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Quantifying land-use change impacts on the dynamic evolution of flood vulnerability

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ABSTRACT

Recently, dramatic flood disasters have occurred incrementally in several regions of the world. Land-use change as one of the main affecting factors becomes a key component in flood risk management. This study strives to deal with quantifying how changes in land use to affect the dynamic evolution of flood vulnerability. The floodplains of Wuhan, which are located in the Yangtze River Basin, have been selected as an example. In this paper, we use GIS to gather different historical geometric data as sources of land-use information. By proposing the Simpsons-dominance index and location index to analyze the characteristics of land-use changes, and building a quantitative model to measure flood vulnerability, a series of flood vulnerability maps demonstrate differential flood vulnerability of floodplains of Wuhan in three inundation scenarios and four historical periods. Finally, the non-parametric correlation is used to reveal the interactive effect of land use and flood vulnerability. Based on this study, comprehensive flood disaster management strategies for land-use planning are proposed for government decision-makers to reduce the flood vulnerability of Wuhan in future.

1. Introduction

On a global scale, flood disasters have increased dramatically in frequency and intensity over the past decades. Climate changes which generate more extreme precipitation patterns are the driving force. But more importantly, the rapidly urbanizing developments of floodplain catchments cause population and capital to become increasingly exposed and vulnerable to flood disasters (Munich Re, 2006). Historically, floodplain management has been transferred from 'keeping the people away from the river' to 'learning to live with floods' (Green et al., 2000). From an engineering perspective, many protection projects (e.g. dams, dikes, drains and reservoirs buildings) are built to fulfill the society's requirement for safe and floodplain development. The hypothesis of this is that these protection projects can completely resist floods, but this is just another way to push the damage somewhere else or postpone it for another time.

Urbanization and urban expansion which induces the development of floodplains is inevitable. This raises the question that how we can counterpoise the development issues and the flood risks to maximize the net-benefits of floodplains, at the same time, to ensure the sustainable development (APFM, 2007). So numerous studies are focus on dealing with the relationship between land-use changes and flood risk (Schilling et al., 2010): (1) Some scientists have investigated hydrological models to evaluate the impact of land-use changes on the rainfall-runoff regime (Wheather and Evans, 2009; Chang and Franczyk, 2008), flood peak (Hollis, 1975; Zhang and Zhu, 2011), magnitude (Mahe et al., 2005) and frequent (Petrow and Merz, 2009); (2) Some researches have emphasized that the vegetative cover changes cause greater flood risk, particularly the effects of the deforestation on peak-flows (Brown et al., 2005; Tao et al., 2011), flood runoff discharge (Turner et al., 2002; Costa et al., 2003), flood magnitude and frequency (Blöschl et al., 2007; Lin et al., 2009). Most of these studies above have concentrated on the adoption of technological and physical measures to analyze the interaction between land-use changes and flood risk. Unfortunately, not more attention has been given to analyze the impact of land-use changes on flood risk from a social perspective. Vulnerability as the key element of flood risk, reflects the intrinsic characteristic of the hazards' receptors. It is the root cause of the uneven distribution of flood risk in different regions. Much of recent literature on disaster science uses the concept of vulnerability to illustrate which areas are vulnerable to what and why. These researches suggest that vulnerability "zooms" the effect of flood hazards (Annan, 1999). Over the past two decades, the concept of vulnerability has changed constantly, which has formed several research branches to define, evaluate, and measure flood vulnerability: (1) some researchers have argued the component factors of flood vulnerability, including exposure (e.g. Turner et al., 2003; Thieken et al., 2005), sensitivity (e.g. Kienberger, 2012; Miceli et al., 2008), and resilience (e.g. Birkmann

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and Wisner, 2006; Luna et al., 2011); (2) Some researchers have dealt with the different categories of flood vulnerability, involving physical vulnerability (e.g. Wood et al., 2010; Fuchs, 2009), and social vulnerability (e.g. Pelling, 2005; Wisner and Uitto, 2009); (3) Some researchers have modeled the conceptual frameworks of flood vulnerability, such as flood risk-disaster model (Burton et al., 1993), flood pressure and release model (Blaikie et al., 2004), bidirectional structural model of flood vulnerability (Bohle, 2001), flood disaster-location model (Cutter et al., 2003), the model of the extended flood vulnerability, and BBC conceptual model (Bogardi and Birkmann, 2004); (4) Other researchers have laid emphasis on modeling flood vulnerability by different approaches and methods, including designing a series of indicators to evaluate various properties of flood vulnerability, e.g. human vulnerability (Cardona, 2004), socio-economic and ecological vulnerability (Thywissen, 2006); assessing different regional levels of flood vulnerability, e.g. national level (Pelling, 2003; Fernando, 2007), watershed level (Hurd et al., 1999), and county and local level (Cutter and Finch, 2007); assessing the influence of some environmental conditions on flood vulnerability, such as climate change (e.g.Leichenko and O'Brien, 2008); and developing the integrated models to measure flood vulnerability (e.g. Mimura et al., 2007; Adger et al., 2005).

A large number of experts and scholars have made a great contribution to land-use changes research and flood vulnerability research, respectively. But few study has addressed the interaction between land-use changes and flood vulnerability. Particularly, past flood disasters have triggered many policy makers and urban planners to face difficult decisions of on-going urban development and flood vulnerability reduction. Especially in China, as the rapid urbanization developing country, the unplanned and unmanageable large-scale construction of floodplains might enhance the potential flood vulnerability. So the main goal of this research is to quantify land-use change impacts on the dynamic evolution of flood vulnerability for a selected example of Wuhan in the Yangtze River Basin. The objectives of this study are: (1) to identify distribution pattern of land use in a 50-year study period by GIS, and to analyze the priority and aggregation of land-use categories by the Simpsons-dominance index and the location index; (2) to evaluate and map flood vulnerability of floodplains, and to demonstrate the dynamic evolution of flood vulnerability by statistical methods; (3) to measure the influence of land use on flood vulnerability by the non-parametric correlation. It is expected that the research findings will contribute to help decision makers to make floodplains safer when flood vulnerability information is recognized as being relevant to local development, and also provide valuable information for urban planners to make land-use decision based on the comprehensive and sustainable flood risk management.

2. Study area

The majority of our study has focused on Wuhan (latitude 29°58′N–31°22′N and longitude 113°41′E–115°05′E), which lies at the east of Jianghan Plain, and the intersection of the middle reaches of Yangtze and Han rivers. The Yangtze River is the longest and busiest river in Asia and the third longest river in the world after the Nile and the Amazon. It is responsible for 70%–75% of China's floods. At least several hundred people are killed in Yangtze River floods every year. Fig. 1 shows the location and flood frequency of Wuhan from 1949 to 2010. The average flood frequency of Wuhan is more than 0.18 times a year, which belongs to the highest flood risk level compared with other cities in the Yangtze River Basin. Wuhan is located in the downstream of Yangtze River, and the low-lying of Wuhan makes its floodplains always be threatened by river floods in the rainy season. Particularly from the twentieth century, the catastrophic river floods have occurred in the floodplains of Wuhan more frequently (e.g. 1931, 1954, 1998 and 1999). And the rapidly urbanization increases investment and population in floodplains of Wuhan, which leads to the outbreak of the catastrophic river flood disasters to affect more people and induce more damage to property and infrastructure.

3. Data and method

3.1. Data of floodplains of Wuhan in four historical periods

In this paper, we choose the land-use maps of Wuhan in four historical periods as the base maps. These base maps are obtained from "Wuhan Land Resources and Planning Bureau" and "Landsat TM remote sensing images of the Earth System Science Data Sharing Agency", and are digitized by using the GIS (Geographic Information System). And the scale of these digital maps (Fig. 2) are 1:10,000. They are distinguished into 8 land-use categories (e.g. commercial, industrial, public service, public building, residential, transportation, grassland and wetland, rivers and lakes) according to "urban cadastral investigation rules (TD1001-1993)" of the Ministry of Land and Resources. The floodplains are divided according to the historical data of the flood inundation extent, which are acquired from "Yangtze River Scientific Research", "Wuhan Statistical Yearbook", "the aerial photos and electronic maps of China's National Geographic Information Center", and so on. And the maximum submerged areas of Wuhan in history (the catastrophic river flood occurred in 1931), as 1.4 km distance from the Yangtze River Basin, are defined as the selected study areas of floodplains of Wuhan (the gray shaded areas in Fig. 2). These digital maps are an important source of information for quantifying land-use changes of the floodplains of Wuhan in the past 50 years.

3.2. Measuring the characteristic of land-use changes

In order to measure the characteristic of land-use changes of floodplains of Wuhan in four historical periods, we use the Simpsons-dominance index and the location index to represent the extent of dominance and aggregation of the land-use categories.

The Simpsons-dominance index is an information statistic index, which is used in ecology, as a mathematical measure to calculate the species diversity in a given community. In this paper, the Simpsons-dominance index is used to measure the relative dominant of each land-use category in the floodplains of Wuhan in four historical periods. This index can reflect which land-use categories dominate the entire floodplains, and what the extent they are. Some of the land-use categories which have the larger value of Simpsons-dominance index, are predominant in the entire floodplains. Conversely, when the value of Simpsons-dominance index is zero, it indicates that the proportion of each land-use category is equal in the floodplains. The Simpsons-dominance index can be written in a simple form as follows:

$$D_i = H_{\max} - H_i \tag{1}$$

Where D_i is the Simpsons-dominance index of the i_{th} land-use category in the floodplains; H_i is the entropy of the i_{th} land-use category in the floodplains, the function as:

$$H_i = -\sum_{j=1}^{m} P_{ij} \ln P_{ij} \tag{2}$$

Where P_{ij} is the proportion of the i_{th} land-use category in the j_{th} region of the floodplains; m is the number of the regions in the floodplains.

And H_{max} is the maximum of H_i; when $P_{i1} = P_{i2} = \cdots = 1/n$, H_i reaches the maximum value, H_{max} can explicitly be written as:

$$H_{\max} = m \ln n \tag{3}$$

Where n is the number of the land-use categories.

The location index refers to the degree of spatial aggregation of land-use categories, which uses the ratio of the proportion of a particular land-use category's land area in a given region and its proportion in the entire regions. So in this paper, we use the location index to analyze the different spatial pattern of land use in a certain