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Flood risk assessment model using the fuzzy analytic hierarchy process

Introduction

Natural disasters represent a constant threat to sustainable development and they are closely interlinked. Development is never neutral in relation to catastrophes: it creates, enhances or reduces the risk of their occurrence. Natural hazards, by themselves, do not cause disasters. They arise as a result of exposure, vulnerability and poor readiness for dealing with hazardous events. Water-related disasters such as floods, droughts, hurricanes, storm surges and landslides account for approximately 90% of disaster events worldwide [World Bank, 2013]. Among the disasters associated with climate, flooding has by far the largest share, accounting for 43% during the reporting period [CRED, 2015, p. 10]. Floods occur more frequently and are becoming more destructive as a result of the unsustainability of economic development, especially the poor management of forests and agricultural land, as well as uncontrolled urbanisation.

In May 2014, Serbia was faced with catastrophic floods, followed by landslides that hit more than two-thirds of the country (119 out of 165 municipalities), or 1.6 million people. Total damage is estimated at over 1.7 billion Euros, or about 4.7% of GDP in the year. More than 400 houses were destroyed and about 20,000 housing units were damaged. There was also damage caused to industrial and mining production, which led to the release of hazardous substances and waste into the environment, which caused pollution to surface, groundwater and soil, as well as a secondary impact on ecosystems and wildlife. Damage to homes and buildings has created over 500,000 tons of waste. This data has inspired the authors to deal with the risk analysis and flood risk assessment.

Using different methods and models to identify and analyse the risks, linguistic, descriptive or clear, numerical parameters of the risk level for an

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observed system or process can be obtained. In practice, a frequent problem is objective evaluation and quantification of risk. In the literature there are examples of different methods applied for the assessment and quantification of risk. Fuzzy set theory [Zadeh 1965; Zimmermann 2001; Zhang 2006] has proven advantages within vague, imprecise and uncertain contexts. It was specially designed to mathematically represent uncertainty and vagueness and provide formalised tools for dealing with the imprecision intrinsic to many decision problems. The fuzzy set theory is based on classes and groups of data with boundaries that are not sharply defined.

In this paper, the risk assessment used the fuzzy analytic hierarchy process – FAHP. Firstly, all possible risk elements are analysed based on the AHP method, then the fuzzy set is built and the membership function is constructed based on the experts' experience method.

Methodology

There is numerous research in the area of risk management and there are different methods and models that solve a great variety of problems connected to risk management. Risk assessment is primarily aimed at quantifying the amount of total risk, but includes all procedures that enable quantification of elements and sub-elements of the total risk, as well as procedures after a risk assessment, such as testing, implementation and other possible adjustments. The AHP method [Saaty, 1977, 1980, 1990] is often applied in risk assessment based on expert knowledge of the mutual relationship and the importance of certain elements of risk. AHP is a multi-criteria decision-making method, dealing with a complex problem with multiple conflicting and subjective criteria. It has the advantage of permitting a hierarchical structure of the criteria, which provides users with a better focus on specific criteria and sub-criteria. The criterion pairwise comparison matrix takes the pairwise comparisons as an input and produces the relative weights as an output, and the AHP provides a mathematical method of translating this matrix into a vector of relative weights for the criteria. In certain cases, the AHP method cannot show the nature of human understanding of mutual relations between risk elements [Gajović and Radivojevic, 2012]. This particularly refers to situations when a decision-maker cannot accurately assess crisp values of numerical criteria comparisons, since basic AHP does not include vagueness for personal judgments.

The fuzzy mathematical method, a type of uncertainty method, has an advantage in the complex uncertainty problem-solving and analysis used in flood risk assessment. Until today, different modalities of the FAHP method [Van Laarhoven and Pedrycz, 1983; Chang, 1996; Cheng, 1997] have been proposed by different authors. The most often cited fact is that the experts who make decisions about a particular problem in the FAHP method may present a flexible evaluation, which implies a more realistic view of the observed situation. The disadvantage of the AHP method [Durán and Aguilo, 2008] lies in the fact that it cannot process uncertainty and vagueness on the basis on the discrete scale. In FAHP, the pairwise comparisons of both criteria and the alternatives are performed through the linguistic variables, which are represented by triangular numbers. The FAHP can reduce or even eliminate ambiguity and the lack of clarity that exists in complex decision-making problems and improve the accuracy of the estimate of the given situation in relation to the AHP method (for more information about differences between these methods see Durán and Aguilo, 2008; Meixner, 2009; Zhu et al, 1999].

Numerous authors have applied fuzzy logic and FAHP methods to risk assessment in various areas, but very limited literature is avaliable on the use of fuzzy multi-objective analysis in flood studies [Simonović, 2012, p. 154]. Bender and Simonović (2000) developed fuzzy techniques for the Tisza River in Hungary. Morankar, et al. (2016) used a fuzzy multi-objective approach in irrigation planning. Schumann and Nijssen (2011) investigated the effectiveness of technical flood control measures using the FAHP method.

Fuzzy analytic hierarchy process method

The fuzzy AHP method is a multi-criteria decision analysis method is effective in dealing with fuzzy quantitative variables.In this paper, triangular fuzzy numbers are used to decide the priority of one decision variable over another. The application of fuzzy numbers may improve the accuracy of an expert's assessment and the quality of the output results. Today, there are different FAHP formulation methods. In this model we use Chang's FAHP method (1996), which can be described by the following steps [Wang et al, 2008]:

Step 1. The decision-maker determines the value m_{ij} for elements *i* and *j*, where m_{ij} is a triangular fuzzy number (TFN)whose parameters are a_{ij}, b_{ij}, and c_{ij}. These are the least possible values and a TFN is represented as $(a_{ij},\ b_{ij}, c_{ij})$.

Step 2. Summarising the rows of the matrix $M = (m_{ij})_{n\times n}$ to obtain values

(1) $$RS_i = \sum_{j=1}^{n} M_{ij} = \left(\sum_{j=1}^{n} a_{ij}, \sum_{j=1}^{n} b_{ij}, \sum_{j=1}^{n} c_{ij} \right)$$

Normalisation of value RS_i according to the equation

(2) $$S_i = \frac{RS_i}{\sum_{j=1}^{n} RS_j} = \left(\frac{\sum_{j=1}^{n} a_{ij}}{\sum_{k=1}^{n} \sum_{j=1}^{n} c_{kj}}, \frac{\sum_{j=1}^{n} b_{ij}}{\sum_{k=1}^{n} \sum_{j=1}^{n} b_{kj}}, \frac{\sum_{j=1}^{n} c_{ij}}{\sum_{k=1}^{n} \sum_{j=1}^{n} a_{kj}} \right), i = 1,\dots,n$$

Step 3. The degree of probability that $S_i \geq S_j$ compared to relation $S_i \geq S_j$, where $S_i = (a_i, b_i, c_i)$ and $S_j = (a_j, b_j, c_j)$ is

$$V\left(S_i \geq S_j\right) = \begin{cases} 1, & if \quad b_i \geq b_j \\ \dfrac{c_i - a_j}{\left(c_i - b_i\right) + \left(b_j - a_j\right)}, & if \quad a_j \leq c_i, \quad i, j = 1, \ldots, n;\ j \neq i \\ 0, & \text{other} \end{cases} \tag{3}$$

Determination of the probability that the fuzzy number S_i is greater than other fuzzy numbers according to the equation:

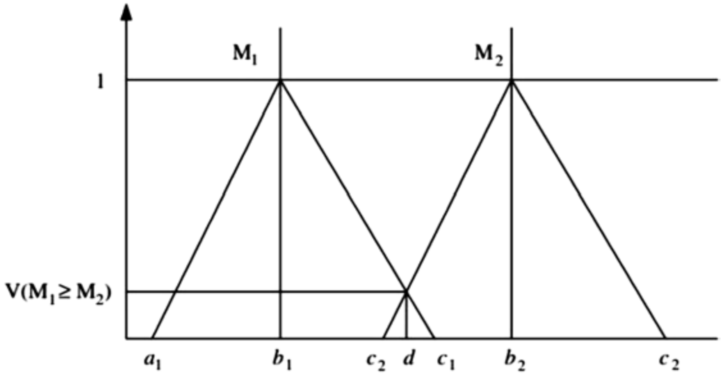
$$V\left(S_i \geq S_j \,\middle|\, j = 1, \ldots, n;\ j \neq i\right) = \min_{j \in \{1, \ldots, n\}, j \neq i} V\left(S_i \geq S_j\right), i = 1, \ldots, n \tag{4}$$

Step 4. Determination of priority vectors $W = (w_1, \ldots, w_n)^T$ of comparison matrix of the fuzzy value M as:

$$w_i = \frac{V\left(S_i \geq S_j \,\middle|\, j = 1, \ldots, n;\ j \neq i\right)}{\sum_{k=1}^{n} V\left(S_k \geq S_j \,\middle|\, j = 1, \ldots, n;\ j \neq k\right)}, \quad i = 1, \ldots, n \tag{5}$$

For illustration, Figure 1 shows the intersection between M1 and M2.

Figure 1. The intersection between M1 and M2



The output result of this model is the value of priority – significance S_i of each risk element (for the first data set $i = 1$ – N_1, $i = 2$ – N_2, $i = 3$ – N_3, $i = 4$ – N_4, $i = 5$ – N_5, $i = 6$ – N_6, $i = 7$ – N_7 and the other data set $i = 1$ – A_1, $i = 2$ – A_2, $i = 3$ – A_3) and the total risk $W = w_1$ – low, w_2 – medium, w_3 – high total risk).

Table 1. shows the AHP and fuzzy AHP scale comparisons parameters that take into account the uncertainty associated with the perception of decision-makers.

Table 1. Conversion scales for AHP and FAHP

Linguistic scale	AHP scale	Fuzzy AHP scale	
		Triangular fuzzy scale	Triangular fuzzy reciprocal scale
Just equal	1	(1,1,3)	(1/3, 1, 1)
Equal to moderate	2	(1,2,3)	(1/3, 1/2, 1)
Moderate importance	3	(2,3,4)	(1/4, 1/3, 1/2)
Moderate to strong	4	(3,4,5)	(1/5, 1/4, 1/3)
Strong importance	5	(4,5,6)	(1/6, 1/5, 1/4)
Strong to very strong	6	(5,6,7)	(1/7, 1/6, 1/5)
Very strong	7	(6,7,8)	(1/8, 1/7, 1/6)
Very strong to extremely strong	8	(7,8,9)	(1/9, 1/8, 1/7)
Extremely important	9	(8,9,9)	(1/9, 1/9, 1/8)

Variables and factors of flood impact

In risk analysis, issues to be addressed include three aspects: the importance of ranking risk factors, the system risk assessment and the choice of risk response measures degree. Two flood hazard indices were defined, one based on natural factors (N) and one based on anthropogenic factors (A). The equation that relates to these indices has the following form:

$$N, A = \sum_{j=1}^{n} c_j w_j \tag{6}$$

where *N*, *A* is the value of flood hazard for each watershed, *w* is the weight of factors *i* and *c* is the sensitivity score of each sub-factor criterion to flooding. Furthermore, the values that were derived from *N* and *A* indices were grouped into four hazard classes according to the probability of flood occurrence. The influence of natural risk elements and anthropogenic risk elements are for the Kassandra Peninsula, in Northern Greece [Stefanidis and Stathis, 2013]. In their work, the authors used the AHP method to assess the flood hazard. Tthe next table shows the natural risk elements of flooding with their influence.

Table 2. The influence of natural risk elements

	Risk elements	Class	Values	Influence
1	Land use (N1)	Cultivated lands, barren land Shrubs, pastures Forests	3 2 1	High Medium Low
2	Erodibility (N2)	Neogene, flysch, alluvial Schists, limestones Crystal igneous	3 2 1	High Medium Low
3	Watershed slope (N3)	>35 % 15–35 % <15 %	3 2 1	High Medium Low
4	Main stream slope (N4)	>7 % 3–7 % <3 %	3 2 1	High Medium Low
5	Permeability (N5)	Neogene, crystal igneous, alluvial Schists, flysch Limestone	3 2 1	High Medium Low
6	Watershed shape (N6)	Roundish Semi-roundish Elongated	3 2 1	High Medium Low
7	Density of hydrographic etwork (km/km^2) (N7)	>3 % 1.5–3 % <1.5 %	3 2 1	High Medium Low

Source: adapted from [Stefanidis and Stathis, 2013].

The next table consists of the anthropogenic risk elements of flooding.

Table 3. The influence of anthropogenic risk elements

	Action	Existence	Description	Values	Influence
1	Disturbance (A1)	yes no	Plenty Almost none	2 1	High Medium
2	Inadequate technical works (A2)	yes no	Designed for flood intervals less than 1/100 years Not designed for flood intervals more than 1/100 years	2 1	High Medium
3	Shaped cross-section at the plain area of the stream (A3)	no yes	Inappropriate Well-shaped	2 1	High Medium

Source: adapted from [Stefanidis and Stathis, 2013].

The comparison matrix of risk elements for the influence of natural risk elements and anthropogenic risk elements given by experts are shown in tables 1 and 2. Weights of each element are calculated on AHP basis. The relative weight of each element can be calculated using the pairwise comparison method and some specialised software.

Table 4. The comparison matrix of risk elements – The influence of natural risk elements

	N1	N2	N3	N4	N5	N6	N7	Weight
N1	1	3	3	5	5	5	5	0.364
N2	1/3	1	2	4	4	5	5	0.234
N3	1/3	1/2	1	2	3	4	4	0.157
N4	1/5	1/4	1/2	1	2	2	3	0.091
N5	1/5	1/4	1/3	1/2	1	1	2	0.06
N6	1/5	1/5	1/4	1/2	1	1	1	0.05
N7	1/5	1/5	1/4	1/3	1/2	1	1	0.044
	λ=7.391		CI=0.065					CR=0.0493

Table 5. The comparison matrix of risk elements – The influence of anthropogenic risk elements

	A1	A2	A3	Weight
A1	1	2	3	0.539
A2	1/2	1	2	0.297
A3	1/3	1/2	1	0.164
	λ=3.111		CI=0.056	CR=0.001

The table shows values for λ – the highest eigenvalue of the decision matrix, CI – consistency index and CR – the ratio of consistency obtained using the AHP method. Considering that CI is less than 10%, we can accept estimate vector of priority [Saaty 1990]. These comparisons indicated that the consistency ratio in both cases is rather smaller than 10%, so the weights of the risk elements are considered reliable.

Fuzzy analytic hierarchy process calculation

Based on AHP method all possible elements are identified. The fuzzy set is built and the membership function is constructed based on the experts' experience method. First the fuzzy evaluation matrix of the criteria is constructed by the pairwise comparison of the different criteria relevant to the overall objective using triangular fuzzy numbers. The consistency of the pairwise judgment of each comparison matrix is also checked using the consistency index calculation method. The value of fuzzy extent with respect to each criterion is calculated by using equation (2) and the formula for algebraic operations of the fuzzy set. The different values of fuzzy synthetic extend with respect to the seven different criteria are noted by N_i and three criteria by A_i.

Table 6. Determination of fuzzy numbers

	a_{ij}	b_{ij}	c_{ij}
Natural risk elements			
N1	0.115	0.318	0.892
N2	0.085	0.251	0.732
N3	0.049	0.174	0.526
N4	0.020	0.105	0.339
N5	0.025	0.062	0.225
N6	0.023	0.049	0.141
N7	0.017	0.041	0.141
Anthropogenic risk elements			
A1	0.118	0.529	2.128
A2	0.074	0.309	1.064
A3	0.085	0.162	0.426

The degree of probability of N_i over N_j can be determined by Equation (3). For example, looking at natural risk elements we obtain the following values:

$$V(N_1 \geq N_1)=1,\ V(N_1 \geq N_2)=1.095,\ V(N_1 \geq N_3)=1.217,\ V(N_1 \geq N_4)=1.345,$$

$$V(N_1 \geq N_5)=1.445,\ V(N_1 \geq N_6)=1.478,\ V(N_1 \geq N_7)=1.484,$$

$$V(N_2 \geq N_1)=0.899,\ V(N_2 \geq N_2)=1,\ \text{etc.}$$

With the help of equation (4), the minimum degree of possibility can be stated as:

$$d'(N_1)=minV(N_1 \geq N_2,N_3,N_4,N_5,N_6,N_7)=\ 1.$$

Similarly,

$$d'(N_2)=0.899,\ d'(N_3)=0.754,\ d'(N_4)=0.551,$$

$$d'(N_5)=0.371, d'(N_6)=0.208, d'(N_7)=0.089.$$

$$d'(A_1)=1,\ d'(A_2)=0.811,\ d'(A_3)=0.456.$$

The weight vectors are given as
$Wo_N=(1,\ 0.899,\ 0.754,\ 0.551, 0.371, 0.208, 0.089)^T$ and $Wo_A=(1,\ 0.811,\ 0.456)^T$.

After the normalisation process, the weight vectors of the overall objective with respect to decision criteria are presented in Table 7.

Table 7. Total risk – weight vector of overall objective with respect to decision criteria

Natural risk elements							
AHP	0.364	0.234	0.157	0.091	0.06	0.05	0.044
FAHP	0.258	0.23215	0.194769	0.14223	0.0959	0.05376	0.022899
Anthropogenic risk elements							
AHP	0.539	0.297	0.164				
FAHP	0.4412	0.35776	0.20107				

The highest priority of natural risk elements has a risk of land use (N1) with 25.8% of influence, and the lowest priority has a risk of density of hydrographic network (N7) with 2.3% of influence on total risk. The highest priority of anthropogenic risk elements has a risk of disturbance (A1) with 44.12% of influence. Furthermore, we can combine elements of both risk factors. By comparing the results obtained by using AHP and FAHP, we get a high similarity. Deviations of the results obtained by applying the AHP and FAHP methods can be considered as acceptable as they resulted from the fact that the FAHP method, with greater significance, acknowledges the subjectivity of experts when comparing criteria and alternatives.

The presented methodology can be applied to any flood hazard map and to classify the watersheds of the research area into types. The model provides a relatively simple process of decomposition of total risk in specific processes to defined risk elements, and obtaining of data on percentage share of each element in total risk. Furthermore, the different attributes can be compared under each criterion separately by following the same procedure as discussed above. The matrix eigenvalue must be normalised and then apply the same process to find the weight vector of each attribute.

Summary

Natural hazards are a phenomena of natural systems stability disruption. They occur suddenly, either independently of each other or interconnected, and are caused by natural processes, lately considerably modified by anthropogenic influences. Despite developments in technology and extensive investments in flood control works, neither flood occurrences nor material damage are decreasing. Flood risk assessment represents a dynamic process that involves constant checking and any corrections of parameters of the established model. Either flood disaster risk itself or risk level classification has fuzziness and uncertainty. The fuzzy analytic hierarchy process method as a multi-criteria evaluation method can be effectively used in flood risk analysis. For the lack of historical and statistical data, it can also give the evaluation results reflected in actual flood control.

In this paper, authors used the FAHP method to assess flood hazards. Two flood hazard indices were defined, one based on natural factors and one based on anthropogenic factors. FAHP is flexible, enabling a relatively simple correction of input parameters and fast generation of values of total risk in specific processes. Moreover, the technique applied in this paper can easily be extended to other areas, where other factors may be considered, depending on the availability of data.

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Model oceny ryzyka powodzi przy użyciu rozmytego analitycznego procesu hierarchicznego (ang. AHP)

Streszczenie

Zrównoważony rozwój i katastrofy naturalne są ściśle ze sobą powiązane. Wpływ wydarzeń o charakterze katastroficznym na środowisko jest nadal trudny do określenia i takie straty są generalnie niedoszacowane. Rozwój nigdy nie jest neutralny w stosunku do katastrof: tworzy on, zwiększa lub redukuje ryzyko ich wystąpienia. Wybór właściwych metod i modeli matematycznych do oceny ryzyka w stosunku do określonych cech i funkcji danego systemu, a także dostępnych informacji i zasobów jest kluczowym parametrem w ocenie wiarygodności. Wielu autorów stosowało metody AHP przy ocenie ryzyka powodzi, ale niewiele publikacji dotyczy zastosowania rozmytej analizy wieloobiektowej w badaniach nad powodziami. W ostatnich latach, rozmyte podejście oceny ryzyka powodzi zyskało na znaczeniu. W niniejszej pracy przedstawiamy model rozmytego analitycznego procesu hierarchicznego (ang. FAHP) do oceny ryzyka powodzi. Zdefiniowano dwa wskaźniki zagrożenia powodzią, jeden oparty na czynnikach naturalnych i jeden na czynnikach antropogenicznych. FAHP został zastosowany w celu zilustrowania modelu.

Słowa kluczowe: rozmyty analityczny proces hierarchiczny, ryzyko, modelowanie

Flood risk assessment model using the fuzzy analytic hierarchy process

Abstract

Sustainable development and natural disasters are closely interlinked. The impact of catastrophic events on the environment is still very difficult to determine, and such losses are generally underestimated. Development is never neutral in relation to catastrophes: it creates, enhances or reduces the risk of their occurrence. Selection of appropriate methods and mathematical models for risk assessment in relation to the specific features and characteristics of the considered system and available information and resources, is a key parameter of reliability assessment. Numerous authors applied AHP methods with flood risk assessment, but very limited literature is avaliable on the use of fuzzy multi-objective analysis in flood studies. In the recent years, the fuzzy approach for flood risk assessments has gained greater importance. In this paper, we present the fuzzy analytic hierarchy process (FAHP) model for flood risk assessments. Two flood hazard indexes were defined, one based on natural factors and one based on anthropogenic factors. FAHP is applied to data sets to illustrate a model.

Key words: fuzzy AHP, risk, modelling

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