Nat. Hazards Earth Syst. Sci., 13, 1723–1734, 2013
www.nat-hazards-earth-syst-sci.net/13/1723/2013/
doi:10.5194/nhess-13-1723-2013

Natural Hazards and Earth System Sciences
Open Access

A relative vulnerability estimation of flood disaster using data envelopment analysis in the Dongting Lake region of Hunan

C.-H. Li[1,2], N. Li[1,3,4], L.-C. Wu[2], and A.-J. Hu[5]

[1]State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, Beijing 100875, China
[2]College of Science, Central South University of Forestry and Technology, Changsha 410004, China
[3]Academy of Disaster Reduction and Emergency Management, Ministry of Civil Affairs & Ministry of Education, Beijing 100875, China
[4]Key Laboratory of Environmental Change and Natural Disaster, Ministry of Education of China, Beijing 100875, China
[5]Hunan Meteorological Bureau, Changsha 410007, China

Correspondence to: N. Li (ningli@bnu. edu. cn)

Received: 24 January 2012 – Published in Nat. Hazards Earth Syst. Sci. Discuss.: –
Revised: 9 December 2012 – Accepted: 15 May 2013 – Published: 4 July 2013

Abstract. The vulnerability to flood disaster is addressed by a number of studies. It is of great importance to analyze the vulnerability of different regions and various periods to enable the government to make policies for distributing relief funds and help the regions to improve their capabilities against disasters, yet a recognized paradigm for such studies seems missing. Vulnerability is defined and evaluated through either physical or economic–ecological perspectives depending on the field of the researcher concerned. The vulnerability, however, is the core of both systems as it entails systematic descriptions of flood severities or disaster management units. The research mentioned often has a development perspective, and in this article we decompose the overall flood system into several factors: disaster driver, disaster environment, disaster bearer, and disaster intensity, and take the interaction mechanism among all factors as an indispensable function. The conditions of flood disaster components are demonstrated with disaster driver risk level, disaster environment stability level and disaster bearer sensitivity, respectively. The flood system vulnerability is expressed as vulnerability $=$ f(risk, stability, sensitivity). Based on the theory, data envelopment analysis method (DEA) is used to detail the relative vulnerability's spatiotemporal variation of a flood disaster system and its components in the Dongting Lake region.

The study finds that although a flood disaster system's relative vulnerability is closely associated with its components' conditions, the flood system and its components have a different vulnerability level. The overall vulnerability is not the aggregation of its components' vulnerability. On a spatial scale, zones central and adjacent to Dongting Lake and/or river zones are characterized with very high vulnerability. Zones with low and very low vulnerability are mainly distributed in the periphery of the Dongting Lake region. On a temporal scale, the occurrence of a vibrating flood vulnerability trend is observed. A different picture is displayed with the disaster driver risk level, disaster environment stability level and disaster bearer sensitivity level.

The flood relative vulnerability estimation method based on DEA is characteristic of good comparability, which takes the relative efficiency of disaster system input–output into account, and portrays a very diverse but consistent picture with varying time steps. Therefore, among different spatial and time domains, we could compare the disaster situations with what was reflected by the same disaster. Additionally, the method overcomes the subjectivity of a comprehensive flood index caused by using an a priori weighting system, which exists in disaster vulnerability estimation of current disasters.

1 Introduction

Although flood vulnerability estimation is very important for minimizing flood damage as much as possible and making the better decisions on sustainable region development, there has been no exact explanation about what vulnerability is.

Since O'Keefe et al. (1976) first introduced the concept of vulnerability by exploring the key role played by socioeconomic factors in creating a weakness in responding to, and recovering from the effects of extreme geophysical events in the context of disasters, the use of the term has varied among disciplines and research areas over the last several decades (Liverman, 1990; Dow and Dowing, 1995; Watts and Bohle, 1993; Cutter, 1996; Vogel, 1997). The meanings of vulnerability have been integrated in three dimensions. (1) Natural sciences mainly focus on the physical system to define vulnerability, leaving out socioeconomic characteristics of the system. For example, the International Panel of Climate Change defined vulnerability as the degree of incapability to cope with the consequences of climate change and sea level rise. It explained the concept of vulnerability as the degree to which a system is susceptible to, or unable to cope with adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude and rate of climate variation to which a system is exposed, including its sensitivity and its adaptive capacity. Downing (2005) looked upon the vulnerability as the residual impacts of climate change after adaptation measures have been implemented. This definition includes the exposure, susceptibility, and the capability of a system to recover, and to resist hazards as a result of climate change; (2) social science takes another point of view to explain vulnerability, focuses on the human's capacity to respond to hazards and to promptly recover from damages and losses. Watts and Bohle (1993) looked to the social context of hazards and relate (social) vulnerability to coping responses of communities, including societal resistance and resilience to hazards. They are trying to find an easier way to understand and reduce the concept through a better understanding of the social background; (3) natural and socioeconomic sciences suggest that a natural disaster is a complex system, involving the above mentioned aspects. Wei et al. (2004) improved definitions on vulnerability, and describes a holistic view of society. Blaikie et al. (1994) described vulnerability as a measure of a person or a group's exposure to the effects of a natural hazard, including the degree to which they can recover from the impact of that event. Cutter (1996) defined vulnerability as a hazard of place that encompasses biophysical risks as well as social response and action. This definition is increasingly gaining significance in the scientific community in recent years. Cardona (2003) also tried to holistically integrate the contributions of physical and social sciences to define a vision of indicators that create vulnerability.

The most important advances in disaster vulnerability are the advent of disaster systems. From the system science's point of view, vulnerability is part of the disaster system function; a regional disaster system can be analyzed from its structure and function. There are different types of systems. Mileti (1999) conceived a three-element disaster system to analyze the function, and he thinks that the disaster consists of an environment subsystem, human system and human related structure system, paying more attention to the role of the disaster bearer in creating the vulnerability. Shi (2005) denoted that the disaster was composed of disaster environment, disaster bearer and disaster driver, emphasizing the hazards, hazard-affected bodies are of equal importance, and the vulnerability could be seen as the interaction function between hazards and hazard-affected bodies under certain hazard-formative environments. Klein et al. (2003) expressed vulnerability for the natural environment as a function of three main components: resistance, the ability to withstand change due to a hazard; resilience, the ability to return to the original state following a hazardous event and susceptibility; and the current physical state, without taking into account temporal changes. Their definition is specifically relevant to society. Klein et al. (2003) developed a scheme to explain the interaction between the components of vulnerability. He defines vulnerability as: vulnerability $= f$(exposure, sensitivity, adaptive capacity). The definition demonstrates that vulnerability is registered not by exposure to hazards (perturbations and stresses) alone but also resides in the sensitivity and resilience of the system experiencing such hazards. Van der Veen and Logtmeijer (2005) described that the vulnerability was characterized as a function of dependence, redundancy and susceptibility. Susceptibility is the probability and extent of flooding. Dependency is the degree to which an activity relates to other economic activities in the rest of the country. Redundancy is the ability of an economic activity to respond to a disaster by deferring, using substitutes or relocating. Redundancy is measured as the degree of centrality of an economic activity in a network. The more central an activity is, the less it encounters possibilities to transfer production and the more vulnerable it is for flooding. Gheorghe (2005) explained vulnerability as a function of susceptibility, resilience, and state of knowledge.

To evaluate flood vulnerability, there are several qualitative or quantitative approaches. Qualitative methods depend on expert opinions. Being partly subjective, the results of these approaches vary based on the knowledge of experts. Nonetheless, qualitative and semi-quantitative approaches are widely used because they are simple and are capable of handling a scarcity of data. Some qualitative approaches, however, incorporate the idea of ranking and weighting, and may become semi-quantitative in nature. Examples are the use of the analytic hierarchy process (AHP) by Wang et al. (2011) and Gao et al. (2007). They calculated the vulnerability indices of flood hazards by the weighting comprehensive evaluation method.

Quantitative methods are based on numerical expressions of the relationship between controlling factors and floods. The two main types of quantitative models are hydrologic and hydraulic models. The hydrologic models, such as the normal distribution or P-III distribution approaches, focus mostly on the line-type distribution of floods (Zhang and Xu, 2002). The hydraulic model, such as the runoff yield model in watersheds, mainly explores flood routing problems of water courses and flood risk zones (Cheng et al., 1996; Zhang et al., 2003; Su et al., 2005). These quantitative model methods can combine various data and reflect abundant information about flood risk, but they need much more high-quality data and their calculations are very complicated. China, like other developing countries, is characterized by a scarcity of good quality data on which flood risk assessment can be based. However, because of the complexity in the issue of vulnerability, its analysis is usually subjective and the analytic results depend upon the method adopted. Traditional methods for vulnerability analysis are to calculate sub-indices based on disaster frequency, disaster loss and the economy and population of different regions, then to add the sub-indices to get an integrated index for the regional vulnerability. For example, in the regional vulnerability analysis of Chongqing City in China, four sub-indices such as disaster density, disaster frequency, economic loss modulus and population modulus are used to produce an average, integrated index (Jiang et al., 2001). But these methods require a calculation of the weights of sub-indices. Various methods have been developed to calculate the weights, such as the analytic hierarchy process method used by Fan et al. (2001). However, the values of weightings depend to a great extent upon arbitrary decisions, and this reduces the confidence, which can be placed in such weighting methods.

2 Study area and estimation units

Hunan is located in the middle of China. The Dongting Lake region is located in the northern part of the Hunan Province, China, spanning 111° 19′–113° 34′ E, 28° 30′–30° 20′ N (Fig. 1). An intricate water system, flat topography and subtropical monsoon climate make this area the most flood-prone area. Much of the region has an elevation of less than 50 m. The Dongting Lake region is the most flood-prone area in China (Hydraulic Committee of the Changjiang River, 1999).

The frequency of the floods in the Dongting Lake region has increased significantly over time.

From 618 to 1998 AD, the Dongting Lake region suffered 296 floods of different intensities and ranges. Great floods occurred quite often in the last decade of the 20th century. The great 1954 flood breached embankments in 356 places, causing the deaths of 33 000 people and destroying 257 000 ha. The most recent flood in 1998 caused 142 embankment breaches, flooding 43 700 ha, waterlogging 2631 ha, and causing serious economic losses in the region. Hence, it is necessary in this assessment to compare flood vulnerability among different regions and develop risk maps for land-use planning and infrastructure layout.

The study area includes 24 counties (cities or districts at an administrative level equivalent to that of a county). It lies entirely within the Changsha, Yueyang, Changde and Yiyang municipalities of Hunan Province. The administrative units to be considered are listed in Table 1.

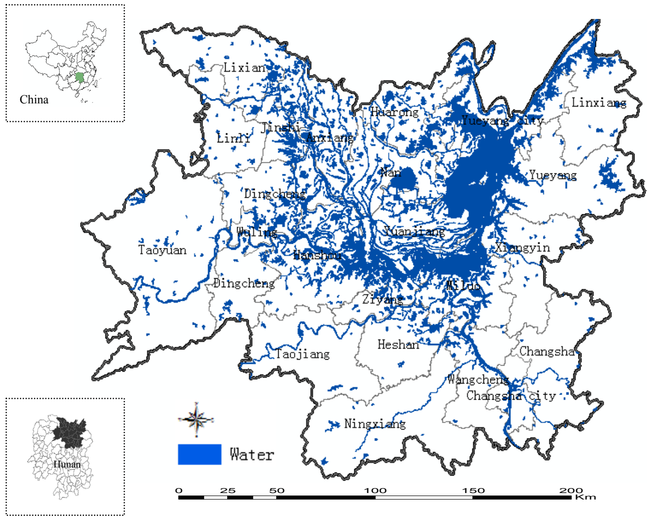

Fig. 1. The location and water body distribution of the Dongting Lake region.

3 Flood disaster vulnerability system assumption

3.1 Flood disaster system and vulnerability framework

A flood disaster system is composed of disaster drivers, disaster environment, disaster bearer and disaster intensity. Flood disaster can be characterized as the product of disaster drivers (DD), disaster environment (DE), disaster bearer (DB) and severity of flood disaster (DI). From the perspective of individual components, disaster drivers are the physical processes of the earth system that threaten human society, which can cause a flood disaster. Disaster environment is the conditions of the physical environment that aggravate or decrease the effects of hazards, such as slope, elevation, soil, and vegetation. Disaster bearer mainly includes all types of human activities, such as the people and economic sectors affected by a flood. The three components (DD, DE, DB) of flood disaster are integrated to bring about the flood losses, which are ordinarily called natural disaster intensity, which is a quantitative index to describe the scale of loss caused by an inundation. The total scope includes social, economic and ecological environment losses (SO, EC, EN) (Fig. 2).

Figure 2 illustrates the three categories of components that interact to generate a flood disaster. The flood disaster intensity index set may be expressed mathematically as

$$(\mathrm{DD}, \mathrm{DE}, \mathrm{DB}) \rightarrow (\mathrm{SO}, \mathrm{EC}, \mathrm{EN}). \quad (1)$$

Obviously there is not simple linear function. In fact, due to the complexity of natural disaster, it is impossible to define a single functional relationship between natural disaster intensity and the various independent variables (Shi, 1996).

Table 1. Administrative units of the Dongting Lake region.

Yueyang Municipality	Changde Municipality	Yiyang Municipality	Changsha Municipality
Yueyang City	Dingcheng District	Ziyang District	Changsha City
Yueyang County	Wuling District	Heshan District	Wangcheng County
Huarong County	Li County	Nan County	Ningxiang County
Lin xiang County	Anxiang County	Taojiang County	Changsha County
Miluo County	Linli City	Yuanjiang County	
Xiangyin County	Jinshi City		
	Taoyuan County		
	Hanshou County		

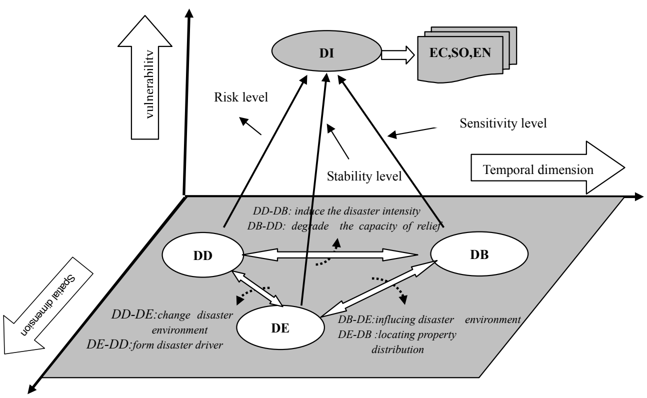

Fig. 2. The flood disaster system and its vulnerability.

3.2 Input–output relationship in a flood system

According to the theoretical framework of a flood disaster system (Fig. 2). The flood disaster process can be regarded as an "input–output" system, analogous to the models used in economics and flood vulnerability, it can be considered as an efficiency index of the system (Wei et al., 2004; Liu et al., 2010). In other words, the severity of flood disaster (i.e., the social loss (SO), economic loss (EC) and environmental loss (EN), as output factors) are the products of interactions within the regional disaster factors (i.e., DD, DE and DB as the input factors).

The relative vulnerability of a flood disaster system can be measured by means of the ratio between the combination of DD, DE, DB and DI, which is the relative efficiency of multiple inputs and outputs. These are decomposed into disaster drivers subsystem (DD–DI, denoting the level of flood risk), disaster environment subsystem (DE–DI, expressed by the level of stability level) and disaster bearer subsystem (DB–DI, indicating the level of sensitivity) (Fig. 3). Every flood subsystem has its own input factors, but a common output factor, i.e., SO, EC and EN.

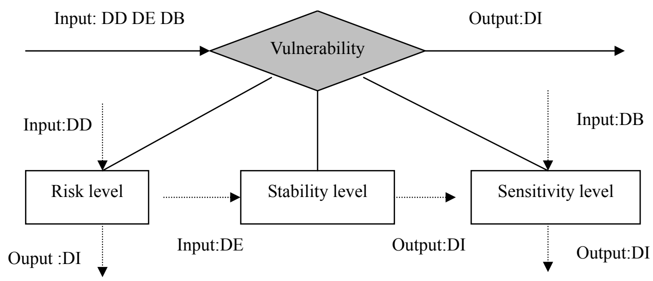

Fig. 3. Flood disaster vulnerability and its decomposition.

3.3 The spatial and temporal dimension of a flood disaster system

The flood vulnerability is the processes structured on spatiotemporal interactions maintained at the socioecological system between the natural hazards. Therefore, the vulnerability has the characteristics of various spatiotemporal scales. Firstly, place-based analysis seeks to detect vulnerability at a certain locality, such as a territory, a region, a country or the planet. Secondly, systems and processes operate at a wide variety of spatial and temporal scales requiring a holistic overview of processes at multiple scales (Kasperson et al., 2001). Thirdly, cross-scale interaction exerts a crucial influence on outcomes at a given scale. Thus, it is not surprising that intensive discussions on scale issues are permeating the vulnerability community.

Furthermore, vulnerability has a strong temporal component. Temporal vulnerability is further explored and used as key dimension in the vulnerability sciences. The temporal character of vulnerability is used as justification to explore (and critique) the links between the increase and expansion of disasters, and the dominant ideas, and institutions. Temporality is generally conceptualized in three different ways. First and most commonly, it is acknowledged that vulnerability is an intrinsically dynamic process. That is to say, vulnerability changes continuously over time and is driven by physical, social, economic and environmental factors. Vulnerability changes through time in unpredictable ways and in varying directions: increasing, decreasing, accelerating, oscillating, concentrating or diffusing. It varies with the interplay of three different time frames: long-term, short-term, and cyclical change.

4 An analytical analysis of a flood system in Dongting Lake

The aim of this study is to investigate the vulnerability to floods in the Dongting Lake region in the Hunan Province of China from a regional macro-perspective scale. At the same time, the complexity of a flood disaster system makes the establishment of an indicator system a complex issue as well, the indicator system must cover economic, social and ecological issues. An indicator system should be chosen and adopted in a scientific and rational way to fit actual conditions and reflect the essentials of flood disasters. To indicate this, it should be systematic, scientific, hierarchical, operational, compatible and widely applicable.

According to the principal, an index system is set up to reflect the input–output characteristics of the flood disaster in the Dongting Lake region. The flood DD's index can be indicated by two indicators: the coincidence of flood peaks from the Changjiang River and four other rivers, and the highest precipitation over three days (mm); flood DE can be represented by two indicators: elevation, and ground cover runoff index; flood DB can be expressed through two indicators: population density (person km^{-2}), and economic density (thousands RMB yuan km^{-2}); flood DI can be measured with three indicators: direct economic loss, human casualties, and area affected (Table 2). Based on the above analysis, we use these indices to analyze floods features in the Dongting Lake district, and specify the data sources.

4.1 Flood disaster drivers (DD)

The flood disaster drivers are factors that can cause a flood disaster (e.g., the timing, depth, flow or duration of rainfall and floodwater, sediment loads, dam collapse, or inadequate drainage capacity) or enhance the risk to health and ecology (e.g., pesticides). The coincidence of flood peaks from the Changjiang River and four other rivers, and the highest precipitation over three days (mm) serve as the disaster drivers for this Dongting Lake region flood vulnerability study.

4.1.1 Coincidence of flood peaks from Changjiang River and four other rivers

The Changjiang's upper reach diverts river water into Dongting Lake through three gates: Songzikou, Taipingkou, and Ouchikou; as well as the four rivers: Xingjiang River, Zishui River, Yuanjiang River and Lishui River (Fig. 4). The period of overlap between flood peaks of the Changjiang's upper reach and the four rivers has been used for the assessment of flood vulnerability. The impacts of floods from the upper reaches of the Changjiang River depend on their timing in combination with the waters of the four rivers.

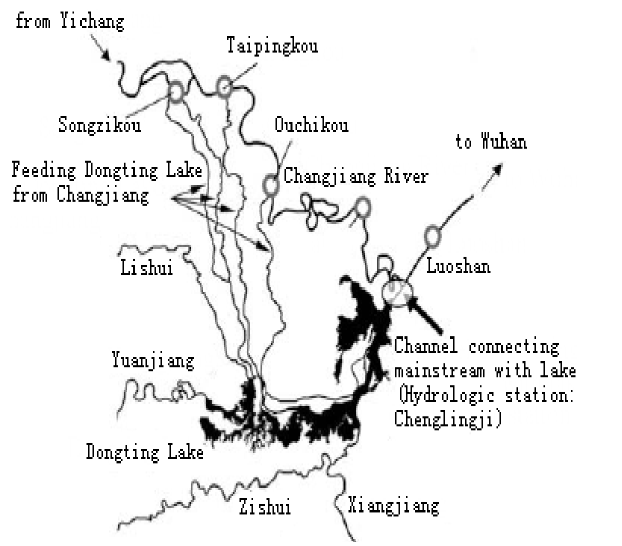

Fig. 4. The relationship between the Dongting Lake area and the Changjiang River.

Using the correlation analysis between the flood peaks of the Changjiang's mainstream coinciding with those of the four rivers, the frequency is calculated. Based on the correlation degree, we create a 10-grade linear rank ordering, with the highest disaster potential set at 10. (Table 3).

4.1.2 The highest precipitation over three days

A 3 day interval has been chosen because it incorporates all or the greatest volume of even an extreme rainstorm. Meanwhile the extent of the flood in Dongting Lake also is influenced by the changing inflow. The precipitation data have been collected from the Meteorological Bureau of Hunan Province. The 3 day maximum rainfall index is determined as statistical mean values using more than 50 yr of data from 1951 to 2009 obtained from 20 rain gauges distributed throughout the Dongting Lake region.

4.2 Flood disaster environment (DE)

Flood disaster environment is the "gestating" environment that enables a disaster to occur in the first place, and includes such factors as the land surface terrain, flood impact zone(s), and the soil and vegetative cover. Human activities that affect this environment include human constructed water projects, logging and lake reclamation. For this study of the Dongting Lake area, we used terrain and ground cover runoff index because they are the most important environmental factors in this region.

4.2.1 Ground elevation scale

The digital elevation model (DEM) is developed by digitization of the contour lines and point elevation from the

Table 2. The selection and processing of indicator systems used for vulnerability assessment.

Flood system components	Indicators	Input–output orientation
Flood disaster drivers (DD)	Coincidence of flood peaks of Changjiang River and four rivers The highest precipitation over three days (mm)	input
Flood disaster environment (DE)	Ground elevation scale Ground cover runoff index	input
Flood disaster bearers (DB)	Population density (people km^{-2}) Economic density (thousands yuan km^{-2})	input
Severity of flood disaster (DI)	Direct economic loss Human casualties Area affected	output

Table 3. The influence level ranking orders of water from the Changjiang's upper reach.

A	<50	50–55	55–60	60–65	65–70	70–75	75–80	80–85	85–90	>90
B	1	2	3	4	5	6	7	8	9	10

A: the frequency of Changjiang's upper reach and four rivers coinciding (%); B: potential disaster-induced order ranking.

1 : 250 000 scale topographical map. Values for the absolute elevation and average regional relief indices are obtained from a grid-based DEM using a geographic information system (GIS). The river and lake distribution and terrain of the Dongting Lake region are displayed in Fig. 5a.

4.2.2 Ground cover runoff index

Each land use/cover has different flood retention capacity. The land use/cover categories in the Dongting Lake area are composed of forest land, urban land, grassland, wetland, farmland, and bareland, of which water bodies and forestlands are major land types. Waterbodies play an important role in flood storage and regulation in the south central area of the Yangtze River in southern China. In the same way, a forest can reduce a flood peak discharge, and delay the advent of flood. Therefore, we set the wetland runoff coefficient at 1, and for the forestland at 2.5.

In consideration of consistency in assessing the flood vulnerability, the relative runoff coefficient is adopted in the evaluation. The flood retention capability can be decided by empirical investigation and expert judgment. We generate corresponding values for other types of land cover (Table 4).

We calculate the regional flood-generating environment level by the following formula:

$$\mathrm{RI}_{\mathrm{lc}} = \sum_{i=1}^{n} \mathrm{type}_i^{\mathrm{lc}} \cdot p_i^{\mathrm{lc}}, \tag{2}$$

where, $\mathrm{RI}_{\mathrm{lc}}$ is the relative generation index of runoff from land use/cover; $\mathrm{type}_i^{\mathrm{lc}}$ is i-th land use/cover, p_i^{lc} is the percentage of each type of land cover; n is the number of land cover types.

The land use data are provided by International Scientific & Technical Data Mirror Site, Computer Network Information Center Chinese Academy of Sciences. The land cover categories in Dongting Lake region are shown in Fig. 5b.

4.3 Flood disaster bearer (DB)

The flood disaster bearers are the people and economic sectors affected by a flood. Distinction is made here between the lives of humans (in terms of casualties and trauma) and the economy (industry, agriculture, livestock, forestry, fisheries, etc.), as well as buildings and structures. The index of per capita gross domestic product (GDP) is selected to reflect economic loss caused by flood. Population density is selected to reflect the casualties caused by flood. The population density (person km^{-2}) and density of economy (thousand RMB yuan km^{-2}) are chosen as indicators of disaster bearers for the Dongting Lake region (Fig. 6).

4.4 Flood disaster severity index (DI)

A flood disaster can affect human society in many different ways, including impacts on (1) human lives (deaths and disappearances, casualties, trauma), (2) the economy (agriculture, transportation, buildings and structures, water works, cities and industry), (3) society (social development, political stability), and (4) resources and the environment (cultivated land, water environment, ecology, etc.).

However, as Cutter (2010) has mentioned a situation that the US still does not have standardized is a loss inventory, accessing these data is also a very difficult task in China. Considering the major impediment of the unavailability of

Table 4. The relative generation index of runoff from land cover.

Types of land use/cover	Forestland	Building area	Grassland	Wetland	Farmland	Bare land
Runoff generation capacity	2.5	9	4	1	5.5	8

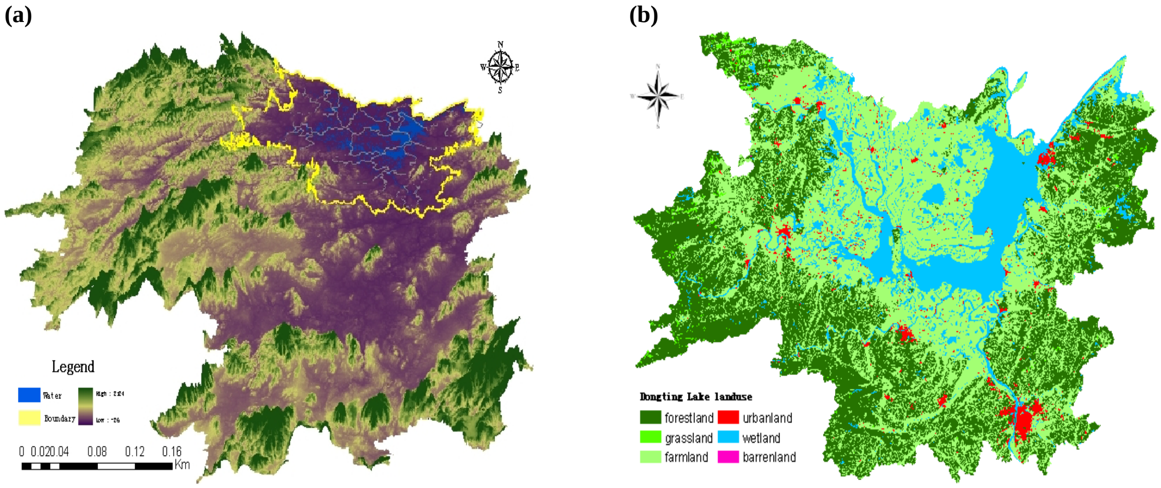

Fig. 5. The elevation **(a)** and land cover types in the Dongting Lake region **(b)**.

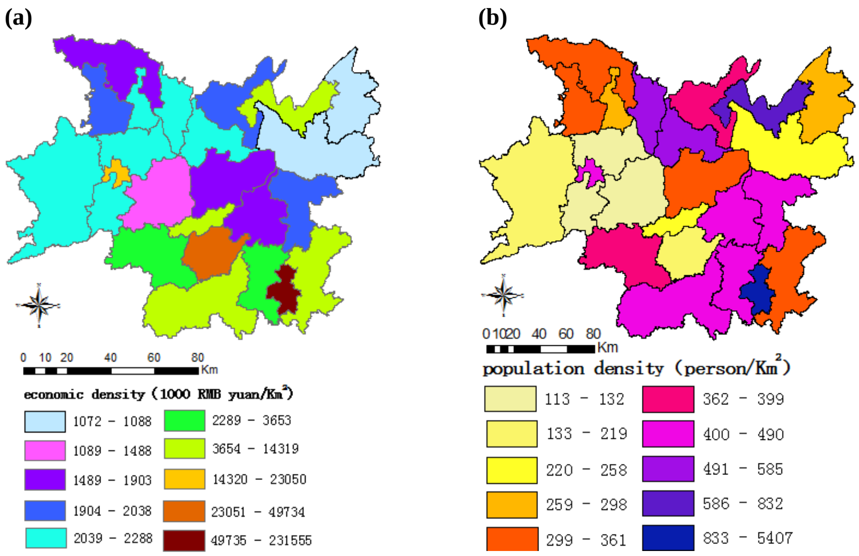

Fig. 6. The economic density (left panel) and population density (right panel) in the Dongting Lake region.

loss data in a digital format, we choose the following indicators as the disaster severity indicators: area affected, human casualties, and direct economic loss. Their average data from 2000–2009 is spatially displayed in Fig. 7.

The economic and social loss data are collected from the assembler of flood and drought compiled by the flood control and drought relief headquarters office of the Hunan Province, other data are obtained from the Hunan Province Rural Statistical Yearbook 2000–2009.

5 Flood vulnerability and its decomposed analysis

5.1 Flood vulnerability estimation

In order to quantitatively analyze vulnerability, we first give the definition of the flood relative vulnerability and its three decomposed components: the flood disaster driver risk level, disaster environment stability level, and disaster bearer sensitivity level.

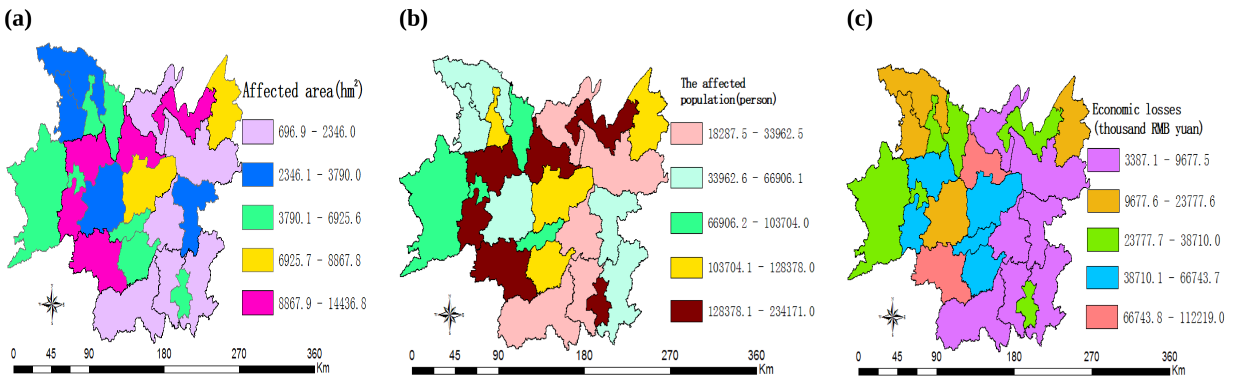

Fig. 7. The flood affected area **(a)**, human casualties **(b)**, and economic loss **(c)** regional variation.

Assume that the variable set $(x_1, x_2, \ldots, x_m)$ and $(y_1, y_2, \ldots, y_s)$ represent input–output, respectively. Flood relative vulnerability can be expressed as

$$\text{Relative Vulnerability} = \frac{\sum_{r=1}^{3} u_r y_r}{\sum_{i=1}^{6} v_i x_i} = \frac{u_1 y_1 + u_2 y_2 + u_3 y_3}{v_1 x_1 + v_2 x_2 + \ldots + v_6 x_6}, \quad (3)$$

where y_r is an amount of output r, u_r represents the weight assigned to output r, x_i is indicated of the amount of input i, and v_i means the weight assigned to input i. x_1: coincidence of flood peak of Changjiang River and four rivers, x_2: the highest precipitation over three days (mm), x_3: ground elevation scale, x_4: ground cover runoff index, x_5: population density (person km^{-2}), x_6: economic density (thousands RMB yuan km^{-2}). y_1: direct economic loss, y_2: human casualties, y_3: area affected. The vulnerability represents the efficiency of regional disaster input–output, the higher the efficiency is, the more severely the disaster is (Liu, 2010).

Furthermore, the relative vulnerability can be divided into three ratios: risk level, stability level and sensitivity level.

$$\text{Risk level} = \frac{\sum_{r=1}^{3} u_r y_r}{\sum_{i=1}^{2} v_i x_i} = \frac{u_1 y_1 + u_2 y_2 + u_3 y_3}{v_1 x_1 + v_2 x_2} \quad (4)$$

$$\text{Stability level} = \frac{\sum_{r=1}^{3} u_r y_r}{\sum_{i=1}^{2} v_i x_i} = \frac{u_1 y_1 + u_2 y_2 + u_3 y_3}{v_3 x_3 + v_4 x_4} \quad (5)$$

$$\text{Sensitivity level} = \frac{\sum_{r=1}^{3} u_r y_r}{\sum_{i=1}^{2} v_i x_i} = \frac{u_1 y_1 + u_2 y_2 + u_3 y_3}{v_5 x_5 + v_6 x_6}. \quad (6)$$

We used a linear programming formulation to objectively obtain weights that situate each geographic area relative to all others within the attribute space (Ratick and Osleeb, 2011).

5.2 Selection of DMUS

In the procedure of data envelopment analysis (DEA), selecting decision-making units (DMUs, in DEA nomenclature) involves two steps. The first step is to determine the boundary from the two spatiotemporal kinds of DMUs. One comprises regional boundaries that define the individual units. The other relates to the time periods used in measuring the DMU's activities. Preferably, the time periods to be considered should be "natural" ones, corresponding to seasonal cycles (Golany and Roll, 1989).

The objectives of this study are to identify temporal and spatial flood vulnerability at the county level in Dongting Lake. We firstly regard the administrative unit as decision making unit, which considers the observations in each year independently (the so-called contemporaneous approach, Tulkens et al., 1995). Using administrative regions as the spatial decision-making unit has some advantages, as administrative unit runs not only the flood mitigation but also underlie the flood preparation planning. Then, the different periods are determined as the temporal decision-making units, which benchmark all observations together independently of their year (inter-temporal approach). This characterizes the dynamic change of vulnerability and its components. In this case we assume that there have not been any technological changes in the years studied.

After the DMU type has been selected, the next step is to determine the size of the comparison DMUs. A rule of thumb established here is that the number of DMUs should be at least twice the number of inputs and outputs considered. According to the rule, we select 23 counties (cities, district) as the spatial DMUs and 10 yr as time periods DMU (Fig. 8).

5.3 A DEA-based flood vulnerability methodology

Data envelopment analysis is developed to measure the efficiency of nonprofit-making organizations, which produces multiple outputs by using multiple inputs. However, DEA has widely exceeded the original idea it was conceived for in the initial paper of Charnes et al. (1978) and has been used as a technique for the analysis of flood vulnerability.

In this paper, four models for flood relative vulnerability and its decompositions are developed based on the classic C^2R model of DEA. The equation of the model is listed as

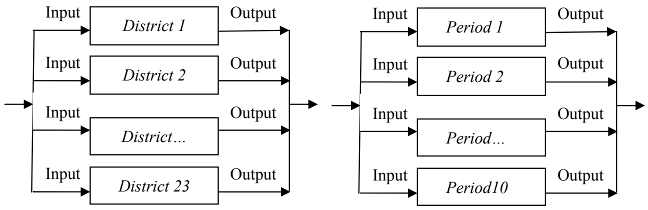

Fig. 8. Spatial and temporal DMUs determination.

follows:

$$\begin{cases} \text{Min } d \\ S.T. \ \sum_{j=1}^{n} x_j\lambda_j + S^- = \mathrm{d}x_0 \\ \qquad \sum_{j=1}^{n} y_j\lambda_j - S^+ = y_0 \\ \qquad \lambda_j \geq 0, j = 1, 2, \ldots n, S^- \geq 0, S^+ \geq 0, \end{cases} \tag{7}$$

where d is efficiency index, λ_j is the weight, S^- is input slacks, S^+ is output slacks, ε is the non-Archimedean infinitesimal and $\varepsilon = 10^{-6}$, n is the number of DMUs, x is the input variables, y is the output variables.

In order to facilitate the understanding of the assessment models of flood relative vulnerability and its components, an example has been given. There are 6 inputs $(x_{1n}, x_{2n}, x_{3n}, x_{4n}, x_{5n}, x_{6n})$ and 3 outputs (y_{1n}, y_{2n}, y_{3n}) in the assessment model of flood relative vulnerability for each district.

For the district with $n = 1$, the inputs are x_{11}, x_{21}, x_{31}, x_{41}, x_{51} and x_{61}, and the outputs are y_{11}, y_{12} and y_{13}. Then, we could rewrite Eq. (7) as follows:

$$\begin{cases} \text{Min } V \\ S.\,T. \ -y_{11} + (y_{11}\lambda_1 + y_{12}\lambda_2 + y_{13}\lambda_3 + \ldots + y_{1n}\lambda_n) \geq 0, \\ \quad -y_{21} + (y_{21}\lambda_1 + y_{22}\lambda_2 + y_{23}\lambda_3 + \ldots + y_{2n}\lambda_n) \geq 0, \\ \quad -y_{33} + (y_{31}\lambda_1 + y_{32}\lambda_2 + y_{33}\lambda_3 + \ldots + y_{3n}\lambda_n) \geq 0, \\ \quad \mathrm{d}x_{11} - (x_{11}\lambda_1 + x_{12}\lambda_2 + x_{13}\lambda_3 + \ldots + x_{1n}\lambda_n) \geq 0, \\ \quad \mathrm{d}x_{21} - (x_{21}\lambda_1 + x_{22}\lambda_2 + x_{23}\lambda_3 + \ldots + x_{2n}\lambda_n) \geq 0, \\ \quad \mathrm{d}x_{31} - (x_{31}\lambda_1 + x_{32}\lambda_2 + x_{33}\lambda_3 + \ldots + x_{3n}\lambda_n) \geq 0, \\ \quad \mathrm{d}x_{41} - (x_{41}\lambda_1 + x_{42}\lambda_2 + x_{43}\lambda_3 + \ldots + x_{4n}\lambda_n) \geq 0, \\ \quad \mathrm{d}x_{51} - (x_{51}\lambda_1 + x_{52}\lambda_2 + x_{53}\lambda_3 + \ldots + x_{5n}\lambda_n) \geq 0, \\ \quad \mathrm{d}x_{61} - (x_{61}\lambda_1 + x_{62}\lambda_2 + x_{63}\lambda_3 + \ldots + x_{6n}\lambda_n) \geq 0, \\ \quad \lambda \geq 0, \end{cases} \tag{8}$$

where $n = 23$ and $\lambda = (\lambda_1, \lambda_2, \lambda_3, \ldots, \lambda_n,)'$.

A minimum value for V is calculated by running Eq. (8). The value of V is the flood vulnerability in the district with $n = 1$ in this example. The nearer the V value approximates to one, the higher the flood vulnerability will be. Therefore when V value equals to one, the district has the highest flood vulnerability.

6 Results and analysis

6.1 Spatial vulnerability and its decomposition

Flood disaster vulnerability is highly correlated in space. The obtained spatial distribution of flooding vulnerability for the Dongting Lake region provides decision-makers useful information to identify hotspots of the study area and evaluate effects of flood-mitigation measures on flood-risk reduction. This allows a more in-depth interpretation of local indicators and pinpoints actions to diminish focal spots of flood vulnerability. It may benefit the flood relief manager if their risk exposures are properly diversified among locations.

6.1.1 The spatial distribution of relative vulnerability

After the selection of indicators and the collection of indicator data, an analysis is performed using DEA to obtain a flood disaster overall relative vulnerability map (Fig. 9a). By using a natural break method, the Dongting Lake region is divided into 5 types of different regions with very low, low, medium, high and very high vulnerability degrees of flood disaster. From Fig. 9a, we can find that (1) most regions with very high and high flood vulnerability are found adjacent to Dongting Lake or river zones. Two reasons can explain this phenomenon. One is because there are some extremely high flood disaster indicators for this region, as compared with other areas, the other is because these regions are mainly located in extreme lowlands or are a short distance from the river and lake banks; (2) those zones with very high vulnerability are in the center and north of the study area, primarily caused by flood disaster driver and environmental conditions with high potential flood risk, such as topography and drainage network. Therefore, these zones are the very highly susceptible to flood disaster. However, there is a special case that happens in some regions. For example, Changsha City is not in a very low-lying region, but most parts of it still are vulnerable to floods. The exception can be explained because of its economic activities exposed to floods. Changsha, the capital of Hunan Province, has a good industrial and economic base. Its gross domestic product (GDP) has grown at an average of 15.4 percent per year from 2003–2007, compared with the national average of 11 percent. Its per capita GDP amounted to over USD 4748 in 2007; (3) the zones with low and very low vulnerability are mainly distributed in the periphery of the Dongting Lake region, for which low vulnerabilities are caused by the highly elevated land or their situation in marginal hills.

6.1.2 Risk, stability and sensitivity level spatial distribution

The above overall vulnerability analysis displays the regionalization of flood vulnerability. However, that can conceal the flood disaster factor vulnerability distinction. The decomposition of whole flood vulnerability can unfold disaster driver

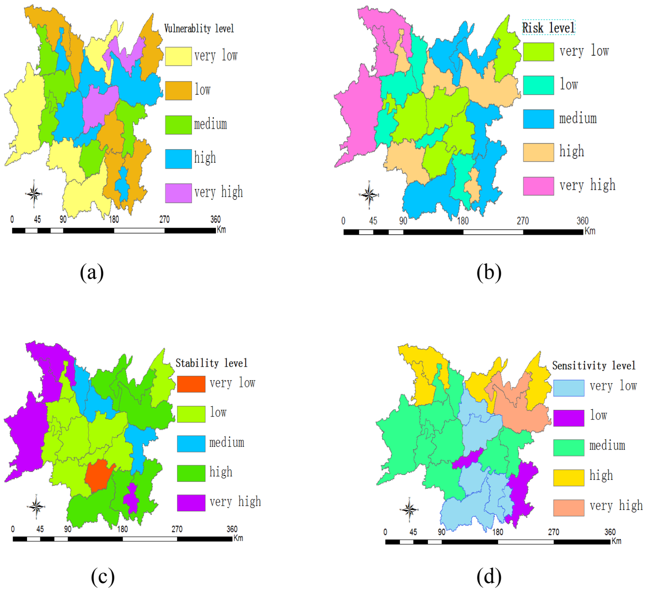

Fig. 9. The flood vulnerability **(a)**, risk level **(b)** the stability level **(c)**, sensitivity level **(d)** in Dongting Lake region.

risk level, the disaster environmental stability level, and disaster bearer's sensitivity level. The results are displayed in Fig. 9b, c and d, respectively.

In terms of disaster driver risk level, Fig. 9b shows the area along the boundary characterized by the high level of flood vulnerability as it has, in addition to the elevation, the high precipitation over three days. Taking Li County (Lixian) in the northwest as an example, it is found to have a high disaster environment index and disaster driver indicators, because of high precipitation, nearness to the Changjiang River, and low terrain. The districts with low risk are in the center of the Dongting Lake area.

In terms of disaster environmental stability level, we can see from Fig. 9b that it has the same trend as the flood drivers. The high stability is in hill and mountain areas of the west and south, while the regions with lower stability are in the central area. It is consistent with the physical and economic background of the Dongting Lake region. The low terrain and stochastic precipitation are in the central and eastern areas, which brings out a relative low stability of flood.

In terms of disaster bearer sensitivity level, Fig. 9c shows clearly that the northeast of the region, including Yueyang City and Linxiang City have the highest flood sensitivity level, followed by Li County and Jinshi City in the northwest, then the southwest, and finally the southeast, which has lowest economic vulnerability.

6.2 Temporal dynamics of vulnerability and its components

Time series analysis enables a DMU to be compared with itself in time periods, and monitors the movement of efficiency of DMUs over panels because of the consideration of multiple time periods in series. It enhances DEA analysis of data over time because it provides a means of assessing the temporal behavior of the DMUs. Additionally, it provides a basis for evaluating the stability of the efficiency rating achieved by the DMUs when they are obtained from different data sets (Charnes et al., 1985). Moreover, the dynamic nature of the data may be evaluated through the use of time series where trends and seasonal effects in the efficiency performance of individual DMUs are identified (Charnes et al., 1995).

6.2.1 The temporal variation of flood relative vulnerability

We here perform a time series DEA analysis and use DEA to evaluate vulnerability of the whole Dongting Lake region for the period 2000–2009, defining each year as a separate DMU. Figure 10a shows the various trends of vulnerability during the period between 2000 and 2009.

The data for six input indicators and 3 output indicators and the model in the Sect. 4.3 are used to estimate the relative vulnerability during the period 2000–2009. The results are that 7 yr have a DEA measure of $V_n = 1$. That is, 7 of the total 10 yr are judged DEA efficient. It is noteworthy that considerably many years attain the maximum measure 1, i.e., most of year's ranks top in terms of their vulnerability level. On the contrary to this, only 3 yr are DEA inefficient, which represents the less-vulnerability situation.

6.2.2 Risk, stability and sensitivity level temporal dynamics

In general, the flood system vulnerability is different from those of its components in the period 2000–2009. Therefore, we cannot simply say that vulnerability of Dongting Lake has gotten either better or worse for the period 2000–2009. This indicates that the decomposition of flood subsystem vulnerability is indispensable in the in-depth analysis.

We can find in Fig. 10b and c that the flood disaster-driver risk level (Fig. 10b) and flood environmental stability (Fig. 10c) present a decreasing trend in the 2000–2009 period. However, their interpretation of the phenomenon are significantly different. The downward trend of flood environmental stability is negative, but that of flood disaster-driver risk is beneficial to the disaster mitigation.

It can be seen in Fig. 10d that the flood disaster-bearer's sensitivity change trend is similar to that of the whole system vulnerability except for 2005. The results indicate that the relationship between system vulnerability and disaster-bearer's sensitivity level is much closer than that of system vulnerability and flood disaster-driver risk level (Fig. 10b) and flood environmental stability level (Fig. 10c).

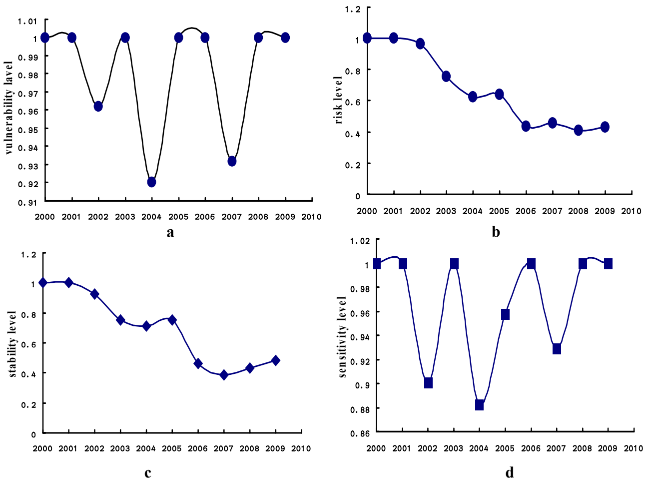

Fig. 10. The flood system vulnerability trend **(a)**, risk **(b)**, the stability **(c)** and sensitivity **(d)** in 2000–2009.

7 Discussion and conclusion

Based on theory of disaster system science and technical support of GIS and RS, a flood vulnerability assessment model based on DEA was developed at the county (city) level in Dongting Lake. Then, the flood relative vulnerability level and its components' levels were calculated on the basis of the flood damage data, physical and socioeconomic statistical data of 23 districts during 2000–2009. This can expose the characteristics of the flood disaster system and identify the vulnerability region across multiple time periods. Flood assessment indices of spatiotemporal vulnerability are simple, the data are easily available, and the models are easily operated, so the assessment method based on DEA would have a high level of transferability to the vulnerability analysis of other types of disasters. The comparison of vulnerability regionalization and temporal variability can identify appropriate actions that can be taken to reduce the vulnerability before the potential for damage is realized.

Compared with previous research using the indicators' weighted sum as an integrated measure, we demonstrate the proposed method based on DEA to estimate the relative vulnerability to floods, which will eliminate the subjectivity of a priori weighting. This methodology can provide multi-faceted information about flood vulnerability that contributes to deepening the understanding of the flood vulnerability. Its implementation could guide policy makers to analyze actions towards better dealing with floods.

It should also be mentioned that a flood disaster system's relative vulnerability is closely associated with its components. However, the flood system and its elements have different vulnerability level. The overall vulnerability is not the aggregation of its element vulnerability.

Meanwhile, it should be pointed out that the calculation of relative vulnerability estimation for floods is a complicated question; therefore it is very important to establish a scientific assessment method. We only carry out the preliminary attempt on the new approaches for the evaluation of relative vulnerability estimation of floods. There still are many questions that need further studies.

Firstly, an additive investigation into the input and output indicators used in the model should be conducted. The flood vulnerability estimation should consider the flood coping capacity. The extension will focus on collecting socioeconomic disaster relief capacity data in more detail (such as flood control project and disaster relief fund, for example, dike density can indicate the fighting-calamity capability of flood control projects) to determine the vulnerability types and levels.

Secondly, sensitivity analysis should be performed to determine which factors have the most impact. This will benefit the determination of which vulnerability and temporal periods resources should be spent on to alleviate the vulnerability the most.

Thirdly, future research efforts will investigate correlations of the same region across multiple years. Cluster analysis may be explored to better group homogeneous DMU types for a more robust analysis. Lastly, vulnerability is a relative concept; it depends on the differential access of the people, buildings and infrastructure to the social, economic, environmental and institutional subsystems. Vulnerability is different for each hazard, is different for each location, different for every person or family.

Acknowledgements. The work described in the paper was supported by National Natural Science Foundation of China (No. 41171401; No. 41101506), National Basic Research Program of China (No. 2012CB955402), International Cooperation Program (No. 2012DFG20710) and ESPRE (No. 2012-TDZY-022).

We would like to express our sincere gratitude to Jiang Lijia, Yin Wen and Zeng Guang from Central South University of Forestry and Technology for their valuable suggestions and careful revision of this paper.

The authors would also like to thank the editor Nicolas R. Dalezios, George Karantounias and one anonymous referee for their constructive suggestions and comments that greatly helped to improve the paper.

Edited by: N. R. Dalezios
Reviewed by: G. Karantounias and one anonymous referee

References

Blaikie, P., Cannon, T., Davis, I., and Wisner, B.: At risk-natural hazards, people's vulnerability and disasters, London, 1994.

Cardona, O.: The need for rethinking the concept of vulnerability and risk from a holistic perspective: A necessary review and criticism for effective risk management, available at: http://www.la-red.org/public/articulos/2003/nrcvrfhp/nrcvrfhp_ago-04-2003.pdf, last access:15 May 2011, 2003.

Charnes, A., Cooper, W. W., and Rhodes, E.: Measuring the efficiency of decision making units, Eur. J. Oper. Res., 2, 429–444, 1978.

Charnes, A., Clark, C. T., and Cooper, W. W.: A developmental study of data envelopment analysis in measuring the efficiency of maintenance units in the US Air Forces, Ann. Oper. Res., 2, 95–112, 1985.

Charnes, A., Cooper, W. W., and Golany, B. A.: Multiperiod analysis of market segments and brand efficiency in the competitive carbonated beverage industry, in: Data Envelopment Analysis: Theory, Methodology, and Applications, edited by: Charnes, A., Cooper, W. W., Lewin, A. Y., and Seiford, L.M., Kluwer Publishing, Boston, 1995.

Cheng, X. T., Yang, L., and Chen, X. J.: Numerical model of flood propagation in detention basin, J. Nat. Disasters, 5, 34–40, 1996 (in Chinese).

Cutter, S. L.: Vulnerability to environmental hazards, Prog. Hum. Geog., 20, 529–539, 1996.

Cutter, S. L.: Social Science Perspectives on Hazards and Vulnerability Science, edited by: Beer, T., Geophysical Hazards, International Year of Planet Earth, 17–30, 2010.

Dow, K. and Downing, E.: Vulnerability research: where things stand, Hum. Dimen. Q., 1, 3–5, 1995.

Downing, T., Patwardhan, A., Klein, R., Mukhala, E., Stephen, L., Winograd, M., and Ziervogel, G.: Assessing Vulnerability for Climate Adaptation, in: Adaptation Policy Framework for Climate Adaptation: Developing Strategies, Policies and Measures, edited by: Lim, B. and Spanger-Siegfried, E., UNDP, Camdridge University Press, Cambridge, UK, 61–90, 2005.

Fan, Y. X., Luo, M. Y., and Cheng, Q. S.: Establishment of weight about vulnerability indexes of a hazard bearing body, J. Catastrophology, 16, 85–87, 2001 (in Chinese).

Gao, J. X. and Xia, K. B.: Flood Vulnerability Assessment – A Case Study of Dongting Lake area, Beijing, China En-Vironmental Science Press, 2004.

Gao, J. X., James, E. N., and Pan, Y. Z.: An assessment of flood hazard vulnerability in the Dongting Lake Region of China, Lakes Reservoirs, Res. Manage., 12, 27–34, 2007.

Gheorghe, A.: Risk, Vulnerability and sustainability for critical infrastructures, available at: http://www.caenz.com/info/2005Conf/pres/Gheorghepdf, last access: 25 July 2011, 2005.

Golany, B. and Roll, Y.: An Application Procedure for DEA, Omega, 17, 237–250, 1989.

Hydraulic Committee of the Changjiang River: Atlas of the Changjiang River Basin. China Map, Beijing, 1999 (in Chinese).

Jiang, Y. J. and Kuang, M. S.: Regional vulnerability analysis, evaluation and vulnerability zoning, J. Catastrophology, 16, 59–64, 2001 (in Chinese).

Kasperson, J. X., Kasperson, R., and Dow, K.: Global environmental risk and society, in: Global environmental risk, edited by: Kasperson, J. X. and Kasperson, R., United Nations University Press, Earthscan, London, 2001.

Klein, R. J. T., Nicholls, R. J., and Thomalla, F.: Resilience to natural hazards: How useful is this concept?, Environ. Hazards, 5, 35–45, doi:10.1016/j.hazards.2004.02.001, 2003.

Liu, Y., Huang, J. Y., and Ma, L.: The assessment of regional vulnerability to natural disasters in China based on DEA model, Geogr. Res., 29, 1153–1162, 2010 (in Chinese).

Liverman, D.: Vulnerability to global environmental change, in: Understanding global environmental change: the contributions of risk analysis and management, edited by: Kasperson, R. E., Dow, K., Golding, D., and Kasperson, J. X., Report on an International Workshop, Clark University, Earth Transformed Program: Worcester MA, 1990.

Mileti, D. S.: Natural Hazards and Disasters-Disaster by Design, Joseph Henry Press, Washington, DC, 1999.

O'Keefe, P., Westgate, K., and Wisner, B.: Taking the naturalness out of natural disasters, Nature, 260, 566–567, 1976.

Ratick, S. J. and Osleeb, J. P.: Measuring the vulnerability of populations susceptible to lead contamination in the Dominican Republic: evaluating composite index construction methods, GeoJournal, 78, 259–272, doi:10.1007/s10708-011-9414-x, 2011.

Shi, P. J.: Theory and practice of disaster Study, J. Nat. Disasters, 5, 6–14, 1996 (in Chinese).

Shi, P. J.: Theory and Practice on Disaster System Research, The Proceedings of Fifth Annual IIASA-DPRI Meeting, Beijing, China, 2005.

Su, B. D., Jiang, T., and Guo, Y. Y.: GIS raster data-based dynamic flood risk simulation model and its application, J. Hehai Univ. (Nat. Sci.), 33, 370–374, 2005 (in Chinese).

Tulkens, H. and Van den Eeckaut, P.: Non-parametric efficiency, progress and regress measures for panel data: methodological aspects, Eur. J. Oper. Res, 80, 474–499, 1995.

Van Der Veen, A. and Logtmeijer, C. J. J.: Economic hotspots: visualizing vulnerability to flooding, Nat. Hazards, 36, 65–80, 2005.

Vogel, C. H.: Vulnerability: meaning, measure and motivation, Paper presented at the Regional Workshop on Risk Reduction in Southern Africa, Disaster Mitigation for Sustainable Livelihoods Project, SADEP, University of the Western Cape, Cape Town, 1997.

Wang, Y. M., Li, Z. W., Tang, Z., and Zeng, G. M.: A GIS-Based Spatial Multi-Criteria Approach for Flood Risk Assessment in the Dongting Lake Region, Hunan, Central China, Water Resour. Manage, 25, 3465–3484, 2011.

Watts, M. J. and Bohle, H. G.: The space of vulnerability: the causal structure of hunger and famine, Prog. Hum. Geog., 17, 43–67, 1993.

Wei, Y. M., Ying, F., and Cong, L.: The assessment of vulnerability to natural disasters in China by using the DEA method, Envrion. Impact Assess. Rev., 24, 427–439, 2004.

Zhang, C., Wan, Q., and Zhang, J. Q.: The method of flood disaster risk evaluation based upon data of grid square, Geo-information Sci., 4, 69–73, 2003 (in Chinese).

Zhang, J. Y. and Xu, X. M.: Test on L-moment estimation method for GEV and P-III Distribution in regional flood frequency analysis, Hydrology, 22, 36–38, 2002 (in Chinese).