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Fuzzy risk analysis of flood disasters based on diffused-interior-outer-set model

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ABSTRACT

Floods are indeed one of the most serious natural hazards for human societies, especially in China. In this paper, we firstly introduce the interior-outer-set model (IOSM) based on information diffusion theory in detail. Then taking consideration its deficiencies, we represent the diffused-interior-outer-set model (DIOSM) to obtain the possibility–probability distribution (PPD). Based on the PPD, we analyze and calculate the risk results. To illustrate the procedure of the proposed method, we apply DIOSM to describe the flood disaster risk quantitatively in China by using statistical data respectively, such as the time of floods, the number of the deaths as well as the economic losses each year from 1990 to 2009. The outcomes of this research offer new insights and moreover new possibility to carry out an efficient way for various future flood disaster prevention and mitigation.

1. Introduction

Flooding is not just a regional problem but a key facet of global water management and the risk it poses is widely ranging. Flood hazard, risk, and disasters are the products of an interaction between environmental and social processes (Parker, 2000). Worldwide statistics indicate that continuously increasing flood damages and losses of human lives remain at high levels unacceptably. It is estimated that losses caused by flood account for 40% of all total losses attributed to all disasters. Obviously, flood disasters are one of the most frequent and devastating disasters over the world (International Federation of Red Cross & Red Crescent Societies, 1998). However, in societal terms, the main emphasis is the risk to people and property. It is neither practically nor economically feasible to eliminate all flood risk. Therefore, the most suitable approach for dealing with flooding must be to manage the risk best (Fleming, 2002).

The risk of flooding is a major concern in many areas nearly all around the world and especially in China. Up to two-thirds of the land in China are at different types and levels of risk from river and coastal flooding, which results from the combined effects of natural, social and economic factors. Floods cause huge economic damage and destruction, and the economic losses are about 22–28.5 billion, which is about 33.3–43.2% of the natural disaster losses every year. What is more, floods occur quite frequently, for there being a larger disastrous flood every 2–3 years in China since 1949. In addition, the span of floods every year is very long. So it is commonly believed that flood risk analysis is suitable and receiving more and more attention within country, for it can provide information on previous, current and future flood risks (Wang & Plate, 2002; Wei, Jin, & Yang, 2002; Zhang, Zhou, Xu, & Watanabe, 2002).

Uncertainty always exists, and therefore, risk is inevitable (Karimi & Hüllermeier, 2007). Besides, future flood variations are an issue of great uncertainty, and the risk analysis of floods is absolutely necessary (Feng, Hong, & Wan, 2010). There are many risk analysis models at present in use that attempt to evaluate and estimate risk. In order to provide valuable support for decision making, most existing risk analysis models based on quantitative techniques rely more on statistical calculations than judgment and give highly subjective results, such as Monte Carlo, Failure Mode and Effects Analysis, Sensitivity Analysis (White, 1995), Simulation and Annual Loss Expectancy (Ngai & Wat, 2005), Fault-tree analysis (Cheng, Lin, Hsu, & Shu, 2009), Annual Loss Expectancy (Rainer, Snyder, & Carr, 1991). However, these traditional approaches have their disadvantages when the available data are insufficient to permit estimating reliably the probabilities of release of risk agents or other characteristics of concern. In many cases, risks are rather fuzzy for our perception because of the shortage of knowledge or information about the systems that determine the adverse incidents (Huang & Ruan, 2008). If pure probabilistic methods are employed to analyze the risk, unreliable results would be obtained, so fuzzy methods to analyze the risk of natural hazards are proposed in succession (Huang, 1996).

Fuzzy mathematics has been widely applied in natural disaster studies to deal with uncertainty problems. After the fuzzy set theory was established by Zadeh (1978), many scholars have used fuzzy mathematical methods to study risk assessment. Misra and Weber (1990) used the fuzzy set theory for level-1 studies in probabilistic safety assessment and risk management. Warmerdama and Jacobsa

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(1994) presented a mathematical model for optimally siting and routing hazardous waste operations. Fisher (2006) adopted fuzzy decision-making frameworks to improve environmental quality in view of the uncertainty. Fu (2008) used a fuzzy optimization method to solve multi-criteria decision making problems under fuzzy environments. Bardossy, Bogardi, and Duckstein (1991) proposed the fuzzy-set risk analysis technique which is also considered as an extension of interval analysis, to combine and rank fuzzy risk estimates for risk management. Lee and Chen (2008) presented a new method for fuzzy risk analysis based on fuzzy numbers with different shapes and different deviations. All these studies above were formalized by using the fuzzy set theory, or combined with other theories to enhance the research for fuzzy risk analysis. But a less common approach is to employ a risk calculation model to deal with the inherent risk of the fuzzy treatment exhaustively (Reyna & Brainerd, 2008).

And Huang (1997) established information diffusion theory which employed fuzzy set theory to complement the probability theory with an additional dimensional of uncertainty, can characterize the fuzziness of the probability by a possibility distribution and enhanced its effectiveness in small sample optimization with inherent imprecision and a scarcity of statistical data (Feng et al., 2010; Karimi & Hüllermeier, 2007). The interior-outer-set model (IOSM) first established by Huang based on information diffusion theory, is capable of calculating the possibility–probability distribution (PPD) values in the occurrence of floods to solve multi-valued risks. And the possibility–probability risk calculated using the IOSM is referred to as fuzzy risk. IOSM has been using to assess the fuzzy risk of natural disaster, and the results are demonstrated better than the conventional probability methods in risk management (Huang, 2004). After all, IOSM also has three deficiencies (Huang, Zong, & Chen, 2007), so we improve it to be a new model called diffused-interior-outer-set model (DIOSM), and we employ DIOSM to calculate the fuzzy risk of flood disasters in China. The results for DIOSM reflect the flood risk in China effectively, which would provide the government and decision-makers with a more suitable and invaluable guide and overview on flooding. Therefore, it is recommended to study flood disasters using DIOSM in China.

In this paper, DIOSM focusing on providing information to help make better decisions in an uncertain world, is applied to calculate the fuzzy risk of flood disaster. And the paper is organized as follows. In Section 2, we firstly introduce IOSM briefly, and then present the measurements to improve it, thus propose DIOSM. There is a case study in Section 3 to show the process of DIOSM. Finally, we discuss and make in Section 4.

2. Diffused interior-outer-set model

2.1. Interior-outer-set model

First we introduce the interior-outer-set model (Huang & Moraga, 2002). Let $X=\{x_i|i=1,2,\ldots,n\}$ be a given sample, $x_i \in \Re$ (set of real numbers), and $U=\{u_j|j=1,2,\ldots,m\}\subset\Re$ be a discrete universe of X, with a given step length Δ, $\Delta \equiv u_j-u_{j-1}$, $j=2,3,\ldots,m$. From the point of view of the information distribution, a sample point x_i can allocate its information with a value of q_{ij} to point u_j, called one dimensional linear information-distribution shown in Eq. (1):

$$q_{ij}=\begin{cases}1-|x_i-u_j|/\Delta, & \text{if } |x_i-u_j|\leqslant\Delta \\ 0, & \text{else}\end{cases} \qquad x_i\in X,\ u_j\in U \tag{1}$$

where x_i is the observation value, u_j is a controlled point, and Δ is the step length of controlled point. q_{ij} is called an information gain.

Let $I_j=\lfloor u_j-\Delta/2, u_j+\Delta/2)$ be the observation interval associated to u_j, intervals are selected so that all of the sample points x_i only lie within a certain interval I_j. For the sake of simplicity, we always use u_j to represent I_j. When a sample point is subjected to random disturbance, it may depart from the interval I_j, while a point outside may also enter the interval. The possibility of sample point x_i leaving or joining the interval I_j is expressed as q_{ij}^- and q_{ij}^+, respectively. For the purpose of computation, the interior set and outer set of I_j is defined by Huang (2004) as follows:

(1) $X_{in-j}=X\cap I_j$ is called an interior set of interval I_j. The elements of X_{in-j} are called the interior points of I_j
(2) $X_{out-j}=X\backslash X_{in-j}$ is called an outer set of interval I_j. The elements of X_{out-j} are called the outer points of I_j

$\forall x_i\in X$, if $\forall x_i\in X_{in-j}$, we say that it loses information, by gain at $1-q_{ij}$, to other interval, and we use $q_{ij}^-=1-q_{ij}$ to represent the loss; if $\forall x_i\in X_{out-j}$, we say that it gives information, by gain at q_{ij} to I_j, we use $q_{ij}^+=q_{ij}$ to represent the added information. So for I_j, with information gain q_{ij}, these possibilities can be formulated as follows Eqs. (2) and (3):

$$q_{ij}^-=\begin{cases}1-q_{ij}, & \text{if } x_i\in X_{in-j}\\ 0, & \text{if } x_i\in X_{out-j}\end{cases} \tag{2}$$

$$q_{ij}^+=\begin{cases}q_{ij}, & \text{if } x_i\in X_{out-j}\\ 0, & \text{if } x_i\in X_{in-j}\end{cases} \tag{3}$$

q_{ij}^- is called the leaving possibility, and q_{ij}^+ the joining possibility. The leaving possibility of an outer point is defined as 0 (for it has gone). The joining possibility of an interior point is defined as 0 (for it has been in the interval).

Let $Q_j^-=\{q_{ij}^-\}$ be the list of membership degrees to the information diffusion distribution from sample points within the observation interval and $Q_j^+=\{q_{ij}^+\}$ be the list of membership degrees to the information diffusion distribution, from sample points outside the observation interval. If $|Q_j^-|=n_j$, we can use Eq. (4) to calculate a possibility–probability distribution (PPD), which is called the interior-outer-set model (IOSM).

$$\pi_{I_j}(p)=\begin{cases}
1st(smallest)\ element\ of\ Q_j^-, & if\ p=0\\
2nd(smallest)\ element\ of\ Q_j^-, & if\ p=\frac{1}{n}\\
\cdots\cdots & \\
Last(largest)\ element\ of\ Q_j^-, & if\ p=\frac{n_j-1}{n}\\
1, & if\ p=\frac{n_j}{n}\\
1st(largest)\ element\ of\ Q_j^+, & if\ p=\frac{n_j+1}{n}\\
2nd(largest)\ element\ of\ Q_j^+, & if\ p=\frac{n_j+2}{n}\\
\cdots\cdots & \\
Last\ (smallest)\ element\ of\ Q_j^+, & if\ p=1
\end{cases} \tag{4}$$

For a size n, the universe of discourse of probability is

$$P=\{p_0,p_1,\ldots,p_n\}=\left\{0,\frac{1}{n},\ldots,\frac{n-1}{n},\frac{n}{n}\right\} \tag{5}$$

And for the sample X, using Eq. (6), we can obtain a PPD, $\pi_{I_j}(p)$, $j=1,2,\ldots,m$; $p\in P$, that is a fuzzy relation on the Cartesian product space $\{I_1,I_2,\ldots,I_m\}\times\{p_0,p_1,\ldots,p_n\}$, written as

$$\Pi=\left(\pi_{I_j}(p_i)\right)_{m\times(n+1)}=\begin{array}{c} \\ I_1\\ I_2\\ \vdots\\ I_m\end{array}\begin{array}{c}\begin{array}{ccccc}p_0 & p_1 & p_2 & \cdots & p_n\end{array}\\ \begin{pmatrix}\pi_{I_1}(p_0) & \pi_{I_1}(p_1) & \pi_{I_1}(p_2) & \cdots & \pi_{I_1}(p_n)\\ \pi_{I_2}(p_0) & \pi_{I_2}(p_1) & \pi_{I_2}(p_2) & \cdots & \pi_{I_2}(p_n)\\ \vdots & \vdots & \vdots & \vdots & \vdots\\ \pi_{I_m}(p_0) & \pi_{I_m}(p_1) & \pi_{I_m}(p_2) & \cdots & \pi_{I_m}(p_n)\end{pmatrix}\end{array} \tag{6}$$