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Państwowej Wyższej Szkoły Zawodowej im. Stanisława Staszica  
w Pile**

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# Flood risk assessment model using the fuzzy analytic hierarchy process

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## 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.

landslides account for approximately 90% of disaster events worldwide [World 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.

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

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

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

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

elements and sub-elements of the total risk, as well as procedures after a risk

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, deal-

has the advantage of permitting a hierarchical structure of the criteria, which

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

cannot accurately assess crisp values of numerical criteria comparisons, since

The fuzzy mathematical method, a type of uncertainty method, has an advantage in the complex uncertainty problem-solving and analysis used in

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 pres-

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

Numerous authors have applied fuzzy logic and FAHP methods to risk assessment in various areas, but very limited literature is available on the use

### 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

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

Normalisation of value  $RS_i$  according to the equation

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

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

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

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

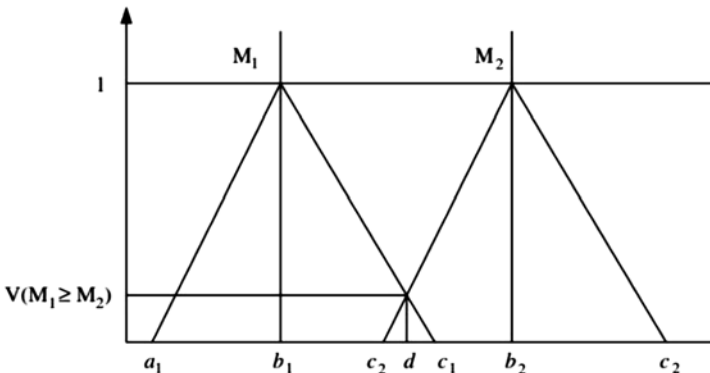
$$(4) \quad V(S_i \geq S_j | j=1, \dots, n; j \neq i) = \min_{j \in \{1, \dots, n\}, j \neq i} V(S_i \geq S_j), \quad i = 1, \dots, n$$

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

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

For illustration, Figure 1 shows the intersection between  $M_1$  and  $M_2$ .

Figure 1. The intersection between  $M_1$  and  $M_2$



$S_i$  of  $i = 1 - N_1, i = 2 - N_2, i = 3 - N_3, i = 4 - N_4, i = 5 - N_5, i = 6 - N_6, i = 7 - N_7$  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
Equal to moderate Moderate importance	1	(1,1,3)	(1/3, 1, 1)
	2	(1,2,3)	(1/3, 1/2, 1)
	3	(2,3,4)	(1/4, 1/3, 1/2)
Moderate to strong Strong importance Strong to very strong	4	(3,4,5)	(1/5, 1/4, 1/3)
	5	(4,5,6)	(1/6, 1/5, 1/4)
	6	(5,6,7)	(1/7, 1/6, 1/5)
Very strong Very strong to extremely strong Extremely important	7	(6,7,8)	(1/8, 1/7, 1/6)
	8	(7,8,9)	(1/9, 1/8, 1/7)
	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 based on natural factors (N) and one based on anthropogenic factors (A). The equation that relates to these indices has the following form:

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

where  $N, A$   $w$  is the weight  
of factors  $i$  and  $c$  is the sensitivity score of each sub-factor criterion to  $N$  and  $A$  indices

and Stathis, 2013]. In their work, the authors used the AHP method to as-

**Table 2. The influence of natural risk elements**

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

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

**Table 3. The influence of anthropogenic risk elements**

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

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

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
	$\lambda=7.391$		$CI=0.065$					$CR=0.0493$

**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
	$\lambda=3.111$		$CI=0.056$	$CR=0.001$

The table shows values for  $\lambda$  – 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

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

ment 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  $N$  can be determined by Equation (3). For example, looking at natural risk elements we obtain the following values:

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

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

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

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

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

Similarly,

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

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

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

The weight vectors are given as

$$W_{O_N} = (1, 0.899, 0.754, 0.551, 0.371, 0.208, 0.089)^T \text{ and } W_{O_A} = (1, 0.811, 0.456)^T.$$

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) priority of anthropogenic risk elements has a risk of disturbance (A1) with tors. 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 experts when comparing criteria and alternatives. to classify the watersheds of the research area into types. The model provides 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

### Summary

Natural hazards are a phenomena of natural systems stability disruption. They occur suddenly, either independently of each other or interconnected, and decreasing. Flood risk assessment represents a dynamic process that involves constant checking and any corrections of parameters of the established model. uncertainty. The fuzzy analytic hierarchy process method as a multi-criteria

correction of input parameters and fast generation of values of total risk in 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**

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przedstawiamy model rozmytego analitycznego procesu hierarchicznego (ang. FAHP)

**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 are generally underestimated. Development is never neutral in relation to catastrophes: it creates, enhances or reduces the risk of their occurrence. Selection of appropriate and characteristics of the considered system and available information and resources, is a key parameter of reliability assessment. Numerous authors applied AHP methods with assessments has gained greater importance. In this paper, we present the fuzzy analytic

FAHP is applied to data sets to illustrate a model.

**Key words:** fuzzy AHP, risk, modelling

**JEL:** B23, B29