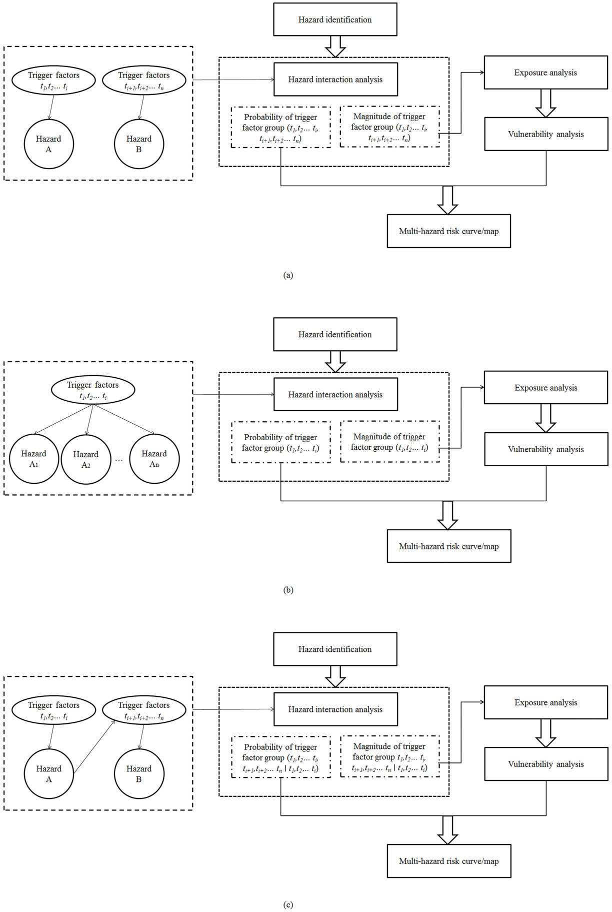

Figure 2. Multi-hazard risk assessment for hazards with different relationships: **(a)** independent relationship, **(b)** parallel relationship and **(c)** series relationship.