Application of Triangular Fuzzy AHP Approach for Flood Risk Evaluation

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Introduction

- **Rationale & significance :**

  The objective of this paper is to develop a hierarchical model for the evaluation of an aggregative risk of failure of emergency response program in FDM. A qualitative (linguistic) modeling technique that combines fuzzy set theory with analytic hierarchy process (AHP) is used.

Design and Approach

- A hybrid evaluation model is established is based on fuzzy AHP and triangular fuzzy number (TFN). Since AHP proved to be the excellent method in dealing with interdependent criteria and the local problems involving both quantitative and qualitative. And fuzzy set theory deals with sets or categories whose boundaries are blurry or, in other words, 'fuzzy.' The combination of these two methods helps in dealing with multiple attribute decision-making problems effectively. The following are proposed methodologies for evaluation model.

- Analytic hierarchy process established by Saaty is a method to solve multiple criteria decision problems by setting their priorities (Erden and Karaman 2012).

Results and Discussions

- A hierarchical model is developed to provide a framework for aggregating risk items of emergency response failure at the event of flooding. Risk is defined as a product of likelihood and peril, where both factors are expressed in terms of qualitative scales defined by fuzzy numbers. The proposed approach is expected to act as tool to the concerned organizations to quantify the risks and accordingly priorities the activities and upgrade the emergency response program at the event of flooding.

Policy Directions

- Policy makers and other interested authorities may consider our findings to evolve scientific assessment structure and to initiate result oriented flood disaster friendly measures from developing countries point of view.

Introduction

- **Rationale & significance :**

  Floods are the most common type of disaster globally and more predominant in developing nations, responsible for human lives in the last decade alone (23:1 low- vs. high-income countries) (Alderman et al. 2012).

  Flood risk evaluation approaches can be divided into two broad categories: (1) methods employing fuzzy logic set theory (Dagoberto et al. 2012) and (2) methods rooted in probability theory, and both are encountering some difficulties in practice (Chen and Tseng 2012)..

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Significance

- The objective of this paper is to develop a hierarchical model for the evaluation of an aggregative risk caused by floods. This paper aims to find an effective method to establish a flood risk evaluation and prediction system for flood-prone locations. Based on the safety evaluation and early warning rating results, proper precautions against the risks and hazards can be made to prevent and reduce the flood damage from developing nations point of view.

Back ground

Several methods have been developed for flood risk evaluation problems, such as analytic hierarchy process (AHP) (Saaty 1996), fuzzy AHP (Saaty 2004), analytic network process (ANP) (Metin et al. 2008).

Fuzzy AHP is a useful tool to deal with imprecise, uncertain, or ambiguous data and the high nonlinearity and complexity of hazard systems. Decision makers usually feel more confident to give linguistic variables rather than expressing their judgments in the form of exact numeric values. Flood risk evaluation is an intrinsically complex multidimensional process including both quantitative and qualitative factors which may be uncertain (Li et al. 2012).

Justification

- Therefore, fuzzy AHP is deemed to be particularly appropriate for flood risk evaluation and prediction.
- According to the characteristics of flood risk analysis, this paper used triangular fuzzy AHP–based model for ranking of important risk indexes and for predicting comprehensive flood risk from developing countries perspective.

AHP Model

- Analytic hierarchy process established by Saaty is a method to solve multiple criteria decision problems by setting their priorities (Erden and Karaman 2012).
- AHP aims to settle the conflict between practical demand and scientific decision making, and it also aims to find a way to blend qualitative analysis and quantitative analysis, which makes it an efficient and effective method under complex contexts, as synthesized in Fig. 1

AHP Model

- Decisions made using the AHP occur in two sequential phases (Saaty 1996): the first is hierarchy design, which involves decomposing the decision problem into a hierarchy of interrelated decision elements (i.e., goal and evaluation criteria); the second is hierarchy evaluation, which involves eliciting weights of the criteria and synthesizing these weights and preferences to determine alternative priorities.
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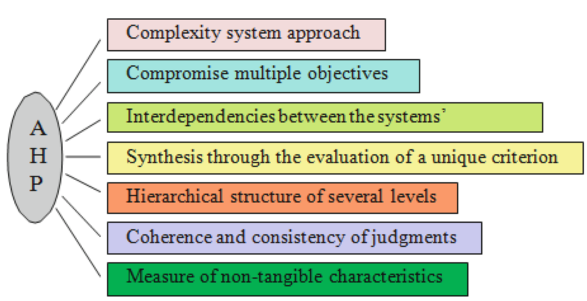

Fig. 1 Using the AHP under complex contexts

Pair wise comparisons are classically carried out by asking how more valuable an alternative A is to criterion C than another alternative B. As shown in Fig. 2

Fig 2. : **Triangular fuzzy scale**

Linguistic scale	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
Just equal	(1,1,1)	(1,1,1)
Equally important	(½, 1, 3/2)	(2/3, 1,2)
Weakly more important	(1, 3/2, 2)	(1/2, 2/3,1)
Moderately more important	(3/2, 2 ,5/2)	(2/5, ½ , 2/3)
Strongly more important	(2, 5/2, 3)	(1/3, 2/5, ½)
Extremely more important	(5/2, 3, 7/2)	(2/7, 1/3, 2/5)

Merits of AHP

- the main advantages of the AHP method is the simple structure. The AHP is designed in a way that represents human mind and nature. Therefore, AHP provides the possibility of searching and evaluating the cause and effect relationship between goal, factor, sub-factor, and alternatives using breaking down the structure of the problem (Pourghasemi et al. 2012). Moreover, the use of AHP does not involve cumbersome mathematics, and thus, it is easy to understand and it can effectively handle both qualitative and quantitative data.

Fuzzy Theory

- In the traditional AHP method, the scale of pair comparisons among criteria is restricted to crisp numbers. Therefore, AHP is criticized for its unbalanced scale of judgment and failure to precisely handle the inherent uncertainty and vagueness in carrying out pairwise comparisons (Pourghasemi et al. 2012).
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Fuzzy Theory

- Fuzzy set theory, resembles human reasoning in its use of approximate information and uncertainty to generate decisions. Good decision-making models should be able to tolerate vagueness or ambiguity (Lious and Wang 1992). Thus, if the uncertainty of human decision making is not taken into account, the results from the models can be misleading.

- A fuzzy set is a class of objects with a continuum of grades of membership. Such a set is characterized by a membership function, which assigns to each object a grade of membership ranging between zero and one.

Flood risk evaluation model

- In this section, the computational steps of the proposed integrated framework of flood risk evaluation model based on a triangular fuzzy AHP approach are presented.

Flood risk indexes

Flood disaster is that the hazard factor acts on the hazard affected body (Yang et al. 2009). Therefore, the recognition of the risk related to the occurrence of flood disasters is the first step within a comprehensive risk evaluation process, to find all relevant risk factors of the cause of flooding and loss, to classify them according to occurrence and characteristics, and to appropriate choices according to their impact on disaster bodies (Power et al. 2001).

Table 1 Flood risk indexes

Flood risk classification	Flood risk indexes
Flood hazard	
Hazard factors	Rainstorm, dam break, typhoon, tsunami
Hazard including environment	Vegetation coverage, drainage density, terrain elevation, proportion of easily flooded farmland
Vulnerability of hazard affected body	
Property characteristics	Population density, residential property, industrial production, agriculture, forestry, animal husbandry, and fishing production
Society's bearing capacity	Flood control standard, the accuracy of flood dispatching, early warning mechanism, disaster relief agencies

Setting up the triangular fuzzy AHP hierarchical structure

- In flood risk evaluation and prediction, issues to be addressed include three aspects: the importance ranking of risk indexes, comprehensive flood risk prediction, and risk response measures analysis. The ultimate goal of evaluating the ideal comprehensive flood risk can be achieved, using four evaluation criteria and twelve sub-criteria as shown in Fig. 4.

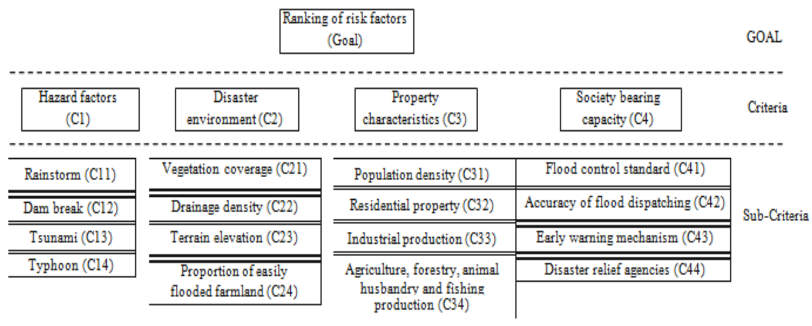


Fig. 4 Triangular fuzzy AHP hierarchical structure

Flood risk indexes importance ranking

- In the triangular fuzzy AHP hierarchical structure of the importance ranking of risk indexes, the first level is the ultimate goal of evaluating the ideal comprehensive flood risk. The second level is flood risk classification that is generally divided into four aspects: hazard factors, disaster environment, property characteristics, and society's bearing capacity. In practice, the classification should be adjusted according to actual situation during the flood, such as the geographical position, flood characteristics, climate condition. The third level is the lowest level of the structure, which includes concrete risk factors of the flood risk indexes classification. A graphical representation of the above outlined hierarchical structure is shown in Fig. 4.

$M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$ are two TFNs; let $V(M_2 \geq M_1) = \mu(d)$, and d is the abscissas of intersection points of M1 and M2, while Eq. (1) is tenable.

$$V(M_2 \geq M_1) = \mu(d) = \begin{cases} \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - u_1)}, & l_1 \leq u_2 \\ 0 & Others \end{cases} \qquad (1)$$

$$\alpha_{ij}^{-1} = \alpha_{ij} = \left(\frac{1}{u_{ij}}, \frac{1}{m_{ij}}, \frac{1}{l_{ij}}\right) \qquad (2)$$

$$a_{ij}^{t} = (l_{ij}^{t}, m_{ij}^{t}, u_{ij}^{t})$$

$$M_{ij}^{k} = \frac{1}{T} \otimes \left(a_{ij}^{1} + a_{ij}^{2} + \cdots . + a_{ij}^{T}\right) \qquad (3)$$

$$S_i^k = \left(\sum_{i=1}^{n_k} \sum_{j=1}^{n_k} M_{ij}^{k}\right)^{-1}, \text{ i= 1, 2, 3,......., } n_k \qquad (4)$$

$$V(S_i^k \geq S_j^k), \text{ i = 1, 2, …, } n_k : i \neq j \text{ and } P_{ih}^{k}(A_i^k) = \min V(S_i^k \geq S_j^k) \qquad (5)$$

Equation (5) represents single ranking of factors in layer k to factor h in layer k - 1, and A_i^k represents factor i in layer k.

$P_{ih}^{k}(A_i^k)$ is normalized and then Eq. (6) represents single ranking of factors in layer k to factor h in layer k - 1.

$$P_h^k = (P_{1h}^k, P_{2h}^k, \ldots, P_{nh}^k)^T \qquad (6)$$

$$P_h^k = (P_{1h}^k, P_{2h}^k, \ldots, P_{nh}^k)^T = \begin{bmatrix} P_{11}^k & P_{12}^k & \cdots & P_{1n_{k-1}}^k \\ P_{21}^k & P_{22}^k & \ddots & P_{2n_{k-1}}^k \\ \vdots & \vdots & \vdots & \vdots \\ P_{n_{k1}}^k & P_{n_{k2}}^k & \cdots & P_{nk_{nk-1}}^k \end{bmatrix} \qquad (7)$$

If $W_{k-1} = (W_1^k, W_2^k, \ldots . W_n^k)^T$ is ranking weight vector of layer k - 1 to goal, and synthesis general ranking W_k can be calculated by Eq. (8).

$$W_k = (W_1^k, W_2^k, \ldots . W_n^k)^T = P_k W_{k-1} \text{ or } W_k = \sum_{j=1}^{n_{k-1}} P_{ij}^k W_j^{k-1}, \text{ i= 1, 2, …., } n_k \qquad (8)$$

Applying Equations (6) and (7), the single ranking of factors in sub layers is obtained as follows:

$$P = \begin{bmatrix} 0.840 & 1 & 1 & 1 \\ 1 & 0.928 & 0.909 & 0.662 \\ 0.869 & 0.695 & 0.320 & 0.836 \\ 0.786 & 0.426 & 0.466 & 0.239 \end{bmatrix}$$

Synthesis general ranking, W_2^*, is calculated by Equation (8) as follows:

$$W_2^* = PW_1 = \begin{bmatrix} 0.840 & 1 & 1 & 1 \\ 1 & 0.928 & 0.909 & 0.662 \\ 0.869 & 0.695 & 0.320 & 0.836 \\ 0.786 & 0.426 & 0.466 & 0.239 \end{bmatrix} \begin{bmatrix} 0.276 \\ 0.297 \\ 0.217 \\ 0.209 \end{bmatrix}$$

$$= \begin{bmatrix} 0.232 & 0.276 & 0.276 & 0.276 \\ 0.297 & 0.275 & 0.270 & 0.196 \\ 0.181 & 0.151 & 0.069 & 0.181 \\ 0.164 & 0.891 & 0.097 & 0.050 \end{bmatrix}$$

The normalized synthesis general ranking W_2 is obtained as:

$W_2 = (w_1, w_2, \ldots, w_{16})$
(0.075, 0.096, 0.061, 0.053, 0.089, 0.089, 0.048, 0.028, 0.089, 0.087, 0.022, 0.031, 0.089, 0.063, 0.058, 0.016)

Judgement Matrix of higher level factors (C1 – C4)

	Hazard factors	Disaster Environment	Property characteristics	Society bearing capacity	Comprehensive Degree Function (S)	Hierarchical Ranking (P)	General Ranking (W)
Hazard factors (C1)	(1,1,1)	(0.67,1,2)	(1.5,2,2.5)	(0.5,1,1.5)	(0.147,0.277,0.526)	0.929	0.276
Disaster Environment (C2)	(0.5,1,1.5)	(1,1,1)	(1,1.5,2)	(1.5,2,2.5)	(0.161,0.305,0.526)	1	0.297
Property characteristics (C3)	(0.4,0.5,0.7)	(1,1.5,2)	(1,1,1)	(0.5,1,1.5)	(0.116,0.222,0.388)	0.731	0.217
Society bearing capacity (C4)	(0.67,1,2)	(0.4,0.5,0.7)	(0.67,1,2)	(1,1,1)	(0.110,0.194,0.426)	0.704	0.209

Judgement Matrix of sub factors in Hazard factors (C11 – C14)

	Rainstorm	Dam Break	Tsunami	Typhoon	Comprehensive Degree Function (S)	Hierarchical Ranking (P)	General Ranking (W)
Rainstorm (C11)	(1,1,1)	(0.5,1,1.5)	(0.5,1,1.5)	(0.5,1,1.5)	(0.101,0.242,0.468)	0.840	0.240
Dam Break (C12)	(0.67,1,2)	(1,1,1)	(0.5,1,1.5)	(1.5,2,2.5)	(0.148,0.303,0.596)	1	0.285
Tsunami (C13)	(0.67,1,2)	(0.67,1,2)	(1,1,1)	(0.5,1,1.5)	(0.114,0.242,0.553)	0.869	0.248
Typhoon (C14)	(0.67,1,2)	(0.4,0.5,0.67)	(0.67,1,2)	(1,1,1)	(0.110,0.212,0.482)	0.786	0.224

Judgement Matrix of sub factors of Disaster Environment (C21 – C24)

	Vegetation coverage	Drainage density	Terrain Elevation	Proportion of easily flooded farmland	Comprehensive Degree Function (S)	Hierarchical Ranking (P)	General Ranking (W)
Vegetation coverage (C21)	(1,1,1)	(0.5,1,1.5)	(1,1.5,2)	(1.5,2,2.5)	(0.176,0.320,0.557)	1	0.327
Drainage density (C22)	(0.67,1,2)	(1,1,1)	(1,1.5,2)	(0.5,1.5,2)	(0.139,0.291,0.557)	0.928	0.304
Terrain Elevation (C23)	(0.5,0.67,1)	(0.5, 0.67,1)	(1,1,1)	(1,1.5,2)	(0.132,0.223,0.397)	0.695	0.227
Proportion of easily flooded farmland (C24)	(0.4,0.5,0.67)	(0.5,0.67,1)	(0.5,0.67,1)	(1,1,1)	(0.105,0.165,0.291)	0.426	0.139

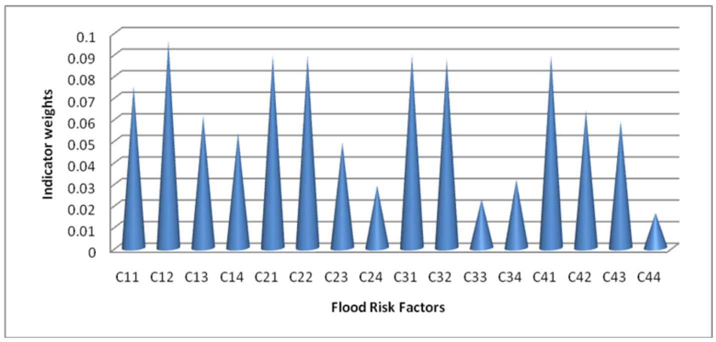
Judgement Matrix of sub factors of Property Characteristics (C31 – C34)

	Population density	residential property	Industrial production	agriculture, forestry, animal husbandary and fishing production	Comprehensive Degree Function (S)	Hierarchical Ranking (P)	General Ranking (W)
Population density (C31)	(1,1,1)	(1.5,2,2.5)	(1,1.5,2)	(1,1.5,2)	(0.198,0.339,0.544)	1	0.370
residential property (C32)	(0.4,0.5,0.67)	(1,1,1)	(1.5,2,2.5)	(1.5,2,2.5)	(0.194,0.311,0.484)	0.909	0.337
Industrial production (C33)	(0.4,0.5,0.67)	(0.4,0.5,0.67)	(1,1,1)	(0.5,1,1.5)	(0.101,0.169,0.278)	0.320	0.118
agriculture, forestry, animal husbandary and fishing production (C34)	(0.5,0.67,1)	(0.4,0.5,0.67)	(0.67,1,2)	(1,1,1)	(0.113,0.179,0.338)	0.466	0.173

Judgement Matrix of sub factors of Society Bearing Characteristics (C41 – C44)

	Flood Control standard	Accuracy of flood dispatching	Early warning mechanism	Disaster relief agencies	Comprehensive Degree Function (S)	Hierarchical Ranking (P)	General Ranking (W)
Flood Control standard (C41)	(1,1,1)	(1,1.5,2)	(1.5,2,2.5)	(1,1.5,2)	(0.194,0.335,0.539)	1	0.365
Accuracy of flood dispatching (C42)	(0.5,0.67,1)	(1,1,1)	(0.5,1,1.5)	(1,1.5,2)	(0.129,0.232,0.395)	0.662	0.242
Early warning mechanism (C43)	(0.4,0.5,0.67)	(0.67,1,2)	(1,1,1)	(2,2.5,3)	(0.175,0.279,0.479)	0.836	0.305
Disaster relief agencies (C44)	(0.5,0.67,1)	(0.5,0.67,1)	(0.3,0.4,0.5)	(1,1,1)	(0.100,0.152,0.251)	0.239	0.087

The importance of different factors is shown in the following figure:



Discussion & conclusion

In this work, the application of a triangular fuzzy AHP approach based on TFN is developed to evaluate flood risk and analyze response measures. A hierarchy evaluation index system is established. Four factors and 16 sub-factors are included in the index system. The TFNs are adopted to determine the weights of the indexes and evaluate the work safety performance of the indexes. The fuzzy evaluating vectors are calculated. Then, flood risk factors ranking, comprehensive flood risk prediction are determined.

This methodology, combining the fuzzy AHP and TFN, provides a new scientific method for flood risk evaluation and makes the evaluation results more reasonable and comprehensive. As the evaluation index system has been developed, it is believed that the proposed method provides a more reliable reference and evaluation method for flood risk management.

Discussion & conclusion

Through the application of a triangular fuzzy AHP approach, we analyze the fuzzy risk of flood disasters and calculate the flood risk quantitatively in the study area by considering the rainfall data, elevation data, land use data, and the social and economic data, and so on.

It is hoped that the results would provide the government, engineers, analysts, decision makers, and local authorities with a more suitable and invaluable guidance and overview on flooding, which is helpful for them to outline the policy and practice of managing flood risk clearly. The proposed hybrid evaluation model based on fuzzy AHP and TFN approach will ensure that we can identify, evaluate quantitatively, control, and mitigate risks associated with human activities, thus managing future flood risk more effectively and which can be generalized to other natural disaster risk analysis.

THANKS TO EVERY ONE