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Research article

Multiple flood vulnerability assessment approach based on fuzzy comprehensive evaluation method and coordinated development degree model

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A B S T R A C T

Flood is a serious challenge that increasingly affects the residents as well as policymakers. Flood vulnerability assessment is becoming gradually relevant in the world. The purpose of this study is to develop an approach to reveal the relationship between exposure, sensitivity and adaptive capacity for better flood vulnerability assessment, based on the fuzzy comprehensive evaluation method (FCEM) and coordinated development degree model (CDDM). The approach is organized into three parts: establishment of index system, assessment of exposure, sensitivity and adaptive capacity, and multiple flood vulnerability assessment. Hydrodynamic model and statistical data are employed for the establishment of index system; FCEM is used to evaluate exposure, sensitivity and adaptive capacity; and CDDM is applied to express the relationship of the three components of vulnerability. Six multiple flood vulnerability types and four levels are proposed to assess flood vulnerability from multiple perspectives. Then the approach is applied to assess the spatiality of flood vulnerability in Hainan's eastern area, China. Based on the results of multiple flood vulnerability, a decision-making process for rational allocation of limited resources is proposed and applied to the study area. The study shows that multiple flood vulnerability assessment can evaluate vulnerability more completely, and help decision makers learn more information about making decisions in a more comprehensive way. In summary, this study provides a new way for flood vulnerability assessment and disaster prevention decision.

1. Introduction

In recent decades, extreme weather events and meteorological disasters have occurred frequently in the context of global warming (Asadi Zarch et al., 2015; Balaguru et al., 2016). Among them, the flood disaster is occurring more frequently and seriously in the world. According to statistics, the current global natural disasters' losses caused by flood account for 20% (Munich Reinsurance, 2010). Flood disaster has become an important factor restricting the sustainable development of society and economy. Based on the above situation, flood vulnerability assessment becomes increasingly important and urgent, which suggests decision makers to take flood prevention measures in advance, minimizing the economic losses and casualties.

Vulnerability has become a central focus of the global environmental change and sustainability science research communities in recent years. Initially vulnerability was defined by the Third Assessment Report of IPCC as the degree to which a system is susceptible to adverse effects of climate variability or extremes (McCarthy et al., 2001). Then Turner et al. (2003) viewed vulnerability as "the degree to which a system, subsystem, or system component is likely to experience harm due to exposure to a hazard, either a perturbation or stress/stressor". Further, Adger (2006) considered that "vulnerability is the state of susceptibility to harm from exposure to stresses associated with environmental and social change and from the absence of capacity to adapt", which includes exposure, sensitivity and adaptive capacity. It can be seen that researchers have a more comprehensive understanding of vulnerability. Vulnerability assessment is a multi-attribute decision making (MADM) problem, which assumes that there exists a set of alternatives with multiple attributes which a decision maker should

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evaluate and analyze (Juwana et al., 2012; Ding et al., 2016). A growing number of vulnerability evaluation methods and indicators were constantly updated and ameliorated. Cutter et al. (2003) used principle component analysis to aggregate county-level socio-economic data to assess the social vulnerability of different municipalities in US. Ouma and Tateishi (2014) used Analytical Hierarchy Process (AHP) to assign decision parameters' weights for creating a flood vulnerability distribution map. Gradually, Geographic Information System (GIS) techniques were applied to evaluate the spatial heterogeneity of vulnerability (Metzger et al., 2006).

However, in these studies few researchers consider the relationship between exposure, sensitivity, and adaptive capacity for assessing vulnerability. They only focus on the total scores. Supposing that total vulnerability scores of different areas is in the same, the actual vulnerable degree may be still different. In addition, precise data pertaining to measurement indicators is very hard to extract from human judgments. Decision makers prefer natural language expressions over exact numbers when assessing criteria and alternatives. The AHP cannot take into account uncertainly when assessing and tackling a problem effectively. FCEM can tackle fuzziness or the problem of vague decision-making more efficiently by using fuzzy scales with lower, median and upper values (Yang and Mak, 2017). It has been applied to various fields, including water quality (Icaga, 2007), education systems (Chen et al., 2015) and landslide susceptibility (Zhao et al., 2017). Based on above discussions, this study introduces a multiple flood vulnerability assessment approach based on FCEM and CDDM. We try to apply FCEM to assess exposure, sensitivity and adaptive capacity, considering that the flood vulnerability assessment is a fuzzy concept with multiple indicators. For the relationship between multiple systems, CDDM has been investigated (Long et al., 2016; Ngai, 2003). In this paper, exposure, sensitivity and adaptive capacity are regarded as three systems for flood vulnerability and the CDDM is used to assess the relationship of them.

Based on the concept of multi-attribute decision making, FCEM and CDDM, our work is developed as follows: Firstly, a multiple flood vulnerability assessment approach is proposed, which includes establishment of index system, assessment of exposure, sensitivity and adaptive capacity, and multiple flood vulnerability assessment. Secondly, the approach is applied to the study area to reveal the internal relation of exposure, sensitivity, and adaptive capacity. Thirdly, based on the results of multiple flood vulnerability results in the study area, a decision-making process for rational allocation of limited resources is proposed. In the end, the limitations and future studies of our work are discussed.

2. Multiple flood vulnerability assessment approach

Our study proposes a multiple flood vulnerability assessment approach, which is different from the previous total score ranking. The approach is divided into three phases. Firstly, an evaluation index system for flood vulnerability is established and quantified, using a hydrodynamic model and statistical data. Secondly, exposure, sensitivity and adaptive capacity of objects are evaluated by FCEM. Thirdly, exposure, sensitivity and adaptive capacity are considered to be three systems and CDDM is used to quantify the relationship of the three systems of flood vulnerability. Then, six multiple flood vulnerability types and four levels are proposed to assess flood vulnerability from multiple perspectives. The whole framework is introduced as Fig. 1.

2.1. Establishment of index system

Based on a literature review for flood vulnerability indictors (Balica et al., 2012; Fekete, 2009; Karagiorgos et al., 2016; Koks et al., 2015) and the concept of multi-attribute decision making, which is an important part of modern decision science (Steuer and Na, 2003), an index system for flood vulnerability is established. The index system includes indicators in exposure, sensitivity and adaptive capacity. The exposure indices are mainly calculated by hydrodynamic simulation and they represent natural factors' impact on flood vulnerability. The sensitivity and adaptive capability indices reveal the impact of social and economic factors on flood vulnerability. The definition of these three aspects and the selection process of the indicators are as follows.

Exposure is seen as the degree to which an area is in contact with a perturbation (Adger, 2006). Chang and Huang (2015) define the runoff as the exposure of an area to an extreme climate event. Milanesi et al. (2015) points out that the maximum flood velocity and maximum water level are the main flood features to influence villages. Based on the previous researches, the exposure indices here are focused on flooding characteristics, including mean maximum flood velocity, mean maximum water depth and flooded area. The relevant data can be gained from a hydrodynamic model.

Sensitivity is the degree to which a system is likely to be affected by a perturbation like an extreme climate event (Gallopín, 2006). Here, evaluated object for rural areas, population sensitivity,

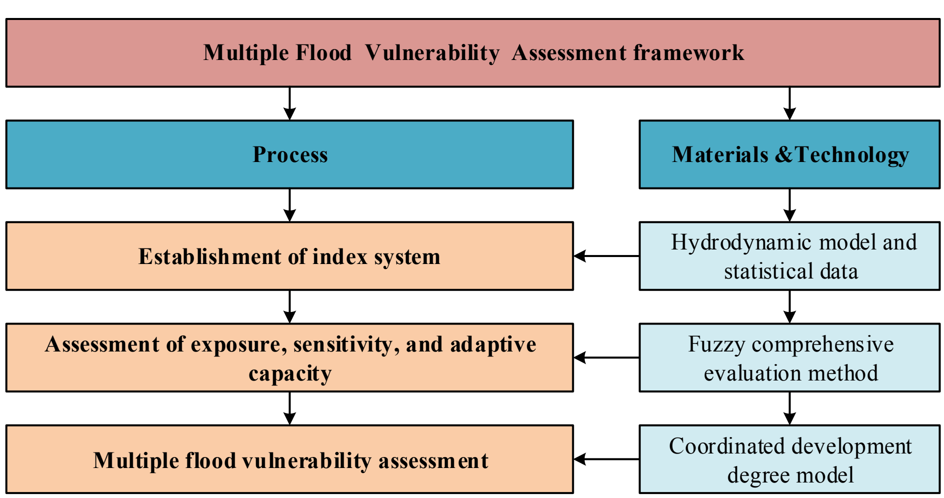

Fig. 1. Stepwise framework for multiple flood vulnerability assessment approach.