

Regional flood disaster resilience evaluation based on analytic network process: a case study of the Chaohu Lake Basin, Anhui Province, China

Honghu Sun¹ · Xianfu Cheng¹ · Mengqin Dai¹

Received: 9 August 2015 / Accepted: 19 January 2016 / Published online: 1 February 2016
© Springer Science+Business Media Dordrecht 2016

Abstract Improving natural disaster resilience is one of the important methods for coping with climate change and natural disasters, and quantitative evaluation of natural disaster resilience is the primary problem to be solved urgently. In this paper, an index system for evaluating regional flood disaster resilience is constructed based on a review of the literature regarding natural disaster resilience and with full consideration of the five dimensions (i.e., nature, society, economy, technology and management) which have a great influence on flood disaster resilience. Subsequently, the overall level and five dimensions of flood disaster resilience in the Chaohu Lake Basin can be evaluated quantitatively by adopting analytic network process to dynamically analyze the influencing relationships of factors. The results obtained in this research indicate that: (1) overall, the majority of the Chaohu Lake Basin exhibits intermediate to high flood disaster resilience, but there are distinct variations within the basin. The resilience is clearly influenced by the natural dimension indexes, the highest resilience levels are mainly located in the hilly, mountainous regions, and the lowest resilience levels mainly occur in the south–southeast plain of the Chaohu Lake Basin and the river estuary of the Chaohu Lake. Considering the administrative regions, the regions with the greatest areas of intermediate and high resilience are Hefei Municipal District, Chaohu City, Feidong County, Feixi County, Lujiang County, Hanshan County, Shucheng County, most parts of He County, Wuwei County and Jiujiang District of Wuhu City. (2) Preliminary validation indicates that evaluation results regarding flood disaster resilience in the Chaohu Lake Basin are consistent with the actual conditions. Therefore, the evaluation results and method can provide a valuable approach to the rapid diagnosis of weak links in the construction of flood disaster resilience infrastructure and will ultimately improve the level of flood disaster resilience in the Chaohu Lake Basin.

✉ Xianfu Cheng
xianfucheng@sina.com

¹ Anhui Key Laboratory of Natural Disaster Process and Prevention, School of Territorial Resources and Tourism, Anhui Normal University, Wuhu 241003, China

Keywords Flood disaster resilience · Evaluation index system · Analytic network process · The Chaohu Lake Basin

1 Introduction

Climate change and natural disasters have affected the sustainable development of human society. The frequency and harm degree of extreme climate events are rising in recent years, and the natural disasters risk are in sustained growth (Field et al. 2012). Climate change is already affecting and continues to affect living environment and conditions for development of many areas in China (National Development and Reformation Committee 2013). Effective adaptation principle of reducing vulnerability, exposure degree and increasing climate resilience was put forward, and adaptation was affirmed to play a positive role in climate disaster risk management (IPCC 2014).

Under this background, natural disaster resilience has increasingly become the focus of international concern. Many international organizations and programs take it into consideration (Asian Development Bank 2008; World Bank 2008a, b). The concept of disaster resilience is also enriched constantly (Mileti 1999; Adger et al. 2005; Liu et al. 2006; Mayunga 2007; Kang et al. 2007; Cutter et al. 2008; World Bank 2008a, b; UNISDR 2009; UK Department for International Development 2011; Fei et al. 2014). It is the first time that resilience was considered as acceptable level of loss in an extreme natural event for a region from the perspective of disaster (Mileti 1999). Subsequently, it was defined from two aspects of generalized sense and narrow sense. The generalized conception of disaster resilience included the ability of resistance during disaster (static part) and recovery after disaster (dynamic part), while the narrow conception of disaster resilience only included the ability of adjustment, adaptation, recovery and reconstruction after a disaster under the condition that system was not destroyed completely. (Liu et al. 2006). And the social, economic, cultural, physical and natural capital was considered to be the decisive factors of resilience (Mayunga 2007). Disaster resilience was also defined as capacity of resistance or change in a system, community or society, determined by the capacity of the ability of self-organization, learning and adaptation, including the ability to recover from the disaster (UNISDR 2009). Recently, a new view was that the natural disaster resilience referred to the ability to protect residents' life, the corresponding infrastructure from disturbance and to recover from natural disasters in an integrated social–ecological system. (Fei et al. 2014). It can be seen that the connotation and extension of disaster resilience are in expansion and considered as a system with different scales, a kind of ability emphasizing adaptation and learning; moreover, the definition began to take social–economic system and natural–ecological system into account.

Disaster resilience of integrated social–ecological system is influenced by the natural, social, economic and other factors. It has high complexity and uncertainty, difficult to use quantitative methods to make an accurate measurement. At present, the idea of index system is used in most studies on disaster resilience (Shaw and IEDM Team 2009; Shaw and Fernandez 2010; Zhang et al. 2011; Prashar and Shaw 2012; Chan et al. 2014), and the specific methods include capacity and vulnerability analysis (Cannon et al. 2003), cost benefit analysis (FEMA 2003), SWOT analysis (World Economic Forum 2008), disaster resilience index analysis (Shaw and IEDM Team 2009; Shaw and Fernandez 2010; Zhang et al. 2011; Prashar and Shaw 2012), scenario analysis (Plough et al. 2013). However, these

methods are mainly qualitative analysis, lack of comprehensive research, rarely involving the basin scale. In fact, due to the inherent nature of flood disaster, the impact of flood disaster often has the basin scale, can not only focus on the community scale. Therefore, the flood disaster resilience evaluation can be carried out on the basin scale and provide a scientific basis for regional flood disaster management. Compared with resilience evaluation on the community scale whose measurement method is always based on community actors' perception and index system is complex which can only be applied to small scale, there are the advantages of easy to obtain, quantitative analysis and horizontal comparison on the basin scale. On the basis of previous studies, considering the influence dimension of nature, society, economy, technology, management of flood disaster resilience, an index system for evaluating regional flood disaster resilience was constructed, and then, 17 indexes were chosen according to the characteristics of flood disaster resilience in the Chaohu Lake Basin. In order to investigate the interrelationships of indexes, network structure of influence relationships were built by using ANP analysis. Finally, the weights of indexes were also obtained. Subsequently, the overall level and five dimensions of flood disaster resilience in the Chaohu Lake Basin are evaluated, which can provide a valuable tool for the rapid diagnosis of weak links in the construction of flood disaster resilience infrastructure and will ultimately improve the level of flood disaster resilience in the Chaohu Lake Basin.

2 Study area and data sources

2.1 Study area

The Chaohu Lake Basin is located in the central part of Anhui Province, covering an area of 13,350 km², which belongs to the Yangtze River Basin, and the Chaohu Lake is one of the five largest fresh water lakes in China. Monsoon climate is significant here, and its flood season is from May to September; precipitation in this time accounts for about 60 % of annual precipitation. Landform types include platform in a hilly area of Jianghuai, hilly and mountain area in West Anhui, plain area along the Yangtze River. Restricted by topographic conditions, the river system forms radial distribution with large density and mainly supplied by precipitation.

Administrative regions consist of Hefei municipal districts, Feidong County, Feixi County, Lujiang County, Chaohu City, Wuwei County, Shucheng County, He County, Hanshan County, Jiujiang District of Wuhu City (Fig. 1), all located in Wanjiang City Belt, the population accounts for 14 percent of the population of Anhui Province, and the total GDP in 2013 accounts for 27 percent of Anhui Province. Moreover, Hefei City is the political, economic, cultural center in Anhui Province. Complicated natural conditions and frequent social and economic activities make Chaohu Lake Basin become a flood-prone area.

2.2 Data sources

Meteorological data are the average precipitation in the flood season of years in the Chaohu Lake Basin. Data of digital elevation, land use and vegetation coverage which are interpreted from Landsat 8 satellite remote sensing image in May 14, 2013, with 30 m resolution are provided by International Scientific & Technical Data Mirror Site, Computer

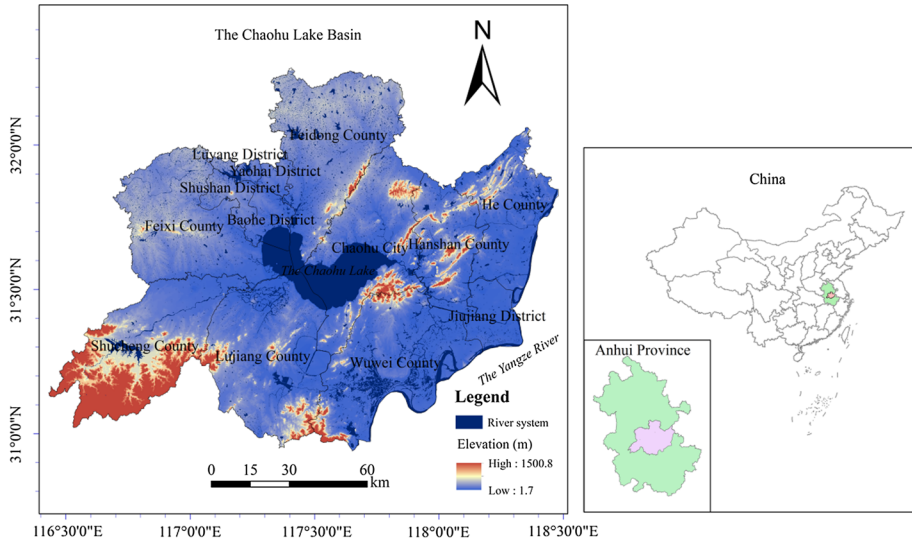


Fig. 1 Chaohu Lake Basin

Network Information Center, Chinese Academy of Sciences (<http://www.gscloud.cn>). The social, economic and other dates are collected from “Statistical Yearbook of Anhui Province,” “Statistical Yearbook of Hefei City” in 2014 and the economic and social development statistics bulletin of cities and counties in 2013.

3 Methodologies

Study methods mainly include ANP, RS and GIS analysis technology.

Analytic network process (ANP) is a decision-making method which is suitable for complex structure (Saaty 1996), it derives from analytic hierarchy process (AHP) which assumes the decision parameters are independent of each other, and the ANP method takes the dependence and feedback among elements into account based on the actual situation which expands and improves AHP so that it can simulate the complex interrelationships of reality better. Therefore, ANP has been widely used in multi-attribute decision analysis in various fields such as environment management, multi-dimensional forecast, strategic decision, project selection, and product planning (Cheng and Li 2005; Xu and Chan 2013; Armaghan and Reza 2014; Mei et al. 2014). Due to the computational complexity, ANP decision process can be achieved with the aid of super decisions (SD) software. The basic steps are as follows:

1. According to the principle of ANP and the evaluation index system, the ANP network evaluation model can be established (Fig. 2). Double arrow indicates the influence between each other. A single arrow points to influencing direction.
2. Based on interaction of various elements in the network model, they can be compared with each other. According to the Saaty 1–9 scales, compared in pairs through the expert questionnaire, the expert scoring can be integrated by using geometric mean method.

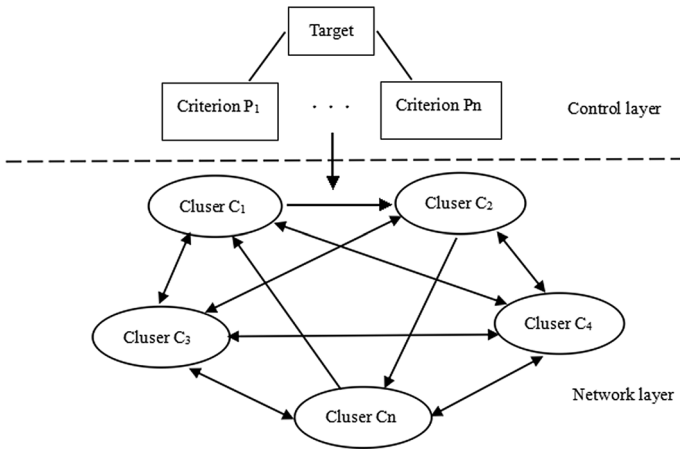


Fig. 2 ANP network evaluation model

3. The unweighted supermatrix should be determined and checked for consistency. Firstly, in the control layer, the indirect dominance of elements needs to be compared in order to get weight vector by the eigenvalue method. Subsequently, through the consistency test, local weight matrix can be obtained. Similarly, the relationships of elements in other clusters need to be compared to get unweighted supermatrix W , which consists of ranking vector resulting from influence of elements in the network layer.

$$W = \begin{bmatrix} W_{11} & W_{12} & \cdots & W_{1N} \\ W_{21} & W_{22} & \cdots & W_{2N} \\ \cdots & \cdots & \cdots & \cdots \\ W_{N1} & W_{N2} & \cdots & W_{NN} \end{bmatrix}$$

4. Calculate weighted supermatrix. Each subsystem of unweighted supermatrix is only considered the rank of elements within subsystem to a certain criterion. Effect on the criterion of other subsystems is not estimated. Therefore, each column of unweighted supermatrix is not normalized, so each subsystem (or level) should be taken as an element, and given a comparison with subsystems to obtain a weighted matrix A . Finally, elements of unweighted supermatrix W are weighted to get weighted supermatrix \bar{W} .

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1N} \\ a_{21} & a_{22} & \cdots & a_{2N} \\ \cdots & \cdots & \cdots & \cdots \\ a_{N1} & a_{N2} & \cdots & a_{NN} \end{bmatrix}, \quad \bar{W} = \begin{bmatrix} a_{11} \times w_{11} & a_{12} \times w_{12} & \cdots & a_{1N} \times w_{1N} \\ a_{21} \times w_{21} & a_{22} \times w_{22} & \cdots & a_{2N} \times w_{2N} \\ \cdots & \cdots & \cdots & \cdots \\ a_{N1} \times w_{N1} & a_{N2} \times w_{N2} & \cdots & a_{NN} \times w_{NN} \end{bmatrix}$$

5. Calculate the limit supermatrix to determine weight of elements. In order to reflect the relationship between elements, the stability of weighted matrix is needed. Weighted matrix should be multiplied by itself until matrix product converges. At last, the weight value of each element would be obtained $W^\infty = \lim_{k \rightarrow \infty} (\bar{W})^k$.

4 Construction and analysis of evaluation index system of flood disaster resilience in the Chaohu Lake Basin

4.1 Evaluation index system of flood disaster resilience

Flood disaster resilience is influenced by many factors, involving natural, social, economic, technology, management dimensions. Investigate the influencing factors of flood disaster resilience in the Chaohu Lake Basin, in natural dimension, flood disaster was mainly due to concentrated precipitation, low capacity of water storage, low-lying terrain, serious soil erosion; in social and economic dimension, owing to the relative concentration of population, and material wealth in plain area along the Chaohu Lake and the Yangtze River the disaster loss was relatively serious, but flood disaster resilience was greater in virtue of the relative abundance of material resources and financial support; in technology dimension, the internal differences of the basin are also obvious, and on the overall level, there were still some problems such as small reservoir capacity, weak dyke facilities; in management dimension, government was still the subject of disaster management, and under other conditions which are unchanged, its management ability was closely related to the area, population and wealth which were under its management. Therefore, considering the science, representative, availability of indexes, the selection of 17 indexes to characterize the impact factors and the construction of evaluation index system from five dimensions were reasonable (Table 1). The network model was established to investigate the inter-relationships of indexes by using SD software (Fig. 3); then, unweighted supermatrix (Table 2), weighted supermatrix (Table 3), limit supermatrix (Table 4) and the weight of each index (Table 5) can be obtained; all passed the consistency check ($CR \leq 0.1$).

4.2 Analysis of influence factors of flood disaster resilience in Chaohu Lake Basin

Indexes were analyzed in ArcGIS 10.0 software using projection coordinate system of WGS_1984_UTM_Zone_50 N and setting resolution to 100 m accuracy. Index layer covers as same space as administrative region of the study area covers. In order to carry out the calculation of indexes, they need standardization. The calculation formulas of the standardization are as follows:

$$\text{For the positive index, } Y = (X - X_{\min}) / (X_{\max} - X_{\min})$$

$$\text{For the negative index, } Y = (X_{\max} - X) / (X_{\max} - X_{\min})$$

In the formula, Y is the standard value of evaluation index, X is the value of each evaluation index, X_{\max} is the maximum value of the evaluation index and X_{\min} is the minimum value of the evaluation index.

4.2.1 Natural dimension

In the natural dimension, precipitation in flood season can be on behalf of the factor which leads to disaster. Surface data of precipitation were obtained by using IDW method in ArcGIS 10.0 (Fig. 4a). Water area density, influence degree of topography, and vegetation coverage were selected to characterize disaster environment. Water area density can be expressed as the total area of water in the unit basin area, which can better reflect the

Table 1 Evaluation index system of flood disaster resilience in the Chaohu Lake Basin

Target	Dimension	Index	Unit	Direction
Flood disaster resilience in the Chaohu Lake Basin A	Nature B ₁	Flood season precipitation C ₁₁	mm	–
		Water area density C ₁₂	km ² /km ²	–
		Influence degree of terrain C ₁₃	–	+
		Vegetation coverage C ₁₄	–	+
	Society B ₂	Population density C ₂₁	people/km ²	–
		Proportion of the labor force population C ₂₂	%	+
		Per capita number of medical staff C ₂₃	people/Per thousand people	+
	Economy B ₃	GDP density C ₃₁	million yuan/km ²	+
		Per capita government revenue C ₃₂	yuan/person	+
		Per capita net income of farmers C ₃₃	yuan/person	+
		Per capita grain yield C ₃₄	kg/person	+
	Technology B ₄	Area proportion of farmland without flood disaster C ₄₁	%	+
		Reservoir capacity C ₄₂	10 ⁴ m ³ /km ²	+
		Proportion of village benefiting from top water C ₄₃	%	+
	Management B ₅	Ratio of the number of administrative region to the area of administrative region C ₅₁	number/km ²	+
		Ratio of the number of administrative region to GDP of administrative region C ₅₂	number/million yuan	+
		Ratio of the number of administrative region to the population of administrative region C ₅₃	number/million people	+

distribution of water system than simple drainage density. The higher the water area density is, the greater the flood disaster impacts; accordingly, more slowly the flood disaster recedes and recovers. Through the establishment of fish net with 1000 m × 1000 m precision and regional statistics, water area density can be obtained (Fig. 4b). Flood is difficult to discharge in a region of low and flat terrain, causing the flood disaster recovery slow. Considering influence of the absolute elevation and the standard deviation of the elevation on flood disaster, influence degree of terrain was constructed. According to the normal water level, the warning level, the highest level in history and the variation of flood level of representative hydrological station in the Chaohu Lake Basin, elevation and the standard deviation of the elevation were divided into five categories, and the relationships of topographic influence were calculated by Con function (Table 6); subsequently, the distribution map of influence degree of topography can be obtained (Fig. 4c). The vegetation coverage is closely related to the ability of soil and water conservation. There exists serious soil erosion in a place with low vegetation coverage, which results in the decrease in capacity of flood storage in rivers and lakes. For example, there

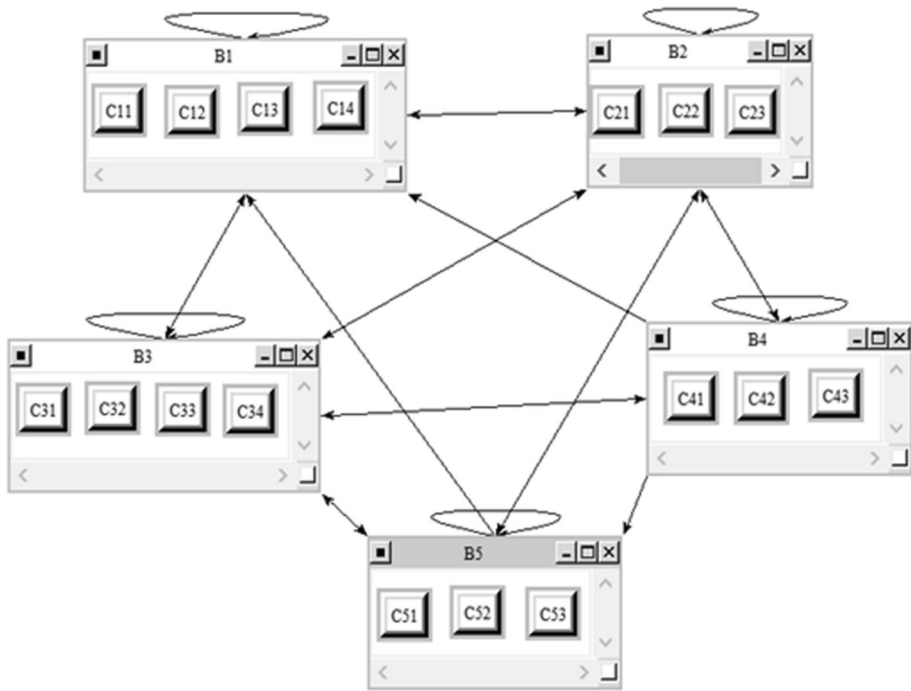


Fig. 3 Network model for interrelationships of evaluation indexes

exists the phenomenon of bank collapse in the south bank of the Chaohu Lake which results from serious soil erosion. Through interpretation of remote sensing images, the distribution map of vegetation coverage in the Chaohu Lake Basin can be obtained (Fig. 4d). At last, the distribution map of the flood disaster resilience in the natural dimension was obtained by weighted stacking of index layers (Fig. 5a).

Figure 5a shows that regions of the low flood disaster resilience in natural dimension are mainly located in the plain area along the Yangtze River, Chaohu Lake and low-lying areas of estuary accessing to the Chaohu Lake and administrative regions include Wuwei County, He County, Jiujiang District, Wuhu City. The reason is that the low-lying terrain, heavy precipitation, high water area density lead to flood easy to converge and difficult to discharge in time and sometimes even effected by trunk stream flood of the Yangtze River, and soil erosion also causes the decrease in capacity of flood storage and release of rivers and lakes.

4.2.2 Social dimension

Population is the most basic “disaster-bearing body.” The distribution, age structure and life safety guarantee of population can qualitatively reflect regional flood disaster resilience of social dimension. Under normal circumstances, in densely populated areas, the population affected by the disaster is more difficult to manage, which requires a lot of manpower, material resources and financial support. Through the statistics of population density, proportion of the labor force population, per capita number of medical staff and weighted stacking of index layers, flood disaster resilience of social dimension in the

Table 2 Unweighted supermatrix

	C ₁₁	C ₁₂	C ₁₃	C ₁₄	C ₂₁	C ₂₂	C ₂₃	C ₃₁	C ₃₂	C ₃₃	C ₃₄	C ₄₁	C ₄₂	C ₄₃	C ₅₁	C ₅₂	C ₅₃
C ₁₁	0.0000	0.3196	0.4000	0.6250	0.2385	0.0000	0.0000	0.0000	0.0000	0.2500	0.2385	0.2449	0.2772	0.0000	0.0000	0.0000	0.0000
C ₁₂	0.2385	0.0000	0.4000	0.1365	0.1365	0.0000	0.0000	0.0000	0.0000	0.0000	0.1365	0.1545	0.1601	0.2000	0.0000	0.0000	0.0000
C ₁₃	0.6250	0.5584	0.0000	0.2385	0.6250	0.0000	0.0000	1.0000	0.0000	0.7500	0.6250	0.5080	0.4673	0.8000	1.0000	0.0000	1.0000
C ₁₄	0.1365	0.1220	0.2000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0926	0.0954	0.0000	0.0000	0.0000	0.0000
C ₂₁	0.0000	1.0000	1.0000	1.0000	0.0000	0.0000	1.0000	0.3333	0.2500	0.0000	1.0000	0.0000	0.0000	1.0000	1.0000	1.0000	1.0000
C ₂₂	0.0000	0.0000	0.0000	0.0000	0.7500	0.0000	0.0000	0.6667	0.7500	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C ₂₃	0.0000	0.0000	0.0000	0.0000	0.2500	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C ₃₁	0.0000	0.0000	0.0000	1.0000	0.5822	0.6667	0.2500	0.0000	1.0000	0.6370	0.0000	0.0000	0.0000	0.0000	0.3333	1.0000	0.3333
C ₃₂	0.0000	0.0000	0.0000	0.0000	0.2354	0.3333	0.7500	0.2500	0.0000	0.2583	1.0000	1.0000	1.0000	1.0000	0.6667	0.0000	0.6667
C ₃₃	0.0000	0.0000	0.0000	0.0000	0.1291	0.0000	0.0000	0.7500	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C ₃₄	0.0000	0.0000	0.0000	0.0000	0.0533	0.0000	0.0000	0.0000	0.0000	0.1047	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C ₄₁	0.0000	0.0000	0.0000	0.0000	0.3196	0.0000	0.0000	0.0000	0.0000	0.7500	0.7500	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C ₄₂	0.0000	0.0000	0.0000	0.0000	0.5584	0.0000	0.0000	1.0000	1.0000	0.2500	0.2500	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C ₄₃	0.0000	0.0000	0.0000	0.0000	0.1220	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C ₅₁	0.0000	0.0000	0.0000	0.0000	0.3333	0.0000	0.1634	0.2500	0.1634	0.0000	0.0000	0.0000	0.0000	0.5000	0.0000	0.0000	0.2500
C ₅₂	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5396	0.7500	0.5396	0.6667	0.6667	0.3333	0.6667	0.0000	0.3333	0.0000	0.7500
C ₅₃	0.0000	0.0000	0.0000	0.0000	0.6667	1.0000	0.2970	0.0000	0.2970	0.3333	0.3333	0.6667	0.3333	0.5000	0.6667	1.0000	0.0000

Table 3 Weighted supermatrix

	C ₁₁	C ₁₂	C ₁₃	C ₁₄	C ₂₁	C ₂₂	C ₂₃	C ₃₁	C ₃₂	C ₃₃	C ₃₄	C ₄₁	C ₄₂	C ₄₃	C ₅₁	C ₅₂	C ₅₃
C ₁₁	0.0000	0.2313	0.2895	0.3906	0.0972	0.0000	0.0000	0.0000	0.0000	0.1092	0.0903	0.1143	0.1538	0.0000	0.0000	0.0000	0.0000
C ₁₂	0.2385	0.0000	0.2895	0.0853	0.0556	0.0000	0.0000	0.0000	0.0000	0.0000	0.0517	0.0721	0.0888	0.0934	0.0000	0.0000	0.0000
C ₁₃	0.6250	0.4042	0.0000	0.1491	0.2547	0.0000	0.0000	0.3784	0.0000	0.3275	0.2365	0.2372	0.2592	0.3735	0.4155	0.0000	0.4155
C ₁₄	0.1365	0.0883	0.1448	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0432	0.0529	0.0000	0.0000	0.0000	0.0000
C ₂₁	0.0000	0.2762	0.2762	0.2385	0.0000	0.0000	0.2236	0.0445	0.0537	0.0000	0.1334	0.0000	0.0000	0.1584	0.1850	0.3164	0.1850
C ₂₂	0.0000	0.0000	0.0000	0.0000	0.0712	0.0000	0.0000	0.0890	0.1610	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C ₂₃	0.0000	0.0000	0.0000	0.0000	0.0237	0.2236	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C ₃₁	0.0000	0.0000	0.0000	0.1365	0.1474	0.3977	0.1491	0.0000	0.3965	0.1812	0.0000	0.0000	0.0000	0.0000	0.0975	0.5006	0.0975
C ₃₂	0.0000	0.0000	0.0000	0.0000	0.0596	0.1988	0.4474	0.0616	0.0000	0.0735	0.2464	0.2831	0.3364	0.2831	0.1951	0.0000	0.1951
C ₃₃	0.0000	0.0000	0.0000	0.0000	0.0327	0.0000	0.0000	0.1848	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C ₃₄	0.0000	0.0000	0.0000	0.0000	0.0135	0.0000	0.0000	0.0000	0.0000	0.0298	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C ₄₁	0.0000	0.0000	0.0000	0.0000	0.0537	0.0000	0.0000	0.0000	0.0000	0.1411	0.1223	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C ₄₂	0.0000	0.0000	0.0000	0.0000	0.0939	0.0000	0.0000	0.1630	0.2623	0.0470	0.0408	0.1584	0.0000	0.0000	0.0000	0.0000	0.0000
C ₄₃	0.0000	0.0000	0.0000	0.0000	0.0205	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C ₅₁	0.0000	0.0000	0.0000	0.0000	0.0255	0.0000	0.0294	0.0197	0.0207	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C ₅₂	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0971	0.0590	0.0683	0.0605	0.0524	0.0305	0.0726	0.0000	0.0357	0.0000	0.0802
C ₅₃	0.0000	0.0000	0.0000	0.0000	0.0509	0.1799	0.0534	0.0000	0.0376	0.0303	0.0262	0.0611	0.0363	0.0458	0.0713	0.1830	0.0000

Table 4 Limit supermatrix

	C ₁₁	C ₁₂	C ₁₃	C ₁₄	C ₂₁	C ₂₂	C ₂₃	C ₃₁	C ₃₂	C ₃₃	C ₃₄	C ₄₁	C ₄₂	C ₄₃	C ₅₁	C ₅₂	C ₅₃
C ₁₁	0.1523	0.1523	0.1523	0.1523	0.1523	0.1523	0.1523	0.1523	0.1523	0.1523	0.1523	0.1523	0.1523	0.1523	0.1523	0.1523	0.1523
C ₁₂	0.1271	0.1271	0.1271	0.1271	0.1271	0.1271	0.1271	0.1271	0.1271	0.1271	0.1271	0.1271	0.1271	0.1271	0.1271	0.1271	0.1271
C ₁₃	0.2503	0.2503	0.2503	0.2503	0.2503	0.2503	0.2503	0.2503	0.2503	0.2503	0.2503	0.2503	0.2503	0.2503	0.2503	0.2503	0.2503
C ₁₄	0.0708	0.0708	0.0708	0.0708	0.0708	0.0708	0.0708	0.0708	0.0708	0.0708	0.0708	0.0708	0.0708	0.0708	0.0708	0.0708	0.0708
C ₂₁	0.1387	0.1387	0.1387	0.1387	0.1387	0.1387	0.1387	0.1387	0.1387	0.1387	0.1387	0.1387	0.1387	0.1387	0.1387	0.1387	0.1387
C ₂₂	0.0235	0.0235	0.0235	0.0235	0.0235	0.0235	0.0235	0.0235	0.0235	0.0235	0.0235	0.0235	0.0235	0.0235	0.0235	0.0235	0.0235
C ₂₃	0.0085	0.0085	0.0085	0.0085	0.0085	0.0085	0.0085	0.0085	0.0085	0.0085	0.0085	0.0085	0.0085	0.0085	0.0085	0.0085	0.0085
C ₃₁	0.0714	0.0714	0.0714	0.0714	0.0714	0.0714	0.0714	0.0714	0.0714	0.0714	0.0714	0.0714	0.0714	0.0714	0.0714	0.0714	0.0714
C ₃₂	0.0450	0.0450	0.0450	0.0450	0.0450	0.0450	0.0450	0.0450	0.0450	0.0450	0.0450	0.0450	0.0450	0.0450	0.0450	0.0450	0.0450
C ₃₃	0.0177	0.0177	0.0177	0.0177	0.0177	0.0177	0.0177	0.0177	0.0177	0.0177	0.0177	0.0177	0.0177	0.0177	0.0177	0.0177	0.0177
C ₃₄	0.0024	0.0024	0.0024	0.0024	0.0024	0.0024	0.0024	0.0024	0.0024	0.0024	0.0024	0.0024	0.0024	0.0024	0.0024	0.0024	0.0024
C ₄₁	0.0103	0.0103	0.0103	0.0103	0.0103	0.0103	0.0103	0.0103	0.0103	0.0103	0.0103	0.0103	0.0103	0.0103	0.0103	0.0103	0.0103
C ₄₂	0.0390	0.0390	0.0390	0.0390	0.0390	0.0390	0.0390	0.0390	0.0390	0.0390	0.0390	0.0390	0.0390	0.0390	0.0390	0.0390	0.0390
C ₄₃	0.0028	0.0028	0.0028	0.0028	0.0028	0.0028	0.0028	0.0028	0.0028	0.0028	0.0028	0.0028	0.0028	0.0028	0.0028	0.0028	0.0028
C ₅₁	0.0068	0.0068	0.0068	0.0068	0.0068	0.0068	0.0068	0.0068	0.0068	0.0068	0.0068	0.0068	0.0068	0.0068	0.0068	0.0068	0.0068
C ₅₂	0.0142	0.0142	0.0142	0.0142	0.0142	0.0142	0.0142	0.0142	0.0142	0.0142	0.0142	0.0142	0.0142	0.0142	0.0142	0.0142	0.0142
C ₅₃	0.0193	0.0193	0.0193	0.0193	0.0193	0.0193	0.0193	0.0193	0.0193	0.0193	0.0193	0.0193	0.0193	0.0193	0.0193	0.0193	0.0193

Table 5 Weight of evaluation indexes

Target	Dimension	Weight	Index	Weight
A	B ₁	0.6004	C ₁₁	0.1523
			C ₁₂	0.1271
			C ₁₃	0.2504
			C ₁₄	0.0708
	B ₂	0.1707	C ₂₁	0.1387
			C ₂₂	0.0235
			C ₂₃	0.0085
	B ₃	0.1365	C ₃₁	0.0714
			C ₃₂	0.0449
			C ₃₃	0.0117
			C ₃₄	0.0024
	B ₄	0.0520	C ₄₁	0.0103
			C ₄₂	0.0390
			C ₄₃	0.0028
B ₅	0.0404	C ₅₁	0.0068	
		C ₅₂	0.0142	
		C ₅₃	0.0193	

Chaohu Lake Basin can be obtained (Fig. 5b). Figure 5b shows that mainly due to the highest population density, the lowest flood disaster resilience of social dimension is in Hefei municipal district. Benefit from the high health conditions and labor ratio, the flood disaster resilience of social dimension in Jiujiang District (Wuhu City) is the highest.

4.2.3 Economic dimension

Generally speaking, financial and material resources support capability of an economically developed region is stronger than a region of low economic level during the disaster-recovery process. Four indexes of GDP density, per capita government revenue, per capita farmer's net income and per capita grain yield are selected to reflect flood disaster resilience level of economic dimension. Finally, through the weighted sum of the corresponding index layer, the flood disaster resilience of economic dimension in the Chaohu Lake Basin can be obtained (Fig. 5c). Figure 5c shows that because of the strong economic strength, the flood disaster resilience of economic dimension in Hefei municipal district, Jiujiang District (Wuhu City), Feixi County are at a high level, and the indicators of Shucheng County are such a low value that its flood disaster resilience of economic dimension is the lowest.

4.2.4 Technology dimension

Construction of infrastructure to cope with the flood disaster is the most direct and customary measure for flood disaster control and mitigation. Indexes that proportion of farmland not threatened by floods, reservoir capacity, proportion of village benefiting from top water can reflect the ability to protect the normal production and life from the flood threat, which can be selected to characterize the flood disaster resilience of technology dimension. Through the weighted sum of the corresponding index layers, the distribution

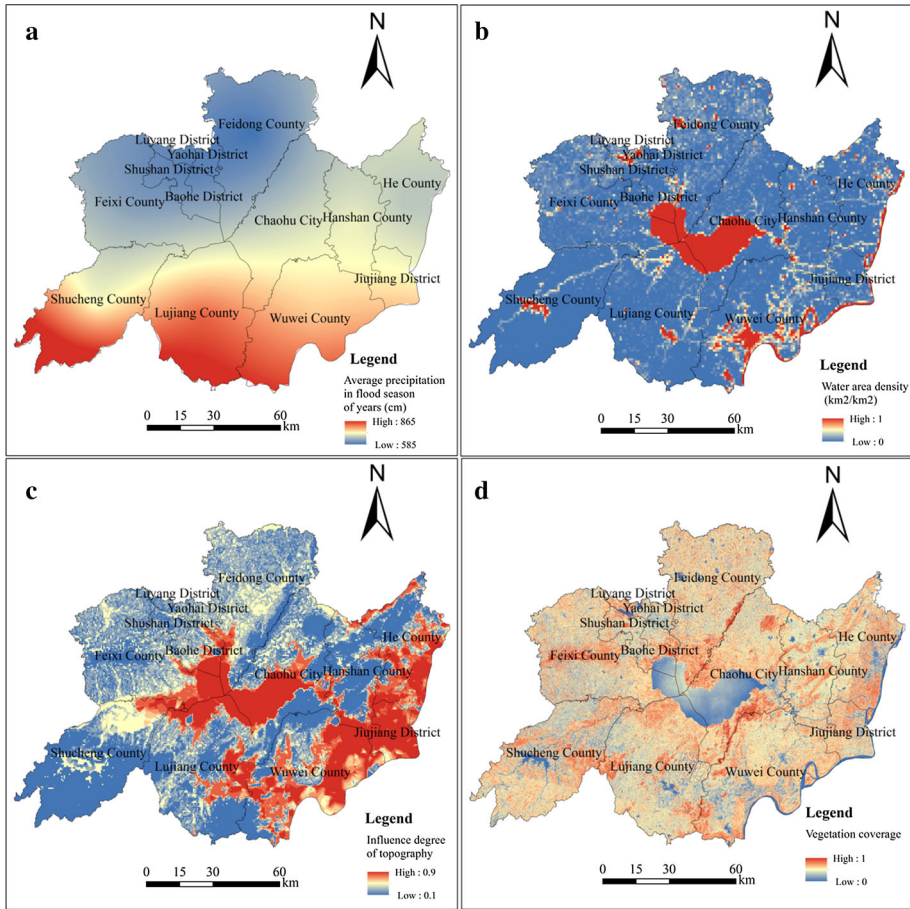


Fig. 4 Indexes of natural dimension. **a** Average precipitation in flood season of years, **b** water area density, **c** influence degree of topography, **d** vegetation coverage

Table 6 Relationship of topographic influence

Elevation (m)	Standard deviation of elevation (m)				
	0–0.5	0.5–1	1–2	2–3	>3
1.7–9	0.9	0.8	0.7	0.6	0.5
9–10	0.8	0.7	0.6	0.5	0.4
10–11	0.7	0.6	0.5	0.4	0.3
11–13	0.6	0.5	0.4	0.3	0.2
>13	0.5	0.4	0.3	0.2	0.1

map of flood disaster resilience of technology dimension in the Chaohu Lake Basin (Fig. 5d) can be also obtained. As is shown in Fig. 5d, flood disaster resilience level of technical dimension in Hanshan County is the lowest, mainly due to the low area proportion of farmland without flood disaster and the low capacity of reservoir. In contrast, the

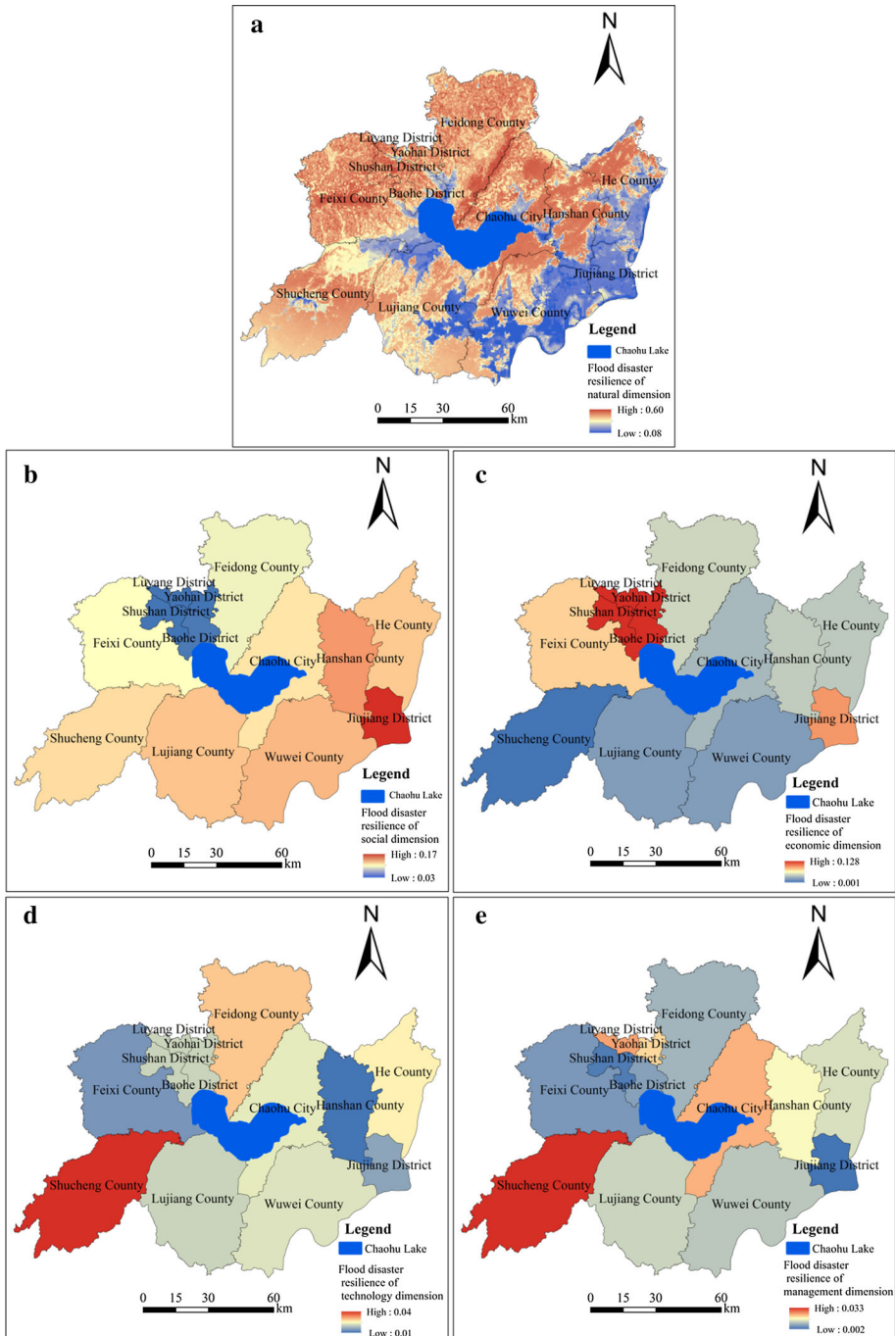


Fig. 5 Flood disaster resilience of five dimensions. **a** Flood disaster resilience of natural dimension, **b** flood disaster resilience of social dimension, **c** flood disaster resilience of economic dimension, **d** flood disaster resilience of technology dimension, **e** flood disaster resilience of management dimension

two indexes of Shucheng County are very high, because the establishment of Longhekou Reservoir greatly reduces the burden from the Hangbu River floods.

4.2.5 Management dimension

Disaster management is the non-engineering measure in disaster prevention and reduction. Scientific management plays a more and more important role in the process of coping with flood disaster, and the timely and efficient leadership of government is a strong guarantee for disaster management. Generally speaking, under the condition of the same administrative area, population and economic conditions, more government agencies mean lower management difficulty. Considering the scientific and availability of indexes, ratio of the number of administrative region to the area of administrative region, ratio of the number of administrative region to GDP of administrative region, ratio of the number of administrative region to the population of administrative region were used to characterize the flood disaster resilience of management dimension, and through the weighted sum of the corresponding index layers, the distribution map of flood disaster resilience of management dimension in the Chaohu Lake Basin can be obtained (Fig. 5e). Figure 5e shows that the flood disaster resilience of management dimension is minimum in Shushan District (Hefei City) and Jiujiang District (Wuhu City), mainly because the two areas have large population and wealth, resulting in management difficulties; the flood disaster resilience of management dimension is maximum in Shucheng County, along with the relatively low density of population and economic, and the management difficulty is reduced.

4.3 Analysis of comprehensive evaluation of the flood disaster resilience in the Chaohu Lake Basin

Comprehensive evaluation map of flood disaster resilience in the Chaohu Lake Basin can be obtained by superposition of flood disaster resilience layers of five dimensions (Fig. 6); using the natural breakpoint analysis method, the map can be divided into five grades of lowest, lower, medium, higher, highest (Fig. 7). The area ratio of flood disaster resilience levels in the whole basin and the counties and districts can be also calculated (Table 7). Figure 7 shows that most areas of the highest and higher resilience level are hilly, mountainous areas, even in the southwest region of abundant rainfall. Owing to the high-elevation, undulating terrain, flood is difficult to accumulate; both population and economic density are low so that disaster losses are also small. Although the terrain of Hefei municipal district is not very high and it has dense population, the management difficulty is also big, due to the relatively low precipitation, strong economic strength, good infrastructure for disaster prevention and mitigation. The flood disaster resilience in most part of this region is also very high. The lower or lowest level areas are mainly in the south, southeast plain of the Chaohu Lake Basin and the estuary accessing to the Chaohu Lake, because the regions have abundant rainfall, low terrain, dense river network, higher population and economic density, the low ability to flood disaster prevention and mitigation, even pressure from trunk stream flood of the Yangtze River.

Table 7 shows that the overall flood disaster resilience in the Chaohu Lake Basin is at the middle and upper level, but internal differences are significant. From the view of administrative region, the area ratio of the lowest flood disaster resilience level in Wuwei County is the highest, which is higher than the overall level of the Chaohu Lake Basin. Regions of the lower resilience level accounting for large area are located in He County, Jiujiang District (Wuhu City) whose area ratios of lower resilience level are all higher than

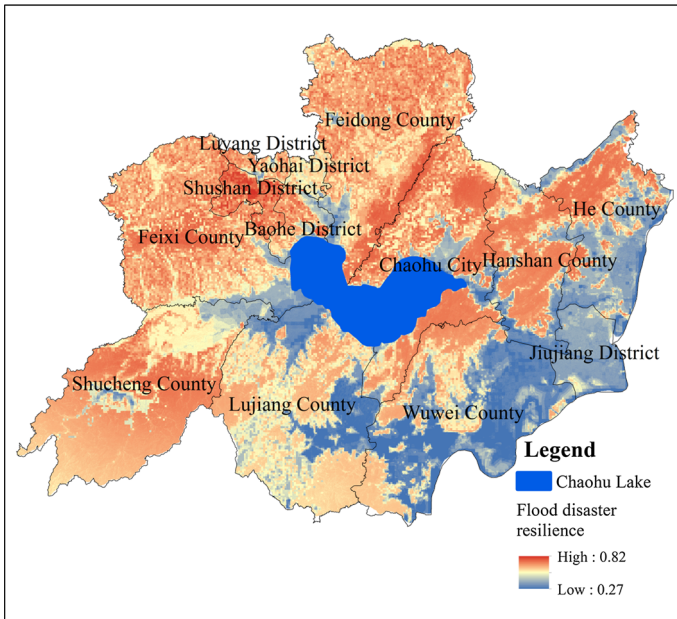


Fig. 6 Flood disaster resilience

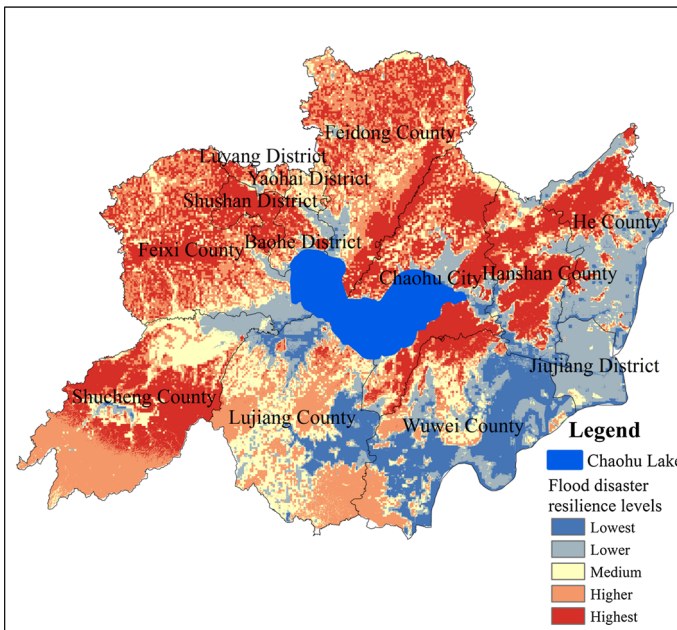


Fig. 7 Flood disaster resilience levels

Table 7 Area ratio of flood disaster resilience levels area in the Chaohu Lake Basin

Area ratio of flood disaster resilience levels area	Hefei municipal districts	Chaohu City	Feidong County	Feixi County	Luijiang County	Hanshan County	He County	Wuwei County	Jiujiang District	Shucheng County	Chaohu Lake Basin
Lowest	0.004	0.018	0.005	0.010	0.160	0.067	0.060	0.412	0.076	0.003	0.096
Lower	0.090	0.110	0.036	0.073	0.141	0.155	0.460	0.212	0.863	0.065	0.160
Medium	0.199	0.141	0.155	0.158	0.315	0.128	0.098	0.146	0.056	0.196	0.174
Higher	0.267	0.221	0.425	0.386	0.372	0.150	0.105	0.162	0.004	0.382	0.286
Highest	0.440	0.512	0.380	0.373	0.014	0.499	0.277	0.068	0.001	0.355	0.284

the overall level of the Chaohu Lake Basin, and most part of Jiujiang District (Wuhu City) is at the lower resilience level. The medium resilience level of Hefei Municipal District, Lujiang County, Shucheng County is higher than the overall level of the Chaohu Lake Basin; regions of the higher resilience level accounting for large part are located in Feidong County, Feixi County, Lujiang County, Shucheng County, whose area ratio of higher resilience level is also higher than the overall level of the Chaohu Lake Basin. Regions of the highest resilience level accounting for large part include Hefei Municipal District, Chaohu City, Feidong County, Feixi County, Hanshan County, Shucheng County, the area ratios of which are all higher than the overall level of the Chaohu Lake Basin. The regions whose most part are at the middle and above level of resilience are Hefei Municipal District, Chaohu City, Feidong County, Feixi County, Lujiang County, Hanshan County, Shucheng County, resilience of the most parts of He County, Wuwei County, Jiujiang District (Wuhu City) are at the lower or lowest level.

In order to verify the rationality of comprehensive evaluation map of the flood disaster resilience in the Chaohu Lake Basin, compared with the results of previous studies, a preliminary validation was done from the spatial distribution of flood disaster and the flood disaster loss distribution in the Chaohu Lake Basin (Yuan et al. 2007; Cheng et al. 2014). The result shows that they have the basically same distribution features, with a strong positive relationship, which proves that the evaluation results can provide reliable reference for disaster management and decision making.

5 Conclusions

1. Considering the influence factors of regional flood disaster resilience from the natural, social, economic, technical, management dimensions, an index system for evaluating flood disaster resilience in the Chaohu Lake Basin was constructed. Using analytic network process (ANP) analysis, network structures of the influencing relationships were built, and the weights of the dependent indexes were obtained. Subsequently, the overall level and five dimensions of flood disaster resilience in the Chaohu Lake Basin are evaluated, which can provide scientific reference for the management and decision of flood disaster in the Chaohu Lake Basin.
2. The results of the study show that the regions of the flood disaster resilience at the middle and above level account for most in the Chaohu Lake Basin. However, internal differences are significant and obviously affected by factors in natural dimension. Areas of flood disaster resilience at the middle and above level are mainly located in the hilly, mountainous area, and the lower or lowest level areas are mainly plain area in the south, southeast of the Chaohu Lake Basin and the estuary accessing to the Chaohu Lake. From the analysis of the administrative divisions, the flood disaster resilience of Hefei Municipal District Chaohu City, Feidong County, Feixi County, Hanshan County, Shucheng County is mainly at the middle and above level, while most part of He County, Wuwei County, Jiujiang District (Wuhu City) are at the lower and lowest level.
3. Many factors affect regional flood disaster resilience, and the factors also influence each other. The scientific and reasonable construction of index system and the correct identification of the relationship between the indexes is significant for evaluating the regional flood disaster resilience, which needs to be further studied and optimized.

Acknowledgments This research is supported by the National Natural Science Foundation of China (Grant No. 41271516), the Anhui Normal University Graduate Student Research and Innovation Project (Grant No. 2014yks090).

References

- Adger WN, Hughes TP, Folke C et al (2005) Social–ecological resilience to coastal disasters. *Science* 309(5737):1036–1039
- Armaghan A-E, Reza K (2014) Evaluating the relative power of water users in inter-basin water transfer systems. *Water Resour Manag* 28(2):495–509
- Asian Development Bank (2008) *Managing Asian Cities: sustainable and inclusive urban solutions*. Asian Development Bank, Tokyo, pp 89–92
- Cannon T, Twigg J, Rowell J (2003) *Social vulnerability, sustainable livelihoods and disasters: report to DFID Conflict and Humanitarian Assistance Department and Sustainable Livelihoods Support Office*. London: Natural Resources Institute, University of Greenwich, pp 78–84
- Chan S-L, Wey W-M, Chang P-H (2014) Establishing disaster resilience indicators for Tan-sui river basin in Taiwan. *Soc Indic Res* 115:387–418
- Cheng L, Li H (2005) Application of ANP in process models: an example of strategic partnering. *Build Environ* 42(1):278–287
- Cheng XF, Hao DD, Han P et al (2014) Flood loss assessment in Chaohu Lake Basin based on grid data. *Resour Environ Yangtze Basin* 23(10):1480–1483 (in Chinese)
- Cutter SL, Barnes L, Berry M et al (2008) A place-based model for understanding community resilience to natural disasters. *Glob Environ Change* 18:598–606
- Fei X, Wen JH, Du S, Xu H et al (2014) Progress in research on natural disaster resilience. *J Nat Disasters* 23(6):20–31 (in Chinese)
- FEMA (Federal Emergency Management Agency) (2003) *Mitigation BCA Toolkit*. Federal Emergency Washington DC, pp 56–64
- Field CB, Stocker TF, Barros VR et al (2012) *Managing the risks of extreme events and disasters to advance climate change adaptation: special report of the intergovernmental panel on climate change*. Cambridge University Press, Cambridge
- IPCC (Intergovernmental Panel on Climate Change) (2014) *Climate change 2014: impacts, adaptation, and vulnerability*. Cambridge University Press, Cambridge
- Kang B, Lee S-J, Kang D-H, Kim Y-O (2007) A flood risk projection for Yongdam dam against future climate change. *J Hydro-Environ Res* 1(2):118–125
- Liu J, Shi PJ, Ge Y et al (2006) The review of disaster resilience reseach. *Adv Earth Sci* 21(2):212–218 (in Chinese)
- Mayunga JS (2007) *Understanding and applying the concept of community disaster resilience: a capital-based approach*. <http://www.ehs.unu.edu/file/get/3761.Pdf>. Accessed 21 Nov 2015
- Mei P, Li GH, Lu S et al (2014) An analytic network process approach for rapid loss assessment of high casualty fires in China. *Fire Technol* 50(5):1163–1179
- Mileti DS (1999) *Disasters by design: a reassessment of natural hazards in the United States*. Joseph Henry Press, Washington DC, pp 45–49
- National Development and Reformation Committee (2013) *National strategy of climate change adaptation*. <http://www.gov.cn/gzdt/att/att/site1/20131209/001e3741a2cc140f6a8701.pdf>. Accessed 8 Dec 2015. (in Chinese)
- Plough A, Fielding JE, Chandra A et al (2013) Building community disaster resilience: perspectives from a large urban county department of public health. *Am J Public Health* 103(7):1190–1197
- Prashar SK, Shaw R (2012) Urbanization and hydro-meteorological disaster resilience: the case of Delhi. *Int J Disaster Resil Built Environ* 3(1):7–19
- Saaty TL (1996) *The analytic network process: decision making with dependence and feedback*. RWS Publications, Pittsburgh
- Shaw R, Fernandez G (2010) *Urban risk management in South Asia*. SAARC Disaster Management Centre (SDMC), New Delhi, pp 23–34
- Shaw R, IEDM Team (2009) *Climate disaster resilience: focus on coastal urban cities in Asia*. International Environment and Disaster Management Lab, Kyoto University, Kyoto, p 4
- UK Department for International Development (2011) *Humanitarian emergency response review*. UK Department for International Development

- UNISDR (United Nations International Strategy for Disaster Reduction) (2009) Terminology on disaster risk reduction. UNISDR, Geneva, p 24
- World Bank (2008a) World Development Report 2009: reshaping economic geography. World Bank, Washington DC, pp 73–78
- World Bank (2008b) A primer on reducing vulnerabilities to climate change impacts and strengthening disaster risk management in East Asian Cities. The World Bank, Washington DC
- World Economic Forum (2008) Building resilience to natural disasters: a framework for private sector engagement. World Economic Forum, Geneva, pp 10–11
- Xu PP, Chan E (2013) ANP model for sustainable Building Energy Efficiency Retrofit (BEER) using Energy Performance Contracting (EPC) for hotel buildings in China. *Habitat Int* 37:104–112
- Yuan Y, Wang XY, Li X et al (2007) Analysis of spatial and temporal characteristics of drought and flood in the Chaohu Lake Basin. *Disaster Sci* 22(2):97–100 **(in Chinese)**
- Zhang L, Chen XH, Qian HS (2011) Diagnosis of resilience to flood hazard in lower reaches of the Beijiang River. *J Hydraul Eng* 42(9):1129–1134 **(in Chinese)**