Spatio-temporal variation of flood vulnerability at the Poyang Lake Ecological Economic Zone, Jiangxi Province, China

Ping Chen and Xiaoling Chen

ABSTRACT

For a long time areas of Poyang Lake have been threatened by floods. It is therefore important to assess flood vulnerability in this area. A composite flood vulnerability index was developed using an indicator approach to detect spatial distribution and temporal variation of flood vulnerability in the Poyang Lake Ecological Economic Zone (abbreviated to PLEEZ). Thematic maps of flood vulnerability showed a spatially ring-shaped distribution. The flood vulnerability ranking of one unit negatively correlated with the distance between the unit and the lake. Although flood vulnerability in PLEEZ declined significantly, the spatial distribution hardly changed from 1997 to 2006. The degree of flood vulnerability is highly related to exposure; variations in flood vulnerability are influenced by sensitivity and adaptive capacity. Based on correlation analysis, three proxies were identified as determinants of flood vulnerability variation over the past 10 years. This approach could provide policymakers with important flood risk information and entry points for flood management.

Key words | determinants, flood vulnerability, Poyang Lake, variation

INTRODUCTION

Floods are considered one of the most dangerous natural disasters in China. Losses caused by floods account for 3% of the gross domestic product (GDP) of the whole nation (Shi et al. 2009). Poyang Lake, connecting to the Yangtze River, is the largest freshwater lake in China. It is characterized by its dramatic seasonal fluctuations in water level (Chen et al. 2006). Hence, floods have frequently threatened areas surrounding it. Identifying areas with high flood vulnerability can help decision makers to find better ways to deal with floods.

The term vulnerability is used in a number of disciplines and its wide usage suggests the identification of diverse operational formulations in specific contexts (Briguglio et al. 2009; Adger 2006). In its Third Assessment Report (TAR), the Intergovernmental Panel on Climate Change (IPCC) defined vulnerability as a function of three components: exposure, sensitivity, and adaptive capacity (McCarthy et al. 2001). Exposure refers to the degree to which a system experiences environmental changes. Sensitivity is the degree to which a system is subject to influences of climate-related stimuli. Adaptive capacity is the ability of the system to adjust to and accommodate changes, and to recover from impending consequences. Exposure, sensitivity, and adaptive capacity jointly determine the vulnerability of a particular unit.

Research on flood vulnerability is still in its infancy. Jiang et al. (1997) conceptual framework on flood vulnerability is composed of environmental, economic, and social factors. Data on losses and insurance from past disaster situations were utilized to evaluate and predict the flood vulnerability of communities (Shi et al. 2009). Using a socioeconomic perspective, Ma et al. (2007) assessed the flood vulnerability of farmers at the village level. Some scholars assessed flood vulnerability by using remote sensing (RS) and a geographical information system (GIS). RS is the acquisition of electromagnetic radiation information about an object or phenomenon without contact with the object. GIS is designed to capture, store, analyze, manage and present all types of geographically referenced data. RS and GIS were employed to enhance the accuracy and efficiency of the vulnerability assessment. Nevertheless, the proxies they selected to assess flood vulnerability by RS and GIS were deficient in number and limited to exposure to floods (i.e., depth of floodwater,
population distribution, and elevation) (Sanyal & Lu 2005; Forte et al. 2006). Socioeconomic factors were disregarded. Vulnerability is a set of conditions and processes resulting from biophysical and socioeconomic factors that increase the susceptibility of a community to the impact of hazards (Kumpulainen 2006). In this paper we assess flood vulnerability by combining more biophysical proxies offered by the RS technique and socioeconomic proxies, which were specialized and organized by GIS.

Spatio-temporal variation is an inherent property of vulnerability. Biophysical and socioeconomic processes determine the spatio-temporal variation of vulnerability (Cutter & Finch 2008). More localized analyses have provided understanding of situations in areas experiencing significant changes in vulnerability (Sonmez et al. 2005; Cutter & Finch 2008). These researchers paid more attention to how and where vulnerability changes. In this study we focus on what affects flood vulnerability by analyzing the variations of flood vulnerability and its components of exposure, sensitivity and adaptive capacity.

**STUDY AREA AND DATA**

**Study area**

The study area is the Poyang Lake Ecological Economic Zone (PLEEZ). It covers a total land area of 51,200 km², about 30.7% of the territory of Jiangxi Province. It consists of 31 urban areas, counties, and cities belonging to nine prefecture-level cities (Figure 1). According to the statistical data of 2007, the population in PLEEZ reached 14.29 million, accounting for 45% of the total population in Jiangxi Province, and with about 60% GDP of the entire province generated in the PLEEZ. Thus, the PLEEZ is the central economic, cultural, and transport area of Jiangxi Province.

Due to the dominance of the lakeshore, fluvial plains, hillocks and highlands in the landscape of PLEEZ, and the vicinity surrounding the Poyang Lake, which covers about 4,000 km² during times of high water level of 20 m (warning water level 19 m) with a lake capacity of $296 \times 10^9$ m³ (Hu et al. 2007), it is always under high risk of floods during the...
summer rainy season. Five major rivers (Xiu River, Gan River, Fu River, Xin River, and Rao River) of the Poyang Lake watershed all flow into the lake. However, the lake’s outlet is not wide enough to drain floodwater into the Yangtze River. Floodwater from the five main streams and the Yangtze River leads to frequent floods in the lake. From 1950 to 2005, flood events occurred 46 times (1.25 year intervals) in the Poyang Lake region (Wang et al. 2008). According to Huang et al. (2005) and the observed data from Xingzi gauging station, from 1980 to 2009 the annual maximum water level has exceeded the warning water level 19 times.

**Data preparation**

In 1998, a great flood occurred in the south of China. The high number of casualties and economic losses exceeded historic records in the PLEEZ. We therefore selected data from 1997 to 2006 to investigate whether flood vulnerability has changed during these periods. The definition of vulnerability by IPCC was applied to measure flood vulnerability. A total of 20 proxies were selected to represent exposure, sensitivity, and adaptive capacity to floods Table 1. In Table 1, ‘+’ and ‘−’ denote positive and negative correlation between proxies and flood vulnerability, respectively. For example, the higher the assessment of farmers’ income in a certain unit, meaning they are more financially able to recover quickly from flood disasters, the lower the vulnerability to floods is in the unit. Therefore, the annual income of a farming population negatively correlates with flood vulnerability. The data set of biophysical features included was processed by ArcGIS 9.0, designed by ESRI, Inc.

In Table 1, the information on elevation and slope was extracted from the digital elevation model (DEM) with a scale of 1:250,000 (at 100 m resolution). The proxy of elevation was based on the percentage of areas with elevation higher than 23 m out of the total area of one unit. An elevation of 23 m is relatively safe against flood as the historic highest water level was 22.58 m in 1998. Average slope is the mean value of the slope of one unit.

Due to the different units and domains of the data sets, all proxies were normalized into a domain ranging from 0 to 1 based on the followed equation:

\[
P_{ij} = \begin{cases} 
\frac{P_{ij} - \min (P_{ij})}{\max (P_{ij}) - \min (P_{ij})} & \text{if } i = 1, \ldots, n, j = 1, \ldots, m \\
1 - \frac{P_{ij} - \min (P_{ij})}{\max (P_{ij}) - \min (P_{ij})} & \text{if } i = 1, \ldots, n, j = 1, \ldots, m 
\end{cases}
\]

\[
P_{ij} = \begin{cases} 
\frac{P_{ij} - \min (P_{ij})}{\max (P_{ij}) - \min (P_{ij})} & \text{if } i = 1, \ldots, n, j = 1, \ldots, m \\
1 - \frac{P_{ij} - \min (P_{ij})}{\max (P_{ij}) - \min (P_{ij})} & \text{if } i = 1, \ldots, n, j = 1, \ldots, m 
\end{cases}
\]

where \(P_{ij}\) is a normalized value of proxy \(i\) of unit \(j\), and \(P_{ij}\) is the raw data of proxy \(i\) of units \(j\). The proxies denoted by ‘+’ were transformed by Equation (1); and the proxies labelled

<table>
<thead>
<tr>
<th>Component</th>
<th>Indicator</th>
<th>Proxy (P_{ij} = 1-20)</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposure</td>
<td>Precipitation</td>
<td>Annual average rainfall +</td>
<td>Weather stations</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ratio of rainfall in wet season +</td>
<td></td>
</tr>
<tr>
<td>Topography</td>
<td>Elevation more than 23 m (% of total area) −</td>
<td>DEM (1:250,000)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Average slope −</td>
<td>DEM (1:250,000)</td>
<td></td>
</tr>
<tr>
<td>Hydrology</td>
<td>Drainage density +</td>
<td>National Topography Dataset</td>
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<tr>
<td></td>
<td>Surface runoff coefficient +</td>
<td>Paper (Chen 2005)</td>
<td></td>
</tr>
<tr>
<td>Demographic distribution</td>
<td>Population density +</td>
<td>Statistical yearbooks</td>
<td></td>
</tr>
<tr>
<td>Sensitivity</td>
<td>Soil type +</td>
<td>Chinese Soil Thematic Map (1:4,000,000)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Woodland coverage rate −</td>
<td>Chinese natural resources database (1998), Statistical yearbooks (2007)</td>
<td></td>
</tr>
<tr>
<td>Agriculture</td>
<td>Cultivated land ratio (% of total area) +</td>
<td>Statistical yearbooks</td>
<td></td>
</tr>
<tr>
<td>Fishery</td>
<td>Fishery production +</td>
<td>Fifth National Census Data</td>
<td></td>
</tr>
<tr>
<td>Infrastructure</td>
<td>Infrastructure investment −</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Demographic structure</td>
<td>Farming population ratio (% of total population) +</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Marginalized population ratio aged among 0–14 and &gt;60 years old (% of total) +</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adaptive capacity</td>
<td>Illiteracy rate (% of population over 15) +</td>
<td>Statistical yearbooks</td>
<td></td>
</tr>
<tr>
<td>Education</td>
<td>Medical resources per 10^4 population −</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medical resource</td>
<td>Annual income of farmer −</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Income</td>
<td>Annual income of urban worker −</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Finance</td>
<td>Deposit of financial institutions per capita −</td>
<td>GDP per capita −</td>
<td></td>
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</tbody>
</table>
‘−’ by Equation (2) to ensure a positive correlation between flood vulnerability and these proxies.

METHODS

An indicator approach was chosen to construct a composite flood vulnerability index (FVI) because of its extensive applications and feasibility in various scales.

Constructing the flood vulnerability index

Analytic hierarchy process (AHP) was chosen to determine the weights of the proxies. The assessment was comprised four hierarchies: overall goal (assessing flood vulnerability), criteria (three components of vulnerability), sub-criteria (14 indicators), and alternatives (20 proxies) (Table 2). Combined with expert suggestions and achievements of past research on flood risk in the Poyang Lake watershed (Fu et al. 2007; Gao et al. 2007), the priority matrices were derived and numerically expressed by pairwise comparisons. Consistency ratios of the matrices were calculated and passed a check of the judgements. The calculated weights of each proxy are shown in Table 2 where \( P_i \) represents the 20 proxies, which are numbered in the order that they appear in Table 1.

Identifying flood vulnerability ranking

The FVI of 1997 and 2006 was divided into quarters and then scored from 1 to 4. A score of 1 was defined as low vulnerability; 2 as medium vulnerability; 3 as high vulnerability; and 4 as the highest vulnerability.

Identifying determinants of flood vulnerability variation

Pearson’s correlation analysis between the difference of FVI and the difference of the values of the proxies of the 31 units for nine 1-year periods from 1997 to 2006 was conducted to detect whether statistically significant relationships existed between the vulnerability variation and the proxies. If so, the key proxies were identified as determinants of the variation of flood vulnerability. Statistical software SPSS13.0 was used for the correlation analysis.

RESULTS AND DISCUSSION

Temporal variations of flood vulnerability

FVI of each unit in PLEEZ from 1997 to 2006 were calculated and illustrated by a line chart. In order to reveal the FVI characteristics of these units, they were categorized into three groups called A, B and C according to the FVI averages of each unit in the 10 years. In Figure 2 the X-axis represents the years from 1997 to 2006 and the Y-axis represents FVI ranging from 0.325 to 0.748. Every line shows the variation of FVI of one unit. At the bottom of Figure 2, UA is the abbreviation for urban area, C for county and CLC for county-level city. The line chart demonstrates a decreasing trend of flood vulnerability. Statistical analysis revealed that the FVI of 20 units in PLEEZ in 2006 reached their minimums within the decade and so did that of five units in 2005. The FVI in a few units, such as Yugan C,
Poyang C, Xinjian C, Zhangshu CLC, increased in the decade. It is concluded that despite the FVIs of a few counties increasing, from 1997 to 2006 flood vulnerability in most areas of the PLEEZ had been decreasing.

**Spatial distribution of vulnerability and its components**

The FVI and its three components of the units in 1997 and 2006 were selected to analyze the spatial distribution of flood vulnerability in the PLEEZ. They were categorized by the equal-interval method into four rankings: low, medium, high, and highest. The thematic maps of rankings revealed the spatial distribution of flood vulnerability (Figure 3). Spatial distribution and variations of exposure, sensitivity, and adaptive capability jointly determined flood vulnerability. Figure 3 displays a low-outer and high-inner ringed pattern of exposure and sensitivity. The rankings of the exposure of 31 units did not change between 1997 and 2006. Flood sensitivity was generally ranked high in 1997. In 2006, the number of units with low sensitivity increased to eight and high sensitivity decreased from 14 to 10. Adaptive capacity was clearly demonstrated in the low-northeast and high-southwest areas in the PLEEZ. This is partly associated with notable differences and polarization in the economy at the Poyang Lake region. Economic development in the eastern region of Poyang Lake fell behind compared with the western region (Gan et al. 2008). Although adaptive capacity increased in 2006, it still maintained the spatial distribution pattern.

As shown in the FVI maps in Figure 3, the ranking of flood vulnerability in the PLEEZ ascended from the periphery to the interior of the PLEEZ with a ring-shaped distribution. The most vulnerable unit was Nanchang County in 1997 and 2006. It is one of the most densely populated counties in the PLEEZ (520 people per km² in 2006). Its low average elevation also exposes it to greater flood hazards. A high cultivated land ratio of over 40% and a developed fishing industry make this unit highly sensitive to floods. The rankings of exposure and sensitivity of Nanchang County therefore were highest in 1997 and 2006 (Figure 3). Its economic development has been far behind that of other units. In 2006, its GDP per capita was about 800 US dollars, far below the average of the counties in the PLEEZ. Therefore, its adaptive capacity could not effectively decrease its flood vulnerability. Wuning County was one of the counties with low vulnerability in the PLEEZ in 1997 and 2006. Despite a high farmer ratio in the area (89%), it had the lowest population (104 people per km² in 2006), a relatively high elevation compared with other units, and the largest average slope (11°) referring to the DEM in Figure 1, which effectively reduced its exposure to flood and flood vulnerability.

According to the spatial distribution of the flood vulnerability and its components, the extent of flood vulnerability is highly related to exposure, and variations in flood vulnerability are influenced by sensitivity and adaptive capacity. Consequently, special flood disaster management schemes should be laid out for each unit according to their degree of flood exposure, sensitivity and adaptive capability. For example, at the centre of the PLEEZ attention should be given to mitigating sensitivity
and exposure to floods, such as adjusting crop planting structures to ensure crop maturity before flood period.

Determinants of vulnerability variation

Three key proxies, relating to sensitivity and adaptive capacity respectively, strongly correlated with the FVI as shown in Table 3 in nine periods from 1997 to 2006. Other proxies have significant correlation coefficients with FVI in less than three out of the nine periods. Consequently, the three proxies are regarded as determinants of the FVI variation. The presentation of 0.773 (**)/0.000 means that 0.773 is the correlation coefficient, 0.000 represents the significance using the two-tailed test. **: significant correlation at 0.01 level; *: significant correlation at 0.05 level.

<table>
<thead>
<tr>
<th>Period</th>
<th>Farming population ratio</th>
<th>Cultivated land ratio</th>
<th>Fishery production</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997–1998</td>
<td>0.773 (**)/0.000</td>
<td>0.358(*)/0.031</td>
<td></td>
</tr>
<tr>
<td>1998–1999</td>
<td>0.781 (**)/0.000</td>
<td>0.613(**)/0.000</td>
<td></td>
</tr>
<tr>
<td>1999–2000</td>
<td>0.476(**)/0.007</td>
<td>0.756(**)/0.000</td>
<td>0.516(**)/0.003</td>
</tr>
<tr>
<td>2000–2001</td>
<td>0.581(**)/0.001</td>
<td>0.461(**)/0.009</td>
<td>0.681(**)/0.000</td>
</tr>
<tr>
<td>2001–2002</td>
<td>0.411(*)/0.022</td>
<td>0.432(**)/0.015</td>
<td>0.632(**)/0.000</td>
</tr>
<tr>
<td>2002–2003</td>
<td>0.531(**)/0.002</td>
<td>0.465(**)/0.009</td>
<td>0.632(**)/0.000</td>
</tr>
<tr>
<td>2003–2004</td>
<td>0.448(*)/0.011</td>
<td>0.503(**)/0.004</td>
<td>0.637(**)/0.000</td>
</tr>
<tr>
<td>2004–2005</td>
<td>0.593(**)/0.000</td>
<td>0.459(*)/0.018</td>
<td>0.637(**)/0.000</td>
</tr>
<tr>
<td>2005–2006</td>
<td>0.368(*)/0.042</td>
<td></td>
<td>0.637(**)/0.000</td>
</tr>
</tbody>
</table>

Farming population ratio

Perfect hydrothermal conditions in the PLEEZ allowed the growth of a highly developed agriculture. The population density in the PLEEZ is much higher compared with others in Jiangxi Province. Here the majority of the population were farmers, accounting for 75% of the total population (17.29 million) in 1997 and 70% of the total population (19.6 million) in 2006. In Figure 4, the left graph demonstrates the increases in the total population and the farming population of the PLEEZ from 1997 to
2006. The lower growth rate of the farming population compared with the total population led to a decrease in the farming population ratio during the decade. The right graph shows the line charts of the average farming population ratio and the average FVI, which decreased at almost equal rate. Farmers are the most vulnerable group in the PLEEZ because agriculture in the floodplain of Poyang Lake is particularly sensitive to floods. The decrease in the proportion of farmers in a unit resulted in a reduction in the sensitivity to flood of the unit. Meanwhile, the slow growth of the farming population as the area of cultivated land decreased effectively relieved the planting pressures on cultivated land, which helped to maintain the quality of land and the income of farmers.

**Cultivated land ratio**

The cultivated land ratio reflects the proportion of farmland area to the total area of a unit. In the Poyang Lake region, the main types of land cover and land use include cultivated land, woodland, water, urban or built-up land and barren land. Along with the economic development in the PLEEZ, the transformations within these types of land cover and land use were bound to happen. Among these types, cultivated land is the most sensitive to floods because the crops are in a critical period of maturation during the flood season. The loss of cultivated land is relatively higher than that of others. From 1997 to 2006, the area of the cultivated land had reduced by 7.9%, about 82061 ha, which was almost changed into the built-up land with the urbanization process in PLEEZ (Ni et al. 2010). Hence, the sensitivity to floods of a unit would be lower due to the reduction in the area of cultivated land.

**Fishery production**

Fisheries are a significant livelihood for populations living around Poyang Lake. Fisheries are a special field because on the one hand they increase the income of the people; on the other hand, they heighten their risk to potential economic losses from floods. Fishing activities in the PLEEZ consist of wild fisheries and farmed fisheries. In recent years, wild fish resources have been severely degraded in Poyang Lake (Yu & Sun 2006). Farmed fisheries have a much higher yield than wild fisheries. The indicator of fishery production mainly reflected the output from farmed fisheries. Floodwater often causes fish to escape from the nurseries, which results in high economic losses even if wild fisheries recuperate a small portion of the losses. For example, due to the great flood in 1998, the production of wild fisheries in the PLEEZ increased to 70,000 tons, doubling the yield compared with the 1990s. That growth primarily came from fish escaping from farmed fisheries. This makes fishery production an important element in assessing flood sensitivity in the PLEEZ.

Due to the absence of literature on the flood vulnerability of the PLEEZ, we compared the results of this study with previous investigations on flood vulnerability in the Poyang Lake region. Our results on the spatial distribution of flood vulnerability agreed with that of Ma et al. (2007) who focused on the flood vulnerability of farmers at the village level and concluded that more than 55% of villages in highly vulnerable areas were situated in the east. Jiang et al. (2008) discovered that land cover patterns and land cover changes in the Poyang Lake region over the last 20 years accompanied a general decline in flood...
vulnerability, which concurs with our conclusion. However, Jiang’s study paid more attention to the delineation of land cover pattern and changes and the other factors affecting flood vulnerability were neglected.

**CONCLUSIONS**

In this study, the feasibility of using a composite index to reveal the spatio-temporal variation of flood vulnerability in the PLEEZ was investigated. It is concluded that this approach is useful for assessing flood vulnerability. Flood vulnerability in the PLEEZ is spatially distributed in a ring-shaped pattern and is negatively correlated with the distance between one unit and the lake. The pattern of spatial distribution was almost unchanged from 1997 and 2006, although the flood vulnerability in the PLEEZ decreased. Three key proxies were identified as the determinants of flood vulnerability in this specific decade at the county level.

This study presents a cost-effective and efficient way to generate maps showing the spatial distribution of flood vulnerability by using RS and GIS techniques. It is convenient to compare flood vulnerability across different periods and space. Furthermore, this approach is widely applicable at different scales because the main data sources including statistical data, remotely sensed images, and meteorological data are readily available and the linear aggregation of proxies can be calculated simply. The unavailability of some socioeconomic data, such as insurance, building quality, level of flood protection and management, restricted our ability to produce more highly accurate results about flood vulnerability. The difficulty of spatializing socioeconomic data in grid type prevents us from revealing the spatial information within a unit and the ranking of vulnerability transited abruptly at boundaries between units. Despite these limits, the study has resulted in a reasonably accurate spatial distribution of flood vulnerability. It provides policymakers with the basis for identifying highly vulnerable units and a way to find key indicators dominating the variation of flood sensitivity and adaptive capability, in order to reduce flood vulnerability.

**ACKNOWLEDGEMENTS**

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