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Citation for published version:
Ni, J, Sun, L, Li, T, Huang, Z & Borthwick, AGL 2010, 'Assessment of flooding impacts in terms of sustainability in mainland China' Journal of Environmental Management, vol 91, no. 10, pp. 1930-1942., 10.1016/j.jenvman.2010.02.010

Digital Object Identifier (DOI):
10.1016/j.jenvman.2010.02.010

Published In:
Journal of Environmental Management

Assessment of Flooding Impacts in Terms of Sustainability in Mainland China

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Abstract An understanding of flood impact in terms of sustainability is vital for long-term disaster risk reduction. This paper utilizes two important concepts: conventional insurance related flood risk for short-term damage by specific flood events, and long-term flood impact on sustainability. The Insurance Related Flood Risk index, *IRFR*, is defined as the product of the Flood Hazard Index (*FHI*) and Vulnerability. The Long-term Flood Impact on Sustainability index, *LFIS*, is the ratio of the flood hazard index to the Sustainable Development Index (*SDI*). Using a rapid assessment approach, quantitative assessments of *IRFR* and *LFIS* are carried out for 2339 counties and cities in mainland China. Each index is graded from 'very low' to 'very high' according to the eigenvalue magnitude of cluster centroids. By combining grades of *FHI* and *SDI*, mainland China is then classified into four zones in order to identify regional variations in the potential linkage between flood hazard and sustainability.

Zone I regions, where *FHI* is graded 'very low' or 'low' and *SDI* is 'medium' to 'very high', are mainly located in western China. Zone II regions, where *FHI* and *SDI* are 'medium' or 'high', occur in the rapidly developing areas of central and eastern China. Zone III regions, where *FHI* and *SDI* are 'very low' or 'low', correspond to the resource-based areas of western and north-central China. Zone IV regions, where *FHI* is 'medium' to 'very high' and *SDI* is 'very low' to 'low', occur in ecologically fragile areas of south-western China. The paper also examines the distributions of *IRFR* and *LFIS* throughout mainland China. Although 57% of the counties and cities have low *IRFR* values, 64% have high *LFIS* values. The modal values of *LFIS* are ordered as Zone I < Zone II ≈ Zone III < Zone IV; whereas the modal values of *IRFR* are ordered as Zone I < Zone III < Zone IV < Zone II. It is recommended that present flood risk policies be altered towards a more sustainable flood risk management strategy in areas where *LFIS* and *IRFR* vary significantly, with particular attention focused on Zone IV regions, which presently experience poverty and a deteriorating eco-system.

Keywords: flood hazard; sustainability; rapid assessment; spatial characteristics; linkage; vulnerability

1. Introduction

The concept of sustainability has brought fundamental changes in terms of development and environment since the 1980s (Lélé, 1991). Sustainability involves considering the consequences of present actions from a long-term perspective, the goal being to achieve a satisfactory quality of life both in the present and in the future (Gasparatos et al., 2008). To help achieve this goal, various tools are being developed in order to obtain integrated measures of sustainability, including interactions between environmental, social and economic issues (Ravetz, 2000). Of these tools, indicators and indices are widely used due to their simplicity. Examples include the 58 national indicators used by the United Nations Commission on Sustainable Development (UNCSD), the Environmental Pressure Indicators (EPIs) developed by the Statistical Office of the European Communities (Eurostat), and the Sustainable National Income (SNI) indicator developed in the Netherlands (Ness et al., 2007). In China, a large number of indicators and indices have been proposed for measuring sustainable development. For example, a five-level indicator system was used to evaluate sustainability in 31 provinces in 1990 (Chinese Academy of Sciences Research Group on Sustainable Development, 1999). In the companion paper, a Sustainable Development Index (*SDI*) has been constructed from data relating to 2339 counties and cities in mainland China, based on a four-layer sustainable development index system with 31 basic indices (Sun et al., 2009).

Certain natural hazards can greatly hinder sustainable development. A major threat is posed by extreme natural water-related disasters, such as the European floods in 2002, the Indian Ocean Tsunami in 2004, and Hurricane Katrina in 2005. Such disasters can be devastating, and threaten to derail sustainable development (Griffis, 2007).

Cumulative impacts are caused by frequently occurring natural disasters. For developing and vulnerable countries, extreme disasters may destroy the groundwork towards sustainable development (Khandlhela and May, 2006). Of natural water-related hazards, flood events occur relatively frequently worldwide and can have severe impacts. Berz (2000) reports that about one-third of all natural disasters are flood-related, and provides data on the economic and human costs of major floods in the late 20th Century. There are some notable floods in history. For example, the Great Flood of 1993, which occurred in the American Midwest, caused between US$ 12 and 16 billion worth of damage (Hipple et al., 2005). Another example is the 2000 Mozambique Flood, which caused the worst flood damage in 50 years to local areas and displaced 450,000 people (Hashizume et al., 2006). China is particularly prone to flood disasters (Zong and Chen, 2000). Huge numbers of people have lost their lives in floods along the Yellow River, including more than 300,000 at Kaifeng in 1642, more than 870,000 in 1887 and between 100,000 and 4 million in 1931 (see e.g. White, 2001). In 1998, China experienced losses in excess of US$ 30 billion caused by the large-scale flooding of the Yangtze River (Berz 2000). However, conventional sustainable development indicators and indices are unable to reflect properly the long-term impacts of flood events.

Flood risk assessment and management are key prerequisites for flood disaster mitigation. As the philosophy of flood risk management evolves, flood hazard management has altered from an emphasis on physical protection schemes to flood risk management that incorporates both physical and socio-economic issues (Parker, 1995; Treby et al., 2006). It is the general consensus that flood risk is the product of physical hazard, exposure to the hazard, and vulnerability (Fedeski and Gwilliam, 2007; Kleinosky et al., 2007). Among the investigations on the relationships of these three basic elements of flood risk, "The Risk Triangle" by Crichton and Mounsey (1997) is notable for its readability and usefulness. At present, flood risk assessment and management focuses mainly on short-term economic losses, and insurance is conventionally used for compensation (Crichton, 2002). Herein, an index of insurance related flood risk (*IRFR*) is used to represent short-term flood impact. Nevertheless, this kind of flood management strategy seldom focuses on sustainable development scenarios.

Comprehensive risk assessment tools need to be developed to incorporate natural hazard risk management within development activities, instead of traditional reactive approaches that focus on humanitarian assistance (Dilley et al., 2005). Increasing attention is being given to the new philosophy of flood management (Ramlal and Baban, 2008; Morris et al., 2008; Hansson et al., 2008; Raaijmakers et al., 2008) and the long-term impact of flood disasters on human society (Birkmann, 2007). From the sustainability point of view, the subject of flood risk management should be widened to include the effect of flooding on sustainable development (associated with complex environmental, social and economic conditions). To measure this kind of flood impact, an index of Long-term Flood Impact on Sustainability (*LFIS*) is utilized in the present paper.

This paper aims to improve our understanding of the linkage between flood hazard and sustainability in modern China. In the companion paper, Sun et al. (accepted by Journal of Environmental Management, 2009) used a rapid assessment technique to evaluate a sustainable development index and hence provide a grading of sustainability. The same rapid assessment method is used in the present paper to represent flood hazards throughout mainland China. A zonation map of mainland China is then constructed using four zonal classes according to the combined distributions of flood hazard and sustainability. Differences between *IRFR* and *LFIS* in each zone are investigated. Based on this information, the relationship between flood hazard and sustainability in different areas in mainland China has been interpreted. The results are valuable for macro decision-making concerned with regional sustainable development strategy.

2. Methods

2.1 Quantitative approaches for IRFR and LFIS

IRFR assessment deals with short-term economic losses caused by flood events, a subject currently being investigated by many researchers (see e.g. Crichton and Mounsey, 1997; Crichton, 2002; Wisner et al., 2003; Tian et al., 2006). For comparison purposes at different spatial scales, it is convenient to use the following simplified flood risk model (Wisner et al., 2003) to estimate the expected value,

$$IRFR = FHI \times V \tag{1}$$

in which *FHI* is the Flood Hazard Index and *V* is the Vulnerability.

Insurance related flood risk (*IRFR*) mainly focuses on short-term flood impacts. Nowadays however, the conflict between the long-term requirement for regional sustainable development and the effect of short-term abrupt hazards threatens to become severe. A single flood hazard event could destroy the accumulated wealth amassed over several decades, and so has unsustainable characteristics. Considering that the conventional Sustainable Development Index (*SDI*) cannot properly reflect the impacts of extreme events on a case-by-case basis and that conventional flood risk assessment seldom focuses on long-term flood impacts, a new framework must be established urgently to evaluate the Long-term Flood Impact on Sustainability (*LFIS*). Usually, selected comparative indicators are used to quantify vulnerability, whose definition extends from intrinsic physical fragility to multi-dimensional vulnerability encompassing physical, social, economic, environmental and institutional features (Birkmann, 2006). It is therefore likely that linkages exist between sustainability and the multi-dimensional concept of vulnerability. Communities and societies with high sustainability could enhance their overall capability with regard to flood prevention, disaster mitigation and resilience. Hence, it could be argued that communities or societies with high sustainability should be less vulnerable to the impacts of disasters. An index of long-term flood impact on sustainability, *LFIS*, may be defined as the ratio of the Flood Hazard Index (*FHI*) to the Sustainable Development Index (*SDI*), as follows

$$LFIS = \frac{FHI}{SDI} \quad . \tag{2}$$

where *SDI* is the topmost index of the indicator system (4 layers with 31 basic indicators) developed by Sun et al. (accepted by Journal of Environmental Management, 2009) to measure the sustainable development in mainland China.

2.2 Assessment of LFIS in mainland China

In order to calculate *LFIS*, both *FHI* and *SDI* are evaluated using rapid assessment approaches developed from an earlier Rapid Zonation of Abrupt Mass-movement Hazard (RZAMH) method (Ni et al., 2006). The method has previously been demonstrated to be efficient, reliable, and capable of handling scarce data. The flow chart in Fig. 1 summarizes the rapid assessment procedure.

Fig. 1

2.2.1 Rapid assessment of FHI in mainland China

The rapid assessment method for flood hazard involves five key steps: (i) establishment of the flood hazard index system; (ii) data collection and preparation; (iii) classification of reference groups based on counties and cities with complete data; (iv) evaluation of missing information for counties and cities with incomplete data; (v) estimation of the degree of flood hazard experienced by counties and cities for which data are unavailable. A total of 2339 counties and cities in mainland China are considered, according to the administrative division of China in 1993. Details of the five key steps are given below.

(i) As shown in Fig. 2, a 3-layer indicator system is established for assessment of the flood hazard index ($i_{1,1}$). The assessment indicators of *FHI* are selected systematically,

Fig. 2

following the approach outlined in previous literature (Mccall et al., 1992; Burton et al., 1993; Rossi et al., 1994; Tian et al., 2006; Fedeski and Gwilliam, 2007). According to the systematic theory of regional disasters, hazard formative factors and environmental factors are important with regard to the evolution of a flood disaster. Three indicators are therefore selected as the 2nd layer sub-indices for the assessment of flood hazard: Climate ($i_{2,1}$), Geomorphology ($i_{2,2}$), and River network ($i_{2,3}$). Storm is a key formative factor for flood hazard. Geomorphologic and River Network parameters are primary environmental factors. The frequency of storms is important, but even a high frequency of occurrence of storms will not necessarily lead to floods if the precipitation does not exceed a certain threshold (e.g. 3 Days maximum rainfall depth above 30 mm). Therefore, Average Annual Rainfall ($i_{3,1}$) and 3 Days Maximum Rainfall ($i_{3,2}$) are selected as the 3rd layer sub-indices of the Climate sub-index. Geomorphology mainly affects the characteristics of runoff. Flood waves usually travel from regions with high absolute elevation and steep relief to low lying flat areas. Therefore, Absolute Elevation ($i_{3,3}$) and Average Regional Relief ($i_{3,4}$) are selected as the 3rd layer sub-indices of the Geomorphology sub-index. Finally, Buffer Zones ($i_{3,5}$) is selected as the 3rd layer sub-index of the River Network sub-index, in order to represent the influence of river systems on the flood attributes. The degree of Buffer Zones is determined according to distance to rivers and lakes, because regions near rivers and lakes are more likely to be affected by floods. Weights of the indicators were determined following Fan (2006).

(ii) A database is established for the 5 primary sub-indices in the 3rd layer for the 2339 counties and cities. Table 1 indicates the data sources and analysis techniques used to estimate the Flood Hazard Index, *FHI* (= $i_{1,1}$). The Average Annual Rainfall ($i_{3,1}$) and 3 Days Maximum Rainfall ($i_{3,2}$) sub-indices are determined as statistical mean values using about 50 years of data from 1951 to 2000 obtained from 620 rain gauges distributed throughout China. Values for the Absolute Elevation ($i_{3,3}$) and Average Regional Relief ($i_{3,4}$) sub-indices are obtained from a grid-based Digital Elevation Model (DEM) using Geographic Information System (GIS). The sub-index, Buffer Zones ($i_{3,5}$) is quantified using GIS Buffer analysis based on a grid-based map of the river basin distribution. Each sub-index in the 3rd layer is normalized to [0, 1] using the modified min-max normalization method. The Climate and River Network related sub-indices relate to positive contributions to the degree of flood hazard, whereas the Geomorphology related indices relate negatively to the degree of flood hazard. **Table 1**

(iii) To predict the flood hazard grading for those counties and cities with missing information, mapping units with complete data are selected as reference units and *K*-means clustering applied to classify the reference groups (Ni et al., 2006) using the statistical software package, SPSS (SPSS 11.5 for windows). Classification of reference groups is carried out sequentially from the primary layer to the middle-layer and finally to the uppermost layer. Of the 2339 mapping units, a total of 2336 counties and cities have complete data by which to determine the flood hazard sub-indices. As shown in Tables 2 and 3, seven reference groups are classified for the 2nd layer sub-indices, and five reference groups are classified for *FHI*. It should be noted that the eigenvalue $k_{m,n,j}$

(j=1, 2,…, K) of cluster centroids $Z_{m,n,j}$ is equal to the value of the sole sub-vector in the centroid or the sum of the sub-vector weighted values in multi-dimensional centroids. The *FHI* grading is then determined according to the magnitude of centroids as 'very low', 'low', 'medium', 'high' and 'very high', as listed in Table 3.

Table 2

Table 3

(iv) Among the 2339 counties and cities, 3 mapping units have incomplete data for the basic flood hazard sub-indices in the 3rd layer. Each test unit is matched to a reference group based on the minimum Euclidean distance from the cluster centroids, omitting blank data in the sub-indices (by means of a discriminating software program developed at Peking University). After identification, the eigenvalue and flood hazard grading of the corresponding reference group is assigned to the test unit. Table 3 lists the total numbers of mapping units.

(v) No counties or cities have blank data with regard to the flood hazard sub-indices.

2.2.2 Rapid assessment of SDI in mainland China

In the companion paper, Sun et al. (accepted by Journal of Environmental Management, 2009) use a sustainable development index, *SDI*, to measure the stability of sustainable development in mainland China. *SDI* places emphasis on development that meets competing social, economic and environmental needs. Sun et al. develop a four-layer sustainable development index system based on a top-down or technocratic process, which contains a total of 44 indicators with 31 sub-indices at the bottom level and *SDI* the unique index in the topmost layer. Three types of indicators are selected in the 2nd layer of *SDI*, i.e. System Development, System Coordination and System

Sustainability. The 3rd layer indicators include: Economic Development, Social Development, Environmental Development, Socio-economic Coordination, Enviro-economic Coordination, Socio-enviro Coordination, Economic Sustainability, Social Sustainability and Environmental Sustainability. A similar rapid assessment approach is applied herein to evaluate *SDI* for the counties and cities considered above. *SDI* was then classified into the following five grades: 'very high', 'high', 'medium', 'low' and 'very low', and mainland China divided into corresponding zones. It is found that regions with a relatively 'low' degree of sustainability account for about 47% of mainland China, regions with 'medium' sustainability account for about 31% of mainland China, whilst the remainder is relatively 'high'.

2.2.3 Grades of LFIS

Using Eq. (2), *LFIS* is then evaluated as the ratio of *FHI* to *SDI*. Five grades of *LFIS*, namely 'very low', 'low', 'medium', 'high' and 'very high', are determined according to the magnitude of the eigenvalues of the centroids of the five classification groups using *K*-means clustering. Table 4 lists the eigenvalues, grades, and number of units **Table 4** assigned to each grading of *LFIS*.

2.3 Assessment of IRFR in mainland China

A simplified form of conventional risk, *IRFR*, is estimated using Eq. (1), which is the product of *FHI* and the vulnerability, *V*. The procedure again involves the following five steps: establishment of the index system, data collection and preparation, classification of reference groups, identification of matching groups and evaluation of blank mapping units.

(i) Vulnerability means the sensitivity, inability or lack of response capability to external stress or disaster (Dixit, 2003; Tian et al., 2006; Dingguo et al., 2007; Speakman, 2008). From the macroscopic point of view, a flood may cause casualties, property loss and infrastructure damage. The index of Per-Capita Gross Domestic Product ($i_{2,1}$) is selected to reflect economic loss caused by flood. Population Density ($i_{2,2}$) is selected to reflect the casualties caused by flood. Arable Land Density ($i_{2,3}$) is selected for agriculture loss in rural areas. Road Density ($i_{2,4}$) is selected to reflect the infrastructure damage **Fig. 3** caused by flood. Fig. 3 shows the indicator system for vulnerability to flood hazard.

(ii) Data on the four 2nd layer sub-indices have been obtained from statistical databases, including the Social and Economic Statistics of County (City) in China, 2005. The collected data are normalized to [0,1] using modified min-max normalization.

(iii) Of the 2339 counties and cities, a total of 1875 mapping units have complete data for each sub-index. These counties and cities are again classified into five reference groups using K-means clustering. The grading of vulnerability to flood hazard is then determined as ‘very low’, ‘low’, ‘medium’, ‘high’ and ‘very high’ according to the magnitudes of centroids of five reference groups. The results are listed in Table 5. **Table 5**

(iv) A total of 464 mapping units have incomplete data. Table 5 also presents the eigenvalues and grading of the matched reference groups for the test counties and cities with incomplete data. The identification process has also been carried out by means of the discriminating software program developed at Peking University.

(v) No counties or cities have blank data regarding the vulnerability related sub-indices.

IRFR is then computed using Eq. (1), and the grading determined using a classification matrix based on the grade of flood hazard and the grade of vulnerability to flood hazard.

3 Results and Discussion

3.1 Zonal classification

Fig. 4 shows a scatter diagram relating *FHI* and *SDI* for all the 2339 counties and cities considered. *FHI* ranges from 0.12 to 0.97 and *SDI* ranges from 0.30 to 0.77. Fig. 5(a) indicates the land area percentage calculated for each zone according to combinations of each grade of *SDI* and *FHI*. Two peaks are evident: one where 21% of the land area of mainland China has 'very low' *SDI* and *FHI* values; the other where 15 % has 'medium' *SDI* and 'very low' *FHI*. Each remaining area with different combinations of *SDI* and *FHI* grades occupies no more than 6 % of the total land area. As shown in Fig. 5(b), four zones were devised according to the various combinations of grades of *FHI* and *SDI*. In Zone I regions, the counties and cities have 'very low' to 'low' grades of *FHI* and 'medium' to 'very high' grades of *SDI*; in Zone IV the reverse is the case. In Zone II, the counties and cities have 'medium' or 'high' grades of both *FHI* and *SDI*. In Zone III, the counties and cities have 'very low' or 'low' grades of *FHI* and *SDI*. Fig. 6 is a zonation map depicting the spatial distribution of these four zones throughout mainland China.

Fig. 4

Fig. 5

Fig. 6

3.2 Characteristics of four types of zones

Table 6 lists the spatial characteristics of the four zones. It is found that Zone I, II, III, and IV regions occupy 31 %, 23 %, 32 % and 14 % of the total land area of mainland China.

Table 6

The terrain of mainland China can be divided into three levels. The first comprises the Qinghai-Tibet Plateau, located at about 3000 to 5000 m AMSL, with Kunlun Mountain as the northern boundary and Hengduan Mountain as the eastern boundary. The second level is located to the east of the first level and to the west of Daxinganling – Taihang Mountain – Wuling Mountain, and includes the Inner Mongolia Plateau, Loess Plateau, Sichuan Basin and Yunnan-Guizhou Plateau. The third level stretches from Daxinganling – Taihang Mountain – Wuling Mountain to Binhai, and includes an alluvial plain located below 200 m AMSL as well as foothills below 1000 m AMSL.

Zone I regions are mainly located in the under-developed areas of north-western China, including Xinjiang province, the west of Inner Mongolia, and parts of Gansu and Qinghai provinces. Other Zone I regions are located in North-China, including Shanxi and Hebei provinces. From a geomorphologic point of view, Zone I is located at the west of the second level, and includes the Tarim Basin, Dzungaria Basin, western Inner Mongolia Plateau and Loess Plateau. From a climatic point of view, Zone I is located at the west of Daxinganling – Helanshan Mountain – Hengduanshan Mountain. The average rainfall in most Zone I regions is lower than 200 mm. There is less likelihood of flood occurrence in Zone I. Instead, water scarcity is the key limiting factor for social-economic sustainable development. Therefore, integrated flood strategies should give priority to the sustainable use of water resources in Zone I.

Zone II regions are mainly located in the rapidly developing areas of central and eastern China, including most north-eastern areas, Hebei, Shandong, South-east plains and southeastern coastal areas. From a geomorphologic perspective, the Zone II regions are mainly located at the third level of the terrain of mainland China, which, along with seven rivers, comprise China's worst flood disaster areas. With respect to sustainability, most counties and cities in Zone II have achieved a high level of social-economic development in addition to abundant scientific, knowledge, financial and management resources. Therefore, the focus should be on systems projects that optimize industrial structure, land use and flood control.

The Zone III regions are mainly located in the resource-based areas of western and north-central China, including Tibet, west of Sichuan, north of Yunnan, Ningxia, Gansu, Qinghai, Shanxi and Shaanxi provinces. With regard to geomorphology, the Zone III regions are mainly located at the first level and northern second level of the terrain of mainland China, including the Qinghai-Tibet Plateau, eastern Inner Mongolia Plateau and Loess Plateau. Snowfall and freezing damage are the main drivers of natural disasters in the Qinghai-Tibet Plateau. As a result of soil erosion and the increasing elevation of the Weihe river bed, relatively low discharges could nevertheless have catastrophic effects that threaten the socio-economic development of the Weinan areas in the Loess Plateau. Moreover, these regions are resources-based development areas: Shanxi province relies on coal production; Shaanxi province is prosperous because of mining. Their economic development mainly depends on the consumption of local stocks of existing resources. In inter-regional terms, these activities lead to trade issues, economic structural imbalances, depletion of resources, and environmental damage. The contradiction between economic development and social and environmental development reduces regional sustainability, increases regional vulnerability, and lowers regional capacity with regard to comprehensive flood control and disaster mitigation. Therefore, the mode of economic development should be altered to reduce the vulnerability of the complex social-economic-environmental system.

Zone IV regions are mostly located in ecologically fragile areas in south-western China, including Sichuan, south Yunnan, Guizhou, and Guangxi provinces. In terms of geomorphology, the Zone IV regions are mostly located at the southeast of the second level and at the transition zone between the first level and the second level of the terrain of mainland China, where the topography is complicated and rainstorms can have extremely high magnitude. Flood disasters are more likely to occur in these regions. For example, the Sichuan basin is prone to ground saturation by water, and landslides are triggered by the floods in the Yunnan-Guizho Plateau. Moreover, Zone IV regions are typically karst areas with serious rocky desertification, and are ecologically sensitive. Poverty and ecological deterioration are the limiting factors for sustainable development in these regions. Ecological deterioration could further increase the likelihood of flood events thus triggering further environmental damage. Thus, restoration and rehabilitation of the ecosystem is vital for the sustainability of Zone IV regions.

Zone I and Zone III regions are of greatest extent and are located mainly in western China and north-central China, both of which areas have relatively low degree of flood hazard mainly due to their high altitude and arid climate. Zone II regions experience relatively high exposure to flood hazards primarily because of their low altitude, proximity to the sea and lower reaches of major rivers, and susceptibility to frequent storms. Zone IV regions generally have a relatively high grade regarding flood hazard; this is partly due to water retention by the Sichuan basin and mountain floods in south-western China. Although Zone I and Zone II regions both have relatively high grades of *SDI*, their characteristics are totally different. Zone II regions tend to involve counties and cities that are undergoing rapid socio-economic development. Due to resource limits, environmental pollution, and ecological deterioration caused by traditional industries, counties and cities in Zone II regions are presently upgrading their industrial bases to be more ecologically sustainable. Zone I regions are in the early stage of industrialization and have low levels of socio-economic development. Their *SDI* values are nevertheless high due to the natural resources available and the quality of the environment. Zone III and Zone IV regions have low levels of social-economic development corresponding to low *SDI*. The combination of resources-based economic growth, high consumption, and high pollution form barriers to the sustainable development of Zone III areas in north-central China. In Zone IV regions, sustainable development is severely impeded by the fragile ecological and geological conditions.

3.3 Comparison of LFIS and IRFR at national and regional levels

Fig. 7 presents frequency bars for *LFIS* and *IRFR* obtained for all the 2339 counties and cities in mainland China. More than 64% of the counties and cities have *LFIS* values in the range from 1.1 to 1.7, which mostly correspond to 'high' grade long-term flood impact on sustainability. About 57% of the counties and cities have an *IRFR* value in the range from 0.01 to 0.10, corresponding to a 'low' degree of conventional insurance related flood risk. These results indicate that the long-term flood risk may be potentially high and measures should be taken to improve current policies aimed at sustainable flood risk management.

Fig. 7

Socio-economic and environmental conditions vary greatly throughout China. Therefore, zonal distributions of *LFIS* and *IRFR* are investigated. Fig. 8 presents the frequency bars for *LFIS* and *IRFR* related to each of the four zones classified above according to the *SDI* and *FHI* grading. For the majority of counties and cities falling within the vertical dashed lines in Fig. 8, the average grading of *LFIS* is generally higher than that of *IRFR*, as also occurs at national level. For *LFIS*, the majority of cities and counties have values from 0.7 to 1.1 for Zone I, from 1.1 to 1.5 for Zone II, from 1.0 to 1.4 for Zone III and from 1.4 to 1.8 for Zone IV. The modal values of *LFIS* are therefore ordered as follows: Zone I $<$ Zone II $\approx$ Zone III $<$ Zone IV. For *IRFR*, its values for the majority of cities and counties lie from 0.01 to 0.05 for Zone I, 0.06 to 0.20 for Zone II, 0.04 to 0.06 for Zone III and 0.01 to 0.14 for Zone IV, with the following modal order: Zone I $<$ Zone III $<$ Zone IV $<$ Zone II. Counties and cities in Zones III and IV have relatively low *IRFR* and relatively high *LFIS*. In certain of these

Fig. 8

areas, potential flood impacts on sustainability may cause long-term poverty or instability of the socio-economic-environmental system. Moreover, uncoordinated development of the socio-economic-environmental system may lead to higher vulnerability to flood hazard. Therefore, more investment or better integrated flood strategies are needed in such regions.

Fig. 9 compares the spatial distribution of the gradings of *LFIS* and *IRFR* in terms of the four zones. As shown in Fig. 9 (a) & (b), 93 % of the Zone I land area corresponds to identical grading of 'very low' or 'low' for both *LFIS* and *IRFR*. This suggests that flood hazard has low impact on the under-developed areas of western China, which is mostly due to the arid climate. From Fig. 9 (c) & (d), it is found that the *LFIS* and *IRFR* grades exhibit marked differences when compared for the same Zone II regions; only 36 % of these areas have identical grading, and are to be found in Heilongjiang, Hebei and Shandong provinces. The following two kinds of area require attention due to substantial differences in grading of *LFIS* and *IRFR*. (i) Liaoning and Jilin provinces in northeast China, where most *IRFR* grades are 'low' and most *LFIS* grades are 'medium'. Extensive agricultural activity has caused heavy soil erosion in these areas, which consequently increases *LFIS*. (ii) Regions in the south-central plain and south-east coastal areas, where *IRFR* grades are 'low' or 'medium', and *LFIS* grades tend to be 'medium' or 'high'. These regions include an area dominated by the lower reach of the Yangtze River where Jiangxi, Anhui and Hunan provinces meet. Most counties and cities near the lower Yangtze River have experienced frequent flood hazards throughout

Fig. 9

recorded history. Furthermore, there is considerable disparity between rural and urban economic development in these regions even though the cities have undergone rapid development while being highly exposed to the flood hazard. This has had the effect of lowering the *IRFR* grading. As shown in Fig. 9 (e) & (f), about 56 % of the Zone III areas correspond to identical grades of *LFIS* and *IRFR*, and are mostly located in Tibet, Qinghai and western Sichuan. However, in northern Yunnan, Shanxi and north-eastern Inner Mongolia, *IRFR* tends to be 'low' grade, while *LFIS* tends to be 'medium' or 'high' grade. In these areas, especially in Shanxi province, the side effects of over-exploitation of natural resources and uncoordinated economic and environmental development have resulted in higher grades of *LFIS* than *IRFR*. From Fig. 9 (g) & (h), it may be observed that 95 % of the Zone IV areas have different grades of *LFIS* and *IRFR*. Most *IRFR* grades are 'low' whilst most *LFIS* grades are 'high' or 'very high'. Areas of particular concern are located in Guangxi, southern Guizhou & Yunnan, and eastern Sichuan, where flood hazards frequently occur along with subsequent debris flows and landslides. The higher level of *LFIS* than *IRFR* experienced in these regions is exacerbated by their Karst topography, uncontrolled land-use, and deteriorating ecological conditions.

3.4 Validation of the results

Present studies on flood risk assessment focus on the evaluation of *IRFR*. Therefore, validation of *IRFR* is carried out through comparison of the evaluation results obtained herein with results obtained by the GIS overlay technique (Li, 2004). To validate the results, 20 cities are selected. The absolute values of *IRFR* evaluated by the two approaches are normalized ($IRFR_i/IRFR_{max}$) to [0, 1] to eliminate scaling effects. As shown in Fig. 10, the normalized values of *IRFR* obtained by the two approaches are **Fig. 10** consistent. An investigation of the similarity between the normalized results obtained by the two approaches demonstrates their close agreement, with Pearson coefficient = 0.938 and Cosine coefficient = 0.990.

Validation of *LFIS* is awkward, because it is presented for the first time (to the authors' knowledge) in this paper. As *LFIS* provides an overall evaluation of the Flood Hazard Index (*FHI*) and the Sustainable Development Index (*SDI*), validation of the assessment results for *SDI* could be used as an indirect means of validating *LFIS*. Validation of *SDI* is carried out in the companion paper (Sun et al., accepted by Journal of Environmental Management, 2009) where close agreement is found between the results obtained by the present rapid assessment approach and a systems analysis technique (with Pearson coefficient = 0.957 and Cosine coefficient = 0.998).

3.5 Recommendations for sustainable flood risk management

Close attention should be paid to changing flood risk management policies in areas where the grading of *LFIS* and *IRFR* is significantly different (i.e. by at least two grades). In particular, Zone IV regions are of concern because their *IRFR* grades are much lower than their corresponding *LFIS* grades. Present flood risk management policies being implemented in these regions may not be sufficiently sensitive to the long-term impact of flood hazard.

For counties and cities in Zone I regions, the likelihood of flood hazard occurrence is very low, and both *LFIS* and *IRFR* grades are 'low' due to the relatively low vulnerability to flood hazard and relatively high sustainability. Water scarcity impedes the regional sustainability of counties and cities in Zone I, and sustainable use of water is vital for the socio-economic development of Zone I regions. Recommendations are as follows: (i) domestic water supply and water for various socio-economic activities should be limited so that the ecological water requirement is met; (ii) water-use efficiency should be improved; and (iii) the protection of natural forest resources and soil and water conservation should be strengthened.

In Zone II regions in central and eastern China where rapid development has already taken place, any major flood event would obviously have a deleterious impact on sustainable development. Integrated flood strategies should focus on systems optimization of the industrial structure, land-use projects, and flood control countermeasures. For example, particular consideration should be given to the lower Yangtze River basin where socio-economic development is occurring rapidly, with a higher level of *LFIS* than *IRFR*. Engineering flood prevention countermeasures should be strengthened due to the relatively high degree of flood hazard. With this in mind, the following recommendations are suggested: (i) utilize integrated management systems to control the soil erosion in river basin; (ii) enhance communications and improve the flood forecasting system; (iii) develop a support system for flood control decision-making and hence improve the flood risk management system; and (iv) upgrade the mode of development through industrial restructuring to reduce the vulnerability of the overall socio-economic-environmental system.

Turning to the Zone III regions in western and north-central China, policy makers should reconsider the prime modes of production by which the natural resources are exploited. This is especially the case for northern Yunnan, Shanxi and north-eastern Inner Mongolia, where flood risk vulnerability is increased by unregulated mining activities. By altering mining practices in these regions as part of a comprehensive flood risk management strategy, considerable improvements could be made to the local ecology and landscape that also have a beneficial effect on flood prevention. In implementing a comprehensive flood strategy, the following actions should be considered: (i) improve the effectiveness of soil and water conservation measures, halt unreasonable development activities, and encourage ecological agricultural practices; (ii) promote the construction of ecological cities whose infrastructure is designed for environmental protection; (iii) develop the circular economy, upgrade industry, and promote alternative industries in order to steer away from the present resources-based economy; and (iv) strengthen the environmental protection of mining areas and improve flood risk management in these areas.

For the ecologically fragile Zone IV region in southwest China, flood risk is associated with other geological hazards, such as landslide and mass movements (Liu et al., 2006). Typical karst areas are mainly located in the Zone IV regions, particularly in Guangxi, southern Yunnan and eastern Sichuan. The karst topography and associated deterioration of the ecological environment influence the environmental factors that affect floods. Three types of flood disaster typically occur in these areas: mountain flood; slope flood; and karst depression flood. Such flood events may induce secondary disasters that have deleterious effects on the already fragile local ecosystem. Therefore, integrated flood strategies should focus on restoration and rehabilitation of the ecosystems in Zone IV regions. In implementing comprehensive flood countermeasures, it is recommended that the following actions should be undertaken: (i) stop reclamation of steep slopes for cultivation, and instead encourage forestation, conversion of cropland to forest, and rehabilitation of the storage and adjusting functions of the forest-soil system; (ii) strengthen overall control of soil erosion, taking small river valleys as treatment units; (iii) improve the 'rocky desertification' of karst development areas, and encourage the restoration and rehabilitation of the fragile karst ecosystem; (iv) promote ecological agriculture to enhance environmental protection; (v) prevent unreasonable economic activity in flash flood-prone areas; (vi) improve forecasting, monitoring and emergency response systems for flash flood related disasters in flood-prone areas; and (vii) increase public awareness of flood disasters to minimize the consequences of floods.

4 Conclusions

China has a long history of natural flood disasters. Over the past three decades, China has enjoyed rapid economic development, and embraced the need for sustainability. With this in mind, the present paper has examined the possible linkages between flood hazard and sustainable development in mainland China. Two parameters have been used to characterize short-term and long-term flood impacts. The first was insurance related flood risk (*IRFR*), based on short-term economic losses caused by floods. The second comprised an index of long-term flood impact on sustainability (*LFIS*), obtained as the ratio of a flood hazard index (*FHI*) to a sustainable development index (*SDI*). Then, *IRFR* was evaluated for counties and cities throughout mainland China using a rapid assessment approach, which is efficient, reliable and able to deal with data scarcity. *LFIS* was determined using *FHI* values estimated using the same rapid assessment method and *SDI* values obtained in the companion paper by Sun et al. (accepted by Journal of Environmental Management, 2009). Both *FHI* and *SDI* have been graded into 'very low', 'low', 'medium', 'high', and 'very high' classes, and four zones determined for mainland China according to a matrix of prescribed combinations of the flood hazard and sustainable development grades. It has been found that Zone I regions are mostly located in under-developed areas in western China, which have relatively low *FHI* and relatively high *SDI* values; Zone II regions are mostly located in rapidly developing areas in eastern and central China, which have relatively high *FHI* and *SDI* values; Zone III regions are mostly located in the resources-based areas of western and north-central China, where *FHI* and *SDI* both have relatively low values. Zone IV regions are mostly located in ecologically fragile areas of southwest China that have relatively high *FHI* and relatively low *SDI*. About 63 % of the total land area of mainland China corresponds to Zone I and Zone III regions.

Comparison between *LFIS* and *IRFR* is helpful to better understand the flood impact in terms of sustainability. At the national level, 64 % counties or cities have high *LFIS*, whilst 57 % have low *IRF*R. This suggests that the Chinese authorities should consider realigning their present flood risk policies for most regions of China towards sustainable flood risk management. In general terms, the policies for Zone III and Zone IV region merit particular attention, because *LFIS* follows the order: Zone I < Zone II ≈ Zone III < Zone IV, whereas *IRFR* follows: Zone I < Zone III < Zone IV < Zone II. For Zone I regions, policy makers should aim for more sustainable economic development. For Zone II regions, integrated flood risk management is recommended, incorporating changes to the industrial, technological and knowledge bases, while enhancing the portfolio of countermeasures available to deal with potential flood events. For Zone III regions, a comprehensive flood risk management strategy is required that ameliorates the effect of unregulated extraction and processing of natural resources. Finally, for Zone IV regions, the flood risk management policy should be in keeping with the needs of the eco-system.

Acknowledgements

Financial support is from the Major State Basic Research Program of People's Republic of China (Grant No. 2007CB407202) and National Natural Science Foundation of China (Grant No. 40371011). Data sources: www.naturalresources.csdb.cn.

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List of Tables and Figures

Tables:

Table 1 Data sources and analysis techniques used to estimate *FHI*

Item	Basic index	Data sources	Technique
Climate ($i_{2,1}$)	Average Annual Rainfall ($i_{3,1}$) 3 Days Maximum Rainfall ($i_{3,2}$)	Daily climatic database of China for 620 stations from 1951 to 2000	Statistical analysis of mean annual values over last 50 years & Interpolation by Kriging technique
Geomorphology ($i_{2,2}$)	Absolute Elevation ($i_{3,3}$) Average Regional Relief ($i_{3,4}$)	1:3,000,000grid-based digital elevation model of China (1km×1km),2000	Sampling the range in elevation (relief) within 5km×5 km grid area & Calculating the average relief with GIS tools
River Network ($i_{2,3}$)	Buffer Zones ($i_{3,5}$)	1: 4,000,000 grid-based map of river basin distribution, 2000	Statistical analysis of the river network data via Buffer analysis of GIS

Table 2 Eigenvalues of centroids for 2nd layer sub-indices for *FHI*

	Class (j)	1	2	3	4	5	6	7
Climate ($i_{2,1}$)	Eigenvalue ($k_{2,1,j}$)	0.98	0.36	0.82	0.72	0.92	0.60	0.83
	Number of units in reference groups	645	165	430	206	456	172	265
Geomorphology ($i_{2,2}$)	Eigenvalue ($k_{2,2,j}$)	0.87	0.50	0.30	0.70	0.53	0.14	0.36
	Number of units in reference groups	226	216	383	373	350	463	328
River Network ($i_{2,3}$)	Eigenvalue ($k_{2,3,j}$)	0.46	0.15	0.02	0.81	0.98	0.29	0.64
	Number of units in reference groups	221	486	1008	86	107	284	144

Table 3 Eigenvalues, ranks and number of units for *FHI*

	Class (j)	1	2	3	4	5
Flood Hazard ($i_{1,1}$)	Eigenvalue ($k_{1,1,j}$)	0.46	0.64	0.55	0.31	0.77
	Number of units in reference groups	341	625	592	312	466
	Ranks	'Low'	'High'	'Medium'	'Very low'	'Very high'
	Total number of units	341	628	592	312	466

Table 4 Eigenvalues, ranks, and number of units for *LFIS*

Class (j)	1	2	3	4	5
Eigenvalue ($k_{1,1,j}$)	1.45	1.23	0.70	1.01	1.75
Ranks	'High'	'Medium'	'Very low'	'Low'	'Very high'
Number of units	708	510	234	379	508

Table 5 Eigenvalues of centroids for vulnerability to flood hazard

	Class (j)	1	2	3	4	5
Vulnerability to Flood Hazard ($i_{1,1}$)	Per-capita GDP	0.84	0.06	0.83	0.04	0.23
	Population Density	0.59	0.23	0.93	0.12	0.45
	Arable Land Density	0.39	0.68	0.41	0.21	0.54
	Road Density	0.61	0.32	0.32	0.25	0.37
	Eigenvalue ($k_{1,1,j}$)	0.64	0.27	0.70	0.13	0.38
	Number of units in reference groups	56	343	81	1129	266
	Ranks	'High'	'Low'	'Very high'	'Very low'	'Medium'
	Total number of units	77	359	146	1489	268

Table 6 Spatial distribution of Zones I, II, III and IV in mainland China

Zones	Regions	No of units	Percentage of land area (%)
Zone I Under-developed areas in north-western China	Xinjiang, west of Inner Mongolia, parts in Gansu, Qinghai & Hebei	193	31
Zone II Rapidly developing areas in central and eastern China	Most north-eastern areas, Hebei, Shandong, South-east plains, east and southeast costal areas	1061	23
Zone III Resource-based areas in western and north-central China	Tibet, west of Sichuan, north of Yunnan, Ningxia, Gansu, Qinghai, Shanxi and Shaanxi	460	32
Zone IV Fragile-ecological areas in south-western China	Sichuan basin, southYunnan, Guizhou, and most Guangxi, minority in south-east plains	625	14

Figures:

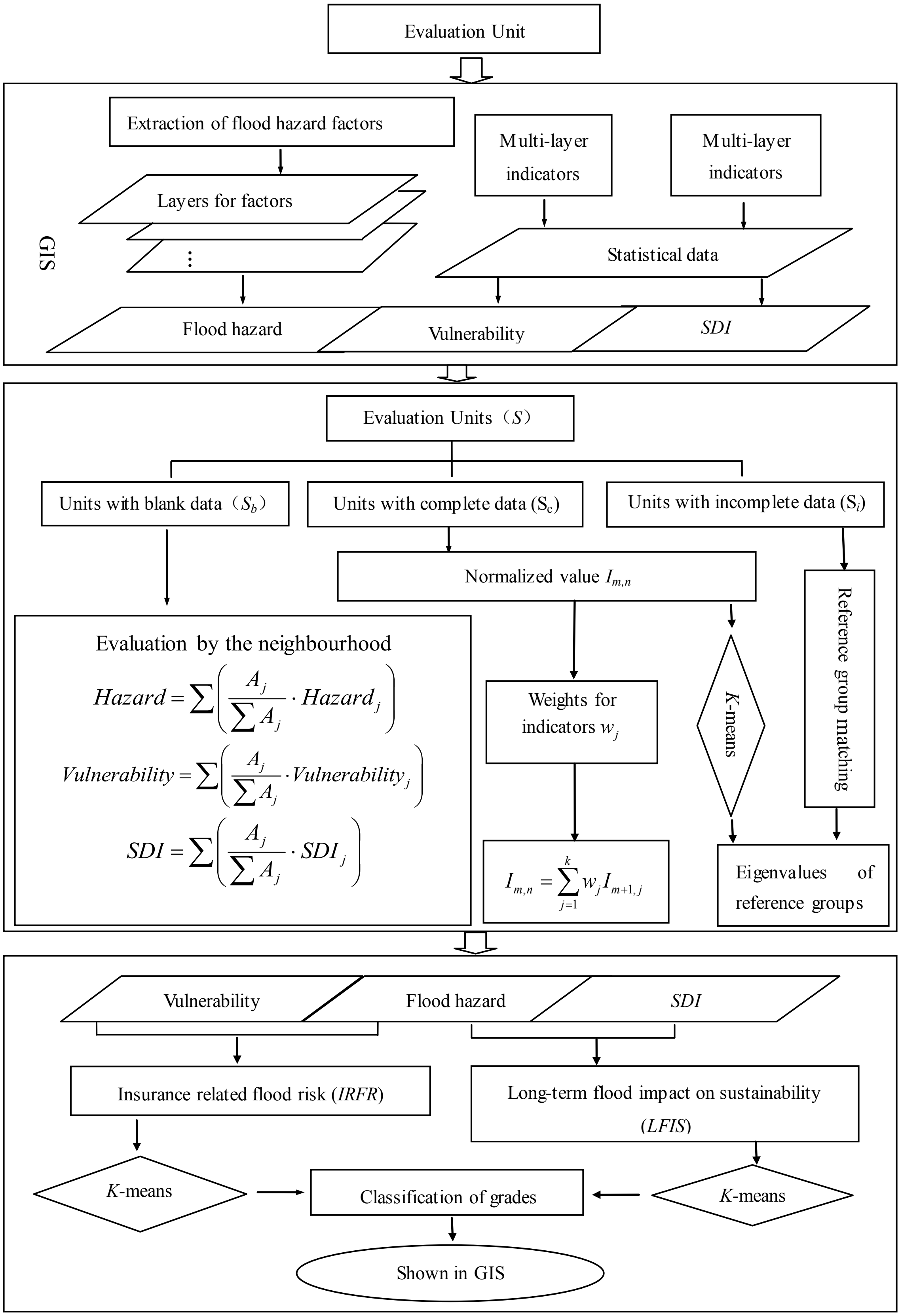


Fig. 1 Technique route of rapid assessment

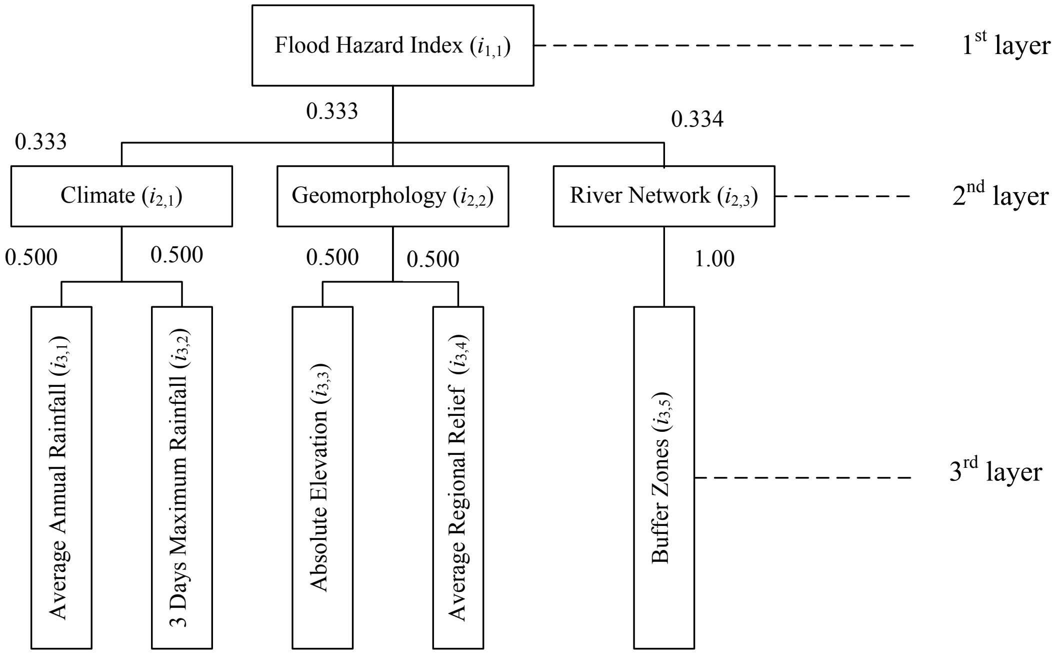


Fig. 2 Indicator system for flood hazard in mainland China

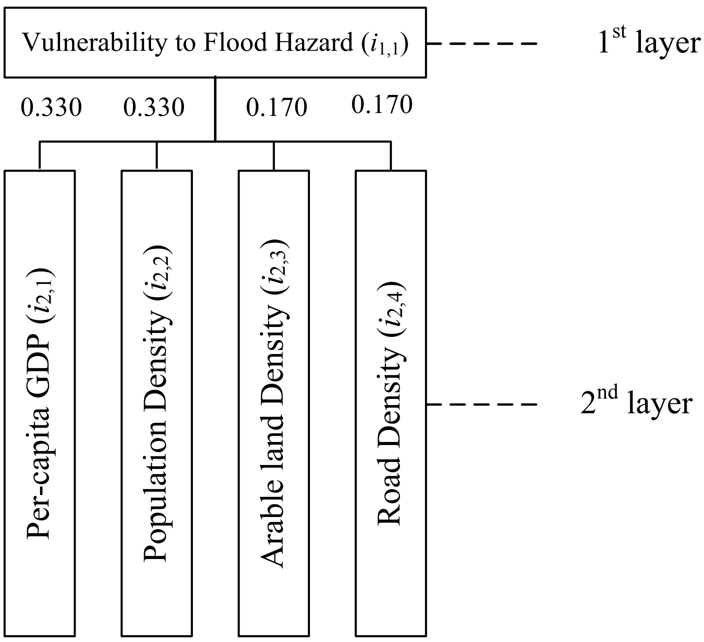


Fig. 3 Indicator system for vulnerability to flood hazard in mainland China

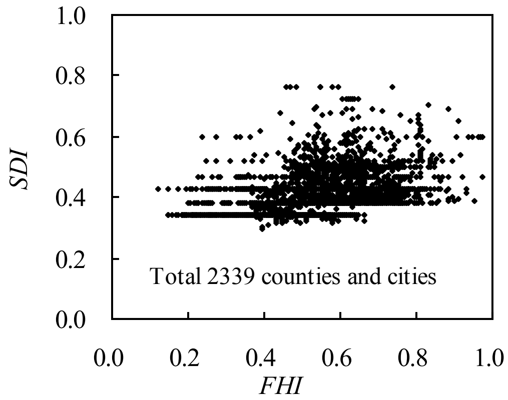
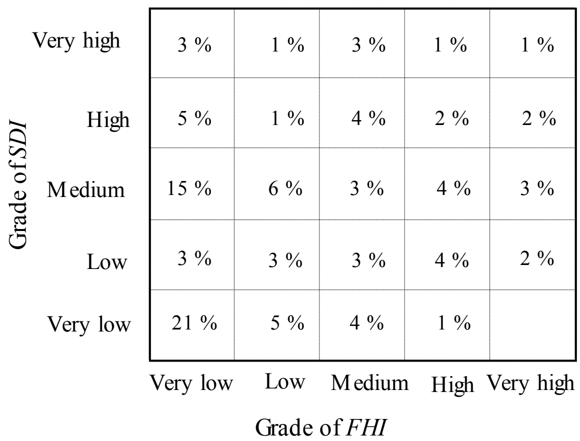
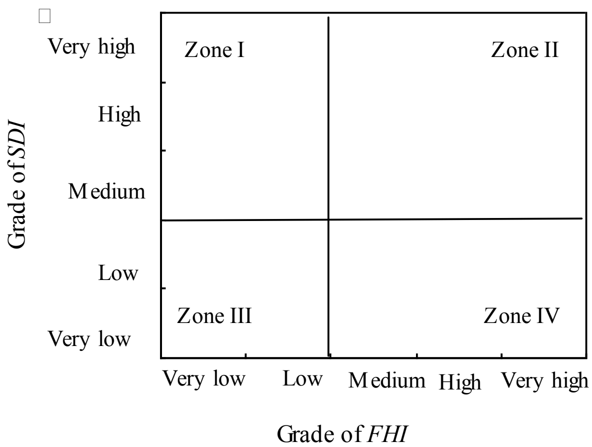


Fig. 4 Scatter plot of *SDI* against *FHI*



(a)



(b)

Fig. 5 Area percentages and combinations of *FHI* and *SDI* according to their grades and Zonal classification according to *SDI* and *FHI* grading

(The number in the grid of (a) is the area percentage of each combination of *SDI* and *FHI*)

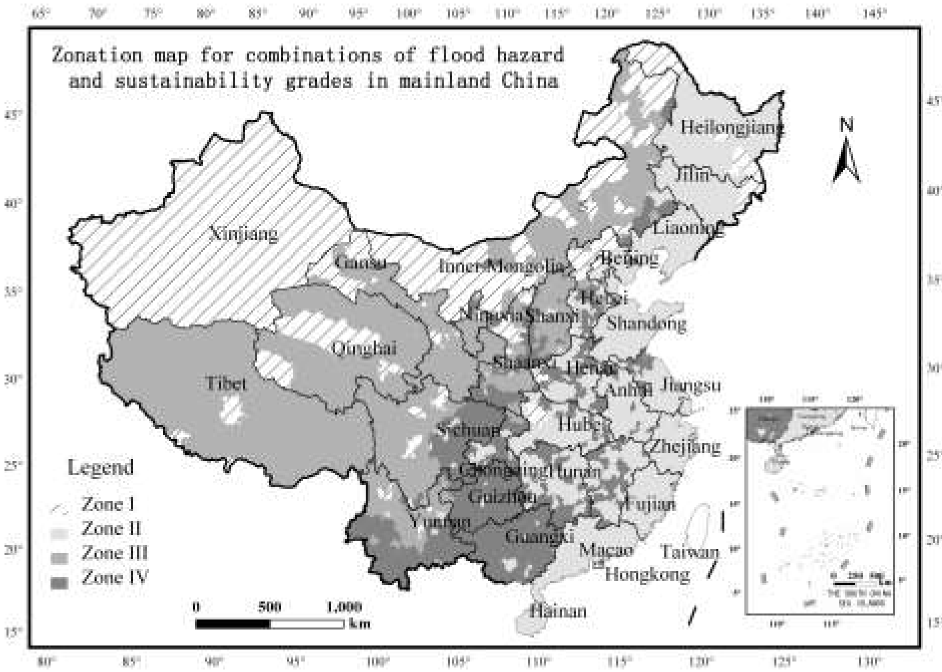


Fig. 6 Zonation map for combinations of flood hazard and sustainability grades in mainland China

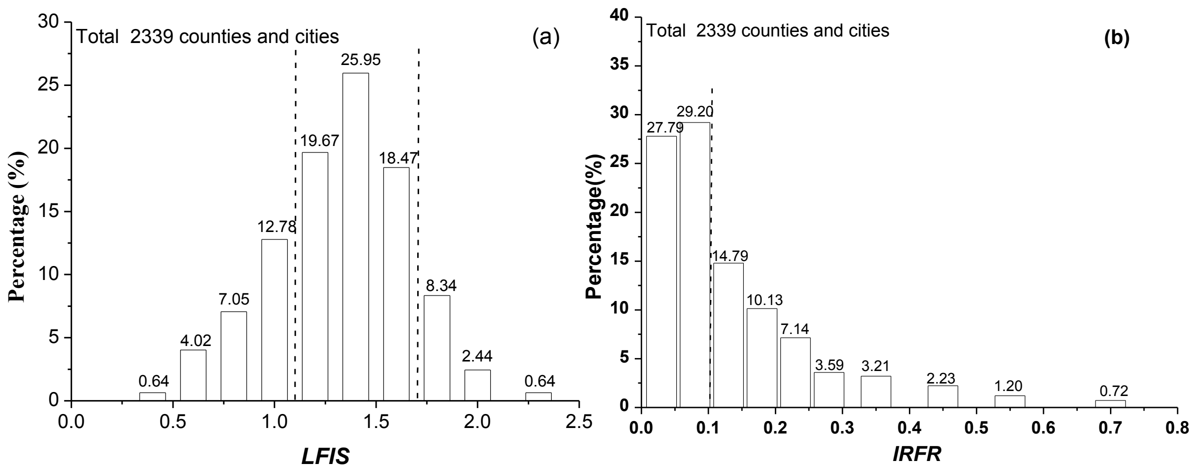
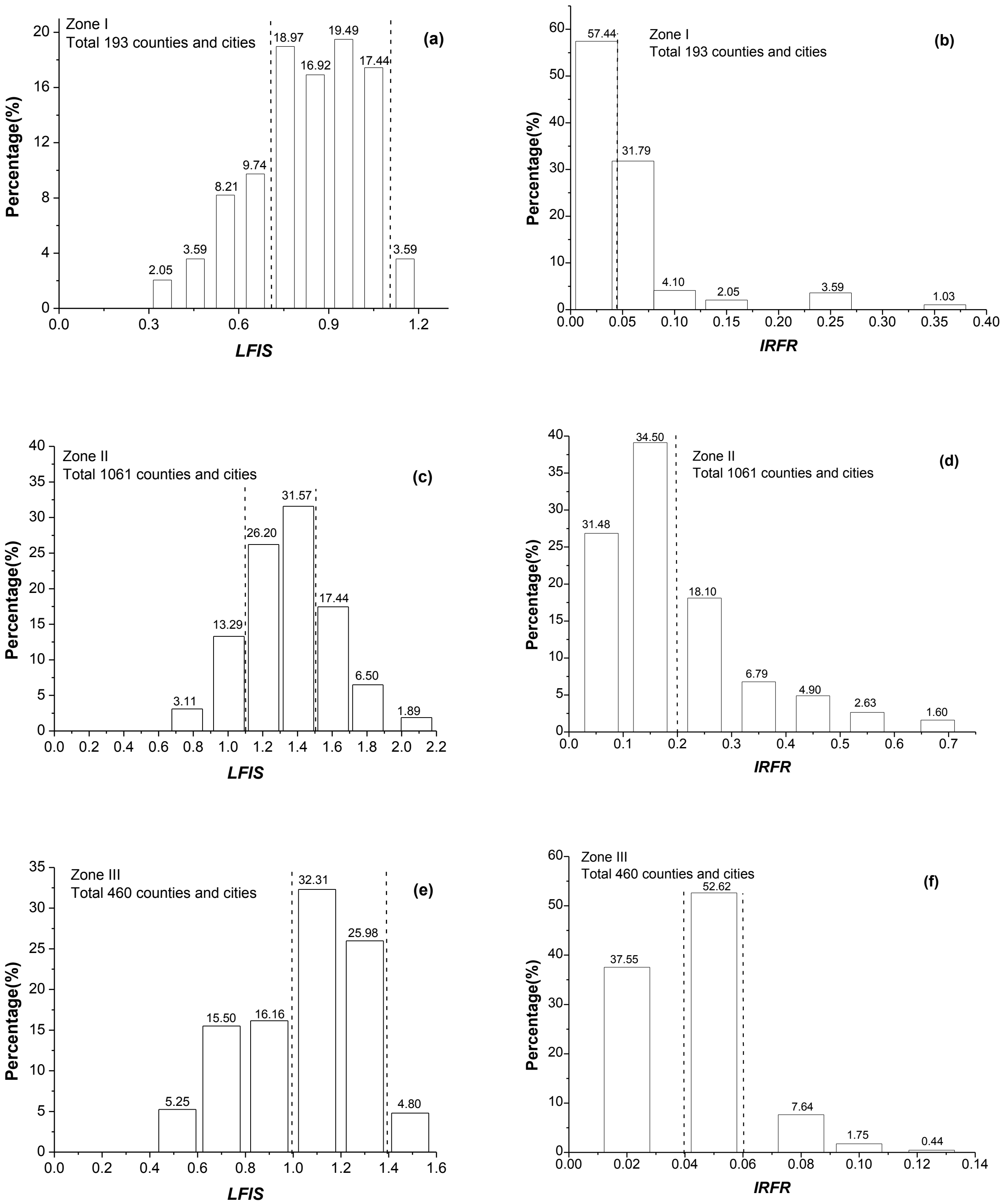


Fig. 7 Frequency bars for *LFIS* and *IRFR* at national level


Zone I
Total 193 counties and cities
(a)
Percentage(%)
LFIS
2.05
3.59
8.21
9.74
18.97
16.92
19.49
17.44
3.59
0.0
0.3
0.6
0.9
1.2
0
4
8
12
16
20
Zone I
Total 193 counties and cities
(b)
Percentage(%)
IRFR
57.44
31.79
4.10
2.05
3.59
1.03
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0
10
20
30
40
50
60
Zone II
Total 1061 counties and cities
(c)
Percentage(%)
LFIS
3.11
13.29
26.20
31.57
17.44
6.50
1.89
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
0
5
10
15
20
25
30
35
40
Zone II
Total 1061 counties and cities
(d)
Percentage(%)
IRFR
31.48
34.50
18.10
6.79
4.90
2.63
1.60
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
5
10
15
20
25
30
35
40
Zone III
Total 460 counties and cities
(e)
Percentage(%)
LFIS
5.25
15.50
16.16
32.31
25.98
4.80
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
0
5
10
15
20
25
30
35
Zone III
Total 460 counties and cities
(f)
Percentage(%)
IRFR
37.55
52.62
7.64
1.75
0.44
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0
10
20
30
40
50
60

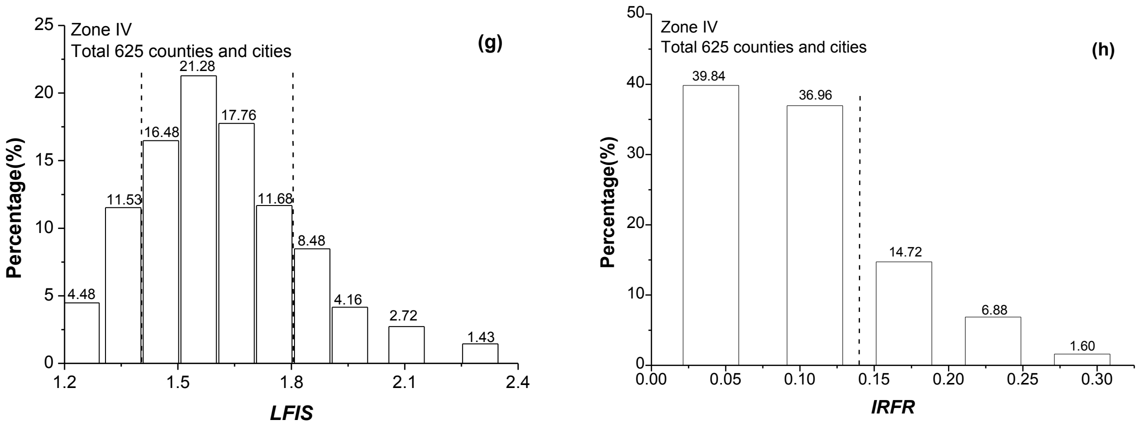
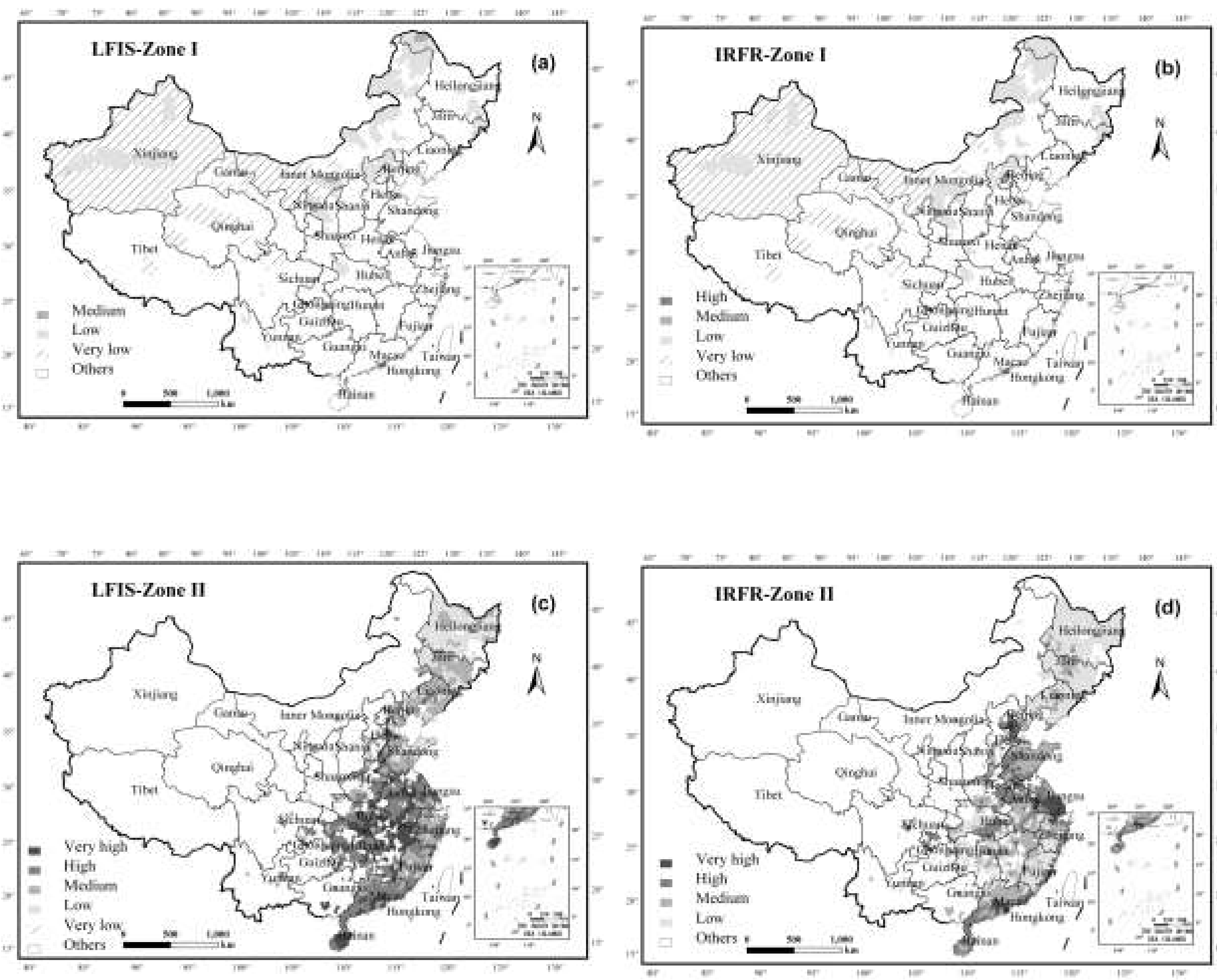


Fig. 8 Frequency bars for *LFIS* and *IRFR* according to the 4 zones



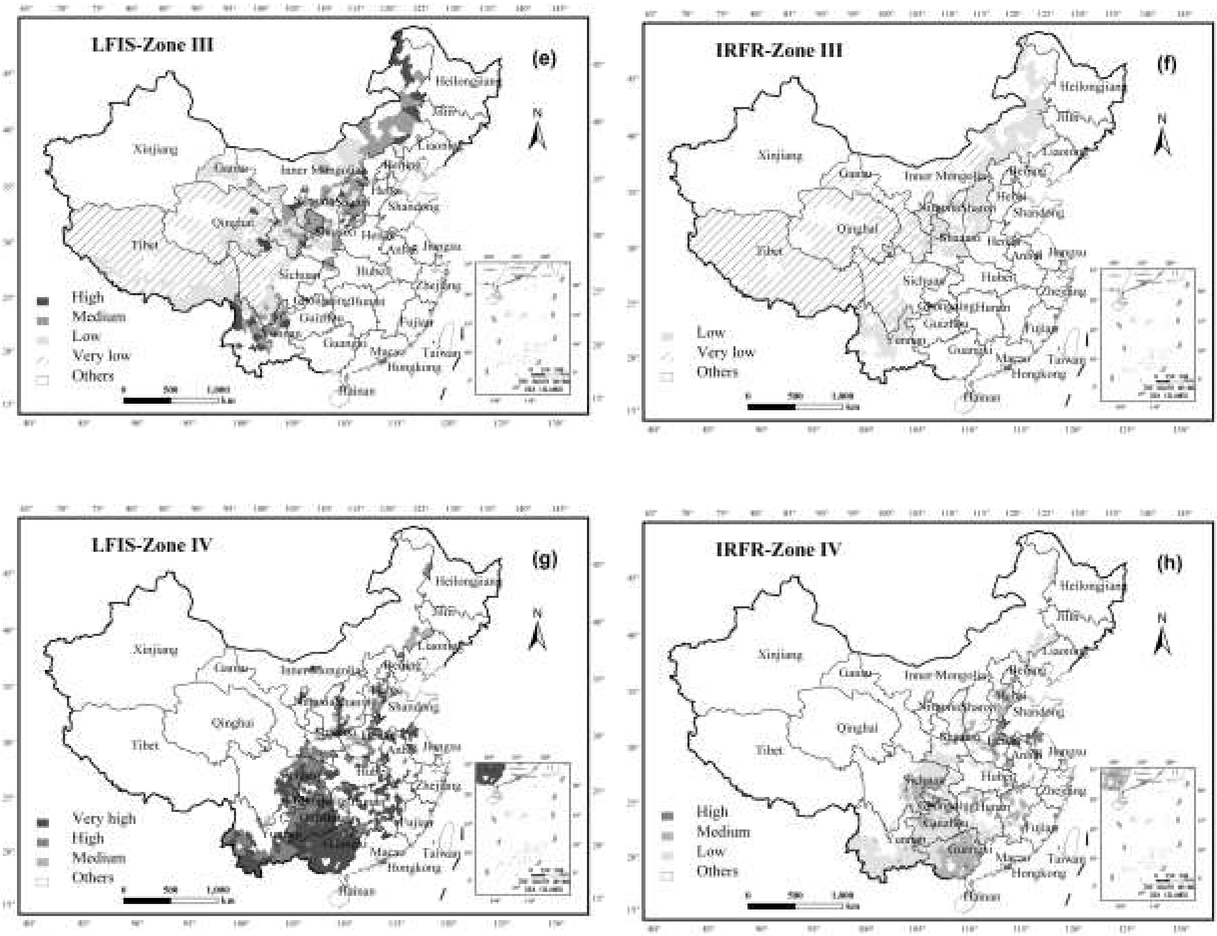


Fig. 9 Spatial distribution of *LFIS* and *IRFR* according to the 4 zones

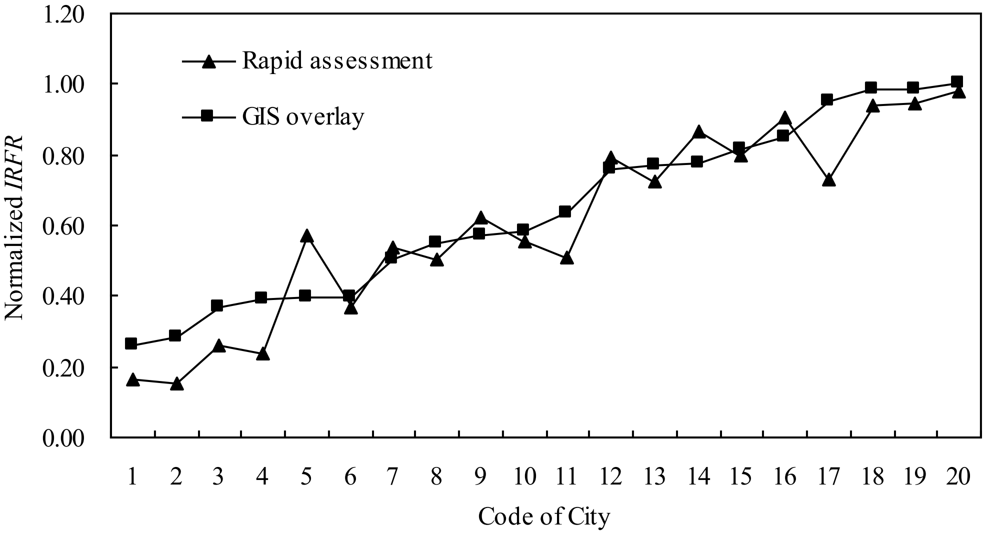


Fig. 10 Comparison of normalized values for *IRFR* obtained using the present approach and GIS overlay approach