Integrated flood hazard assessment based on spatial ordered weighted averaging method considering spatial heterogeneity of risk preference

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HIGHLIGHTS
• An integration framework for flood hazard assessment is developed.
• The indicators regarding different characteristics of the watershed are selected.
• Fuzzy AHP method is applied to evaluate the relative weight of criteria.
• Spatial OWA model considering spatial heterogeneity of risk preference is developed.
• Flood hazard map is created and sensitivity of criteria weights is analyzed.

GRAPHICAL ABSTRACT

ABSTRACT
Flood is the most common natural hazard in the world and has caused serious loss of life and property. Assessment of flood prone areas is of great importance for watershed management and reduction of potential loss of life and property. In this study, a framework of multi-criteria analysis (MCA) incorporating geographic information system (GIS), fuzzy analytic hierarchy process (AHP) and spatial ordered weighted averaging (OWA) method was developed for flood hazard assessment. The factors associated with geographical, hydrological and flood-resistant characteristics of the basin were selected as evaluation criteria. The relative importance of the criteria was estimated through fuzzy AHP method. The OWA method was utilized to analyze the effects of different risk attitudes of the decision maker on the assessment result. The spatial ordered weighted averaging method with spatially variable risk preference was implemented in the GIS environment to integrate the criteria. The advantage of the proposed method is that it has considered spatial heterogeneity in assigning risk preference in the decision-making process. The presented methodology has been applied to the area including Hanyang, Caidian and Hannan of Wuhan, China, where flood events occur frequently. The outcome of flood hazard distribution presents a tendency of high risk towards populated and developed areas, especially the northeast part of Hanyang city, which has suffered frequent floods in history. The result indicates where the enhancement projects should be carried out first under the condition of limited resources. Finally, sensitivity of the criteria weights was analyzed to measure the stability of results with respect to the variation of the criteria weights. The flood hazard assessment method presented in this paper is adaptable for hazard assessment of a similar basin, which is of great significance to establish counterplan to mitigate life and property losses.

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1. Introduction

A large number of flood events around the world lead to thousands of deaths and tremendous losses of social economy. Recently, a study of 616 cities around the world indicated that floods endanger more cities than any other natural hazard, followed by earthquakes and storms (Lukas et al., 2014). Moreover, the prediction of future climate change and urban area expansion tendency indicates that flood risk will be aggravated in many regions (Muis et al., 2015). China is a country which has suffered a lot from flooding. According to statistical review, China ranks first in terms of the economic loss and the affected population caused by flooding in the world (Debarati et al., 2015). Therefore, the development of flood management strategies is urgently necessary.

Generally, flood management mitigation strategies and planning are based on the estimation of the flood hazard in terms of its location, magnitude and distribution. Flood hazard and risk analysis is usually performed using hydrologic and hydraulic model which can simulate flood inundation extent, water depth and velocity through one-dimensional (1D) or two-dimensional (2D) hydraulic model (Mazzoleni et al., 2014), such as 1D Saint Venant model for flood routing of the rivers and TELEMAC 2D for modelling of region flood situation (Ghari et al., 2016). However, this kind of method is typically applied to small scale, due to requirements for data of high quality and lack of macroscopic consideration for large-scale watershed. With more frequent occurrence of heavy rainfall and flood events, the development of an effective flood hazard and risk assessment approach for data scarce watershed is crucial. MCA method integrating the ideas of ranking and weighting with the knowledge of experts is an index-based method which provides another effective way of estimating the flood hazard. It is widely used because of its simplicity in implementing and low requirement in data (Chen et al., 2010; Fernández and Lutz, 2010; Kenyon, 2007; Levy, 2005; Martin et al., 2007; Papaioannou et al., 2015). Urban flood hazard zones have been delineated in Tucumán Province, Argentina, where primary data are scarce, using multicriteria decision analysis (Fernández and Lutz, 2010). In H. Chen et al. (2015), the use of multi-criteria decision analysis has also been presented for flood hazard assessment in the Kujukuri Plain of Chiba Prefecture (Japan). In a recent work (Kazakis et al., 2015), the “FIGUSED” method regarding seven parameters have been included in a multi-criteria analysis, and different parameters were superimposed for flood hazard mapping.

Spatial MCA involves multiple spatial referenced attribute layers, and GIS is an appropriate tool for processing and integrating spatial data with attributes from different sources (Malczewski, 2006). Moreover, the visualization capacity of GIS can make the interpretation of the assessment results intuitionistic. GIS-based spatial MCA has been widely applied in many fields, such as land use and environment planning (Akinci et al., 2013; Chen et al., 2010), natural hazards assessment regarding forest fire (Chhetri and Kayastha, 2015), landslide (Ayalew et al., 2005; Batheiros et al., 2008; Kayastha et al., 2013) and flood hazard (Fernández and Lutz, 2010; Ouma and Tateishi, 2014; Roy and Blaschke, 2013). AHP method proposed by Saaty (1980) is one of the MCA methods that constructs the relevant criteria into a hierarchical framework, which makes complex decision problem easy to analyze and handle with. It estimates the criteria weights using pair-wise comparison with numerical importance scales (Saaty, 2008). However, the decision maker usually can’t provide deterministic preferences but perception-based judgment intervals instead (Leung and Cao, 2000). To deal with uncertainty and vagueness in the decision process, the paper applied a fuzzy extended AHP approach which uses triangular fuzzy numbers to represent decision makers’ comparison judgments and fuzzy analysis (Kwiesielewicz, 1998).

The ordered weighted averaging (OWA) is also a MCA method which makes an integration with ordered evaluation criteria (Yager, 1988). In contrast with AHP-based MCA method, it is characterized as a flexible operator for aggregation through providing control of the degree of optimism (Filev and Yager, 1998; Makropoulos and Butler, 2006). Mendes and Wilson (2001) have developed GIS-OWA approach to urban planning and management in the presence of varying degrees of trade-off and risk attitude. In Mianabadi et al. (2014) OWA method was applied in sea conflict to analyze the effects of different risk attitudes of the negotiators. The OWA method has also been effectively applied in analysing flood vulnerable areas and selecting flood control measures (Despic and Simonovic, 2000; Yalcin and Akyurek, 2004). Although OWA method has been extensively used, the spatial OWA considering spatial heterogeneity problem has seldom been applied. In many previous studies, the attitude towards risk (or risk preference) in OWA approach is globally identical (Amin and Emrouznejad, 2011; Malczewski et al., 2003). Nevertheless, strategies using unified risk preference for the entire study area may cause potential overestimation or underestimation of evaluation result. In our study, taking spatial heterogeneity into consideration, the assignment of risk preference was made differently in space.

In the current study, we developed an integrated flood hazard assessment framework, combining fuzzy AHP and spatial OWA method in the integration process. It was applied in the study area comprising Hanyang, Caidian and Hanhan, where flood events occur frequently. The indicators associated with topographical, hydrological and flood-resistant characteristics were analyzed and selected as assessment criteria. The fuzzy AHP and OWA were introduced to calculate criteria weight and order weight respectively. And the integrated flood hazard assessment model based on spatial OWA method was developed. The integration index derived from economic and demographic data which were the main indicators of the region importance was used as support for the assignment of spatially variable risk preference. Finally, the flood situation under different unified risk preference scenarios was analyzed, and the spatial OWA based flood hazard assessment method was applied to generate the flood hazard map. We also applied sensitivity analysis of the criteria weights. The advantage of the proposed study is that the assignment of the risk preference is spatially variable according to region importance. In contrast with flood assessment cases using unified risk preference for entire study area, the populated and developed areas got high risk aversion and received more attention in our study. It is helpful to identify flood hazard zones and focus on the potential loss areas where mitigation measures should be taken under limited resources.

2. Materials and methods

2.1. Study area

The study area is located in the lower Han River region, as presented in Fig. 1a, which is a part of Wuhan, Hubei Province, China, spanning 113°41′–114°17′E and 30°11″–30°41′6″N. The watershed area is about 1268 km², and its elevation ranges from 16 to 244 m. The study area is wedged between the Yangtze River and the Han River, which are respectively the biggest river in China and the biggest tributary of the Yangtze River.

The climate characteristic of the study area is subtropical humid monsoon with dry winter and humid summer, which makes precipitation relatively concentrated in summer. As shown in Fig. 1b, the large monthly precipitation is mainly concentrated between April and August, and maximum monthly precipitation exceeds 250 mm in four of the nine years. Its mean annual precipitation is about 1170 mm, about 63% of which occurs in summer. Moreover, precipitation records have shown that the intensity of heavy rain can exceed 50 mm/24 h, with certain very heavy rain even exceeding 100 mm/24 h (Ding and Zhang, 2009).

During the past decades, the study area has been attacked by floods several times. The floods caused by intense rainfall, which occurred in May 2007, May 2008, July 2013, July 2015 and July 2016 were the most destructive disaster events on historical record. In each flood event
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