Complex Risk Analysis of Natural Hazards through Fuzzy Logic

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Abstract—**The paper presents a fuzzy logic approach to complex risk analysis in regard to each of the natural hazards for a given monitoring region. This approach is based on the available statistical data and the expert knowledge. The calculations of the complex risk are done for five regions in SW Bulgaria (Dupnitsa, Blagoevgrad, Simitli, Kresna and Sandanski). The proposed risk analysis is envisaged to be implemented as a part of a Web information system for risk management of natural disasters.**

Index Terms—**risk analysis, fuzzy logic, natural hazards, Europe, SW Bulgaria**

I. Introduction

Recently the negative impact of natural hazards on human life, economy and environment is increased [1]. Statistic data and scientific research show a growth in number and severity of natural disasters compared to previous years [2].

The annual losses resulting from floods, hurricanes, droughts, earthquakes, tornadoes, etc. cost billions of dollars. Despite the tremendous progress in science and technology, the natural hazards considerably affect to the socioeconomic conditions of all regions of the globe.

The natural hazards are impossible to avoid, and infrastructure elements and communities cannot be made totally invulnerable. The only viable solution is the complex risk analysis and subsequent development of combination of mitigation and adaptation strategies [3].

There are many qualitative and quantitative methods for the risk analysis. However, it is necessary to point out, that the complex risk analysis from the natural hazards is done under the subjective and uncertain conditions. The fuzzy logic is an appropriate tool for risk analysis. This method provides adequate processing the expert knowledge and uncertain quantitative data [4], [5].

The purpose of the paper is to propose a fuzzy logic approach to complex risk analysis in regard to each of the natural hazard for given monitoring region. This approach is based on the available statistical data and the expert knowledge.

The proposed risk analysis is envisaged to be implemented as a part of a Web information system for risk management of natural disasters. This system can be successfully used in e-government [6].

II. An Approach to Complex Risk Analysis of Natural Hazards through Fuzzy Logic

The idea is the approach to complex risk analysis to take into account quantitative and qualitative characteristics of all natural hazards in monitoring region.

The approach is designed on basis of fuzzy logic and includes the following steps:

- *Step 1:* The basic sets and subsets for risk level of given region and severities of natural hazard are introduced and they are described in natural language:

1) Complete set of risk level of monitoring region *R* is divided into five subsets of the form:
R_1 – subset "*Very low level of regional risk*";
R_2 - subset "*Low level of regional risk*";
R_3 - subset "*Middle level of regional risk*";
R_4 - subset "*High level of regional risk*";
R_5 - subset "*Very high level of regional risk*".

2) Complete set of severity of natural hazard *H* is divided into five subsets of the form:
VS – subset "*Very small severity of natural hazard*";
S - subset "*Small severity of natural hazard*";
M - subset "*Middle severity of natural hazard*";
B - subset "*Big severity of natural hazard*";
VB - subset "*Very big severity of natural hazard*".

Here and below it is assumed that the all elements of set *R* and *D* accept values in the interval [0, 10].

- *Step 2:* The natural hazards (risk indicators) $H=\{H_i\},\ i=1,\dots,n$, which are typical for monitored regions, are determined.

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- *Step 3:* The corresponding degree of importance in the risk analysis λ_i is assigned to each natural hazard H_i. In order to appreciate this degree, it is necessary to arrange all the hazards in decreasing importance so as to satisfy the rule

$$\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_n > 0 \quad \text{and} \quad \sum_{i=1}^{n} \lambda_i = 1 \qquad (1)$$

If all indicators are equal importance, then

$$\lambda_i = \frac{1}{n}, \qquad i = 1,\ldots,n \qquad (2)$$

- *Step 4:* A classification of the current value r of the *level of regional risk* as a criterion to split the set R into fuzzy subsets is constructed (see Table I).
- *Step 5:* The membership function "*severity of natural hazard*" for each value of hazard variable H is calculated

Each hazard variable H_i, $i = 1,\ldots,n$ has a corresponding membership function μ_{ij}, $j = 1,\ldots 5$ to the five fuzzy subsets.

The membership functions μ_{ij} are defined with the following formulae:

$$\mu_{i1} = \begin{cases} 1, & 0 \leq H_i < 1.5 \\ 2.5 - H_i, & 1.5 \leq H_i < 2.5 \\ 0, & 2.5 \leq H_i \leq 10 \end{cases}$$

$$\mu_{i2} = \begin{cases} 0, & 0 \leq H_i < 1.5 \\ H_i - 1.5, & 1.5 \leq H_i < 2.5 \\ 1, & 2.5 \leq H_i < 3.5 \\ 4.5 - H_i, & 3.5 \leq H_i < 4.5 \\ 0, & 4.5 \leq H_i \leq 10 \end{cases}$$

$$\mu_{i3} = \begin{cases} 0, & 0 \leq H_i < 3.5 \\ H_i - 3.5, & 3.5 \leq H_i < 4.5 \\ 1, & 4.5 \leq H_i < 5.5 \\ 6.5 - H_i, & 5.5 \leq H_i < 6.5 \\ 0, & 6.5 \leq H_i \leq 10 \end{cases}$$

$$\mu_{i4} = \begin{cases} 0, & 0 \leq H_i < 5.5 \\ H_i - 5.5, & 5.5 \leq H_i < 6.5 \\ 1, & 6.5 \leq H_i < 7.5 \\ 8.5 - H_i, & 7.5 \leq H_i < 8.5 \\ 0, & 8.5 \leq H_i \leq 10 \end{cases}$$

$$\mu_{i5} = \begin{cases} 0, & 0 \leq H_i < 7.5 \\ H_i - 7.5, & 7.5 \leq H_i < 8.5 \\ 1, & 8.5 \leq H_i \leq 10 \end{cases} \qquad (3)$$

It are carried out the calculation of the values of the five membership functions "*severity of natural hazard*" μ^k_{ij} in regard to each of the natural hazard H_i, $i = 1,\ldots,n$ for each of the monitoring regions X_k, $k = 1,\ldots,m$.

The results are presented in tables for each of the natural hazard, as shown in Table II.

TABLE I. RISK LEVEL CLASSIFICATION OF MONITORING REGION

Risk value interval, r	Classification of the risk level, R_i	Membership function of the risk level, μ_i
$0 \leq r \leq 1.5$	R_1	1
$1.5 < r < 2.5$	R_1	$\mu_1 = 2.5 - r$
	R_2	$1 - \mu_1 = \mu_2$
$2.5 \leq r \leq 3.5$	R_2	1
$3.5 < r < 4.5$	R_2	$\mu_2 = 4.5 - r$
	R_3	$1 - \mu_2 = \mu_3$
$4.5 \leq r \leq 5.5$	R_3	1
$5.5 < r < 6.5$	R_3	$\mu_3 = 6.5 - r$
	R_4	$1 - \mu_3 = \mu_4$
$6.5 \leq r \leq 7.5$	R_4	1
$7.5 < r < 8.5$	R_4	$\mu_4 = 8.5 - r$
	R_5	$1 - \mu_4 = \mu_5$
$8.5 \leq r \leq 10$	R_5	1

- *Step 6:* The value r of the "*level of regional risk"* in regard to all the considered natural hazards for each of the monitoring regions is calculated

The value r_k of the "*level of regional risk"* in regard to all the considered natural hazards H_i, $i = 1,\ldots,n$ for each of the monitoring regions X_k, $k = 1,\ldots,m$ are determined as follows

$$r_k = \sum_{j=1}^{5} \alpha_j \sum_{i=1}^{n} \lambda_i \mu^k{}_{ij} = \sum_{j=1}^{5} \alpha_j q_j^k, \quad q_j = \sum_{i=1}^{5} \lambda_i \mu_{ij} \qquad (4)$$

A node point vector $\alpha = (\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5,)$ is introduced. In this investigation the node point vector has following elements $\alpha = (1,3,5,7,9)$.

TABLE II. MEMBERSHIP FUNCTIONS OF H_i FOR MONITORING REGIONS

No	Monitorin g region, X	Membership functions of H_i				
		VS	*S*	*M*	*B*	*VB*
1.	X_1	$\mu^1{}_{i1}$	$\mu^1{}_{i2}$	$\mu^1{}_{i3}$	$\mu^1{}_{i4}$	$\mu^1{}_{i5}$
2.	...					
3.	X_k	$\mu^k{}_{i1}$	$\mu^k{}_{i2}$	$\mu^k{}_{i3}$	$\mu^k{}_{i4}$	$\mu^k{}_{i5}$
4.	...					
5.	X_m	$\mu^m{}_{i1}$	$\mu^m{}_{i2}$	$\mu^m{}_{i3}$	$\mu^m{}_{i4}$	$\mu^m{}_{i5}$

- *Step 7:* The linguistic classification of the risk level of monitoring regions in regard to all the considered natural hazards is carried out.

The calculated value r of the variable "*level of regional risk"* is classifies on the basis of the data in Table I.

The main result of the classification is linguistic description of the risk level of monitoring region R_i in regard to all the considered natural hazards. Additional result is the degree of expert certainty in the correctness of the classification which is given by value of corresponding membership function μ_i.

Thus the conclusion about "level of regional risk" acquires not only linguistic form, but also characterization for the reliability of this assertion.

III. A Complex Risk Analysis of Natural Hazards for Different Regions in Southwestern Bulgaria

Bulgaria is located on the Balkan Peninsula, Southeastern Europe (see Fig. 1). It is exposed to natural hazards, such as earthquakes, floods, landslides, debris flows, forest fires, hail storms, rock falls, snow avalanches, storm surge, wind storms, extreme temperature.

In particular, the Southwestern (SW) part of the country is the district with the most expressed tectonic and seismotectonic activity on the whole territory of the country. Besides the seismic activity, the simultaneously influence of many endogenous and exogenous factors (recent vertical crustal movements, erosion and ground water level fluctuations) provoke the activation of gravitational processes.

Over the last century several big and destructive landslides have been observed with different degree of the landslide hazard, as part of them happened in SW Bulgaria. In this district the manifestation of active landslides and mud-rock falls can be closely connected with the contemporary tectonic activity, the erosion and the rainfalls [7].

The studied middle valley of the Struma River is characterized by a transition between the moderate-continental and continental-Mediterranean climate. Its main features are: long, hot and dry summers; mild and wet winters. The mean annual temperatures vary between 12^0C to 14^0C from north to south for the studied area [8].

The rainfalls are relatively low 500-650 mm and are unevenly distributed. They are rare, but intense with overflowing character. These rainfalls in combination with easily-disintegrated rock cause the intense erosion, mud-rock flows and floods.

High summer temperatures, which frequency over the last decade increases, are a serious danger for the population. Throughout in the flat part of the Struma valley the annual maximum temperatures reach 38-40^0C. In very hot summers of 2000, 2006, 2007 and 2009 the absolute values over 40^0C are reported, for example in Sandanski - 44.6^0C (2007). In the last decade the average maximum temperature for this town is about 40.3^0C [9].

In this Southwestern part of Bulgaria the international transport corridor № 4, connecting Western with Eastern Europe is situated (see Fig. 1). This corridor is formed from the highway I-1 /E-79/ of the national transport system and the V-th main railway line. The E79 highway, railway line and gas pipeline along the Struma River are a part of the national critical infrastructure.

In present paper, the proposed approach for complex risk analysis of natural hazards through fuzzy logic is applied to five regions in SW Bulgaria: Dupnitsa, Blagoevgrad, Simitli, Kresna, and Sandanski.

The complex risk analysis is performed in respect to the following natural hazards: Seismic, Landslides, Mud rock, Extreme temperature and Floods.

In particular according to the proposed approach is valid: X_1=Dupnitsa, X_2=Blagoevgrad, X_3=Simitli, X_4=Kresna, and X_5=Sandanski.

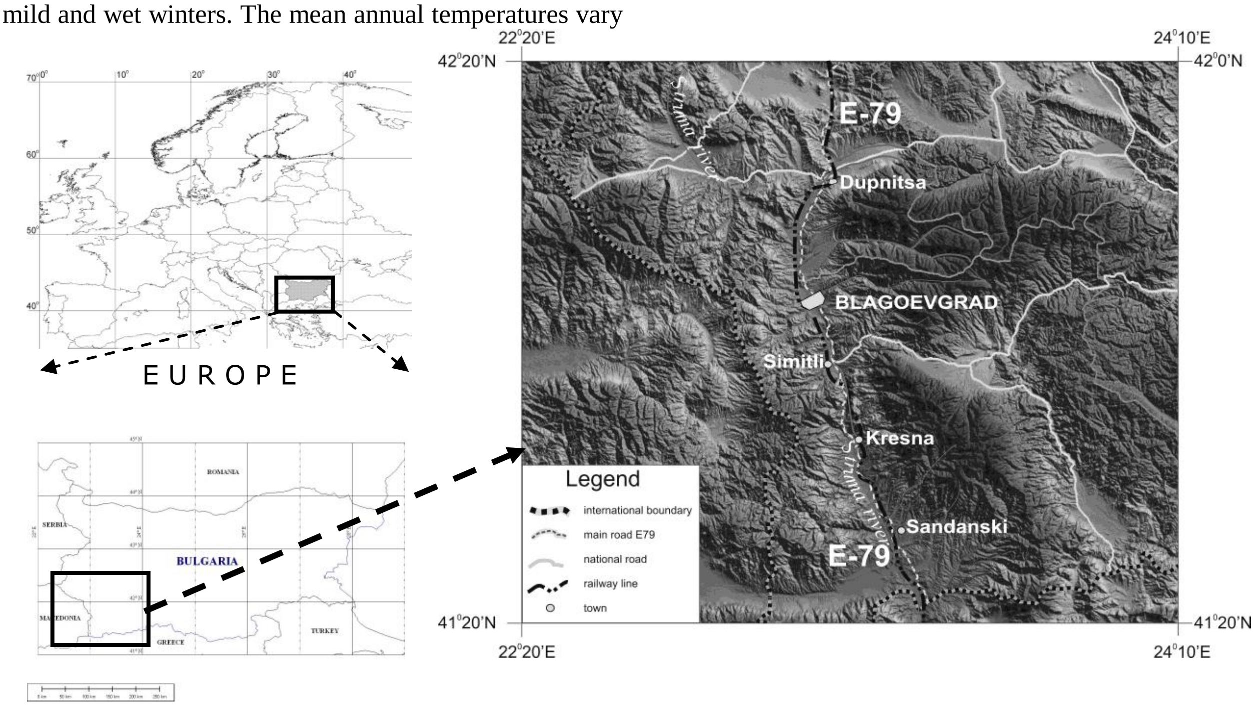

Figure 1. Location of the monitored regions.

TABLE III. NATURAL HAZARDS AND MONITORING REGIONS

No	Natural hazard, H_i	Dupnitsa	Blagoevgrad	Simitli	Kresna	Sandanski
1.	Seismic	7	6	8	10	3
2.	Landslides	8	6	9	7	6
3.	Mud rock	8	6	8	10	4
4.	Extreme temperature	3	3	4	6	10
5.	Floods	5	2	8	10	1

The regions are assessed using quantity statistical data and quality expert evaluations as given in Table III.

It is assigned to each natural hazard H_i, $i = 1,\ldots,5$ the corresponding degree of importance in the risk analysis λ_i. Here the hazards are arranged in decreasing importance as follows: Seismic > Landslides = Mud rock > Extreme temperature = Floods.

Therefore, the above assertion can be overwritten as:

$$H_1 > H_2 = H_3 > H_4 = H_5 \quad (5)$$

where H_1=Seismic, H_2=Landslides, H_3=Mud rock, H_4=Extreme temperature and H_5=Floods.

In this case the corresponding importance degrees of natural hazards in the risk analysis are assigned as follows:

$$\lambda_1 = 0.4;\ \lambda_2 = 0.2;\ \lambda_3 = 0.2;\ \lambda_4 = 0.1;\ \lambda_5 = 0.1 \quad (6)$$

The calculation of the values of the five membership functions "*severity of natural hazard*" $\mu^k{}_{ij}$ in regard to each of the natural hazard H_i, $i = 1,\ldots,5$ for each of the monitoring regions X_k, $k = 1,\ldots,5$ are carried out using the formulae (5) and condition (6). The calculated values of the membership functions are presented for each of the natural hazard H_i, $i = 1,\ldots,5$ in the corresponding tables: from Table III to Table VIII.

TABLE IV. MEMBERSHIP FUNCTIONS OF H_1 AND MONITORING REGIONS

No	Monitoring region	Membership functions of H_1				
		VS	*S*	*M*	*B*	*VB*
1.	Dupnitsa	0	0	0	1	0
2.	Blagoevgrad	0	0	0.5	0.5	0
3.	Simitli	0	0	0	0.5	0.5
4.	Kresna	0	0	0	0	1
5.	Sandanski	0	1	0	0	0

TABLE V. MEMBERSHIP FUNCTIONS OF H_2 AND MONITORING REGIONS

No	Monitoring region	Membership functions of H_2				
		VS	*S*	*M*	*B*	*VB*
1.	Dupnitsa	0	0	0	0.5	0.5
2.	Blagoevgrad	0	0	0.5	0.5	0
3.	Simitli	0	0	0	0	1
4.	Kresna	0	0	0	1	0
5.	Sandanski	0	0	0.5	0.5	0

TABLE VI. MEMBERSHIP FUNCTIONS OF H_3 AND MONITORING REGIONS

No	Monitoring region	Membership functions of H_3				
		VS	*S*	*M*	*B*	*VB*
1.	Dupnitsa	0	0	0	0.5	0.5
2.	Blagoevgrad	0	0	0.5	0.5	0
3.	Simitli	0	0	0	0.5	0.5
4.	Kresna	0	0	0	0	1
5.	Sandanski	0	0.5	0.5	0	0

TABLE VII. MEMBERSHIP FUNCTIONS OF H_4 AND MONITORING REGIONS

No	Monitoring region	Membership functions of H_4				
		VS	*S*	*M*	*B*	*VB*
1.	Dupnitsa	0	1	0	0	0
2.	Blagoevgrad	0	1	0	0	0
3.	Simitli	0	0.5	0.5	0	0
4.	Kresna	0	0	0.5	0.5	0
5.	Sandanski	0	0	0	0	1

TABLE VIII. MEMBERSHIP FUNCTIONS OF H_5 AND MONITORING REGIONS

No	Monitoring regions	Membership functions of H_5				
		VS	*S*	*M*	*B*	*VB*
1.	Dupnitsa	0	0	1	0	0
2.	Blagoevgrad	0.5	0.5	0	0	0
3.	Simitli	0	0	0	0.5	0.5
4.	Kresna	0	0	0	0	1
5.	Sandanski	1	0	0	0	0

The value r_k of the "*level of regional risk*" in regard to all the considered natural hazards H_i, $i = 1,\ldots,5$ for each of the monitoring regions X_k, $k = 1,\ldots,5$ are determined using (4) and obtained results as follows:

$$r_k = \sum_{j=1}^{5} \alpha_j \sum_{i=1}^{5} \lambda_i \mu^k{}_{ij} = \sum_{j=1}^{5} \alpha_j q_j^k, \quad k = 1,\ldots,5, \quad (7)$$

where $\alpha = (\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5,) = (1,3,5,7,9)$.

The calculated values of the membership functions of linguistic variable "*level of regional risk*", r_k $k = 1,\ldots,5$ are given in Table IX.

The main obtain result of the classification is linguistic description of the risk level of monitoring region R_i in regard to all the considered natural hazards are following:

TABLE IX. CALCULATED VALUES OF THE MEMBERSHIP FUNCTIONS OF LINGUISTIC VARIABLES

No	Monitoring area	$r_j = \sum_{i=1}^{5} \lambda_i \mu_{ij}$, j=VL, L, M, H, VH					*Level of regional risk*	*Order*	*Complex risk analysis*
		VL	*L*	*M*	*H*	*VH*			
1.	Dupnitsa	0	0.1	0.1	0.6	0.2	6.8	3	*Large*
2.	Blagoevgrad	0.05	0.15	0.4	0.4	0	5.3	4	*Medium*
3.	Simitli	0	0.05	0.05	0.35	0.55	7.8	2	*Large - Very large*
4.	Kresna	0	0	0.05	0.25	0.7	8.3	1	*Large - Very large*
5.	Sandanski	0.1	0.5	0.2	0.1	0.1	4.2	5	*Low - Medium*

- The *level of regional risk* of the region Kresna (r=8.3) is *Large* with degree of expert certainty μ_4=8.5–*8.3=0.2* and *Very large* with degree of expert certainty μ_5=1-μ_4=1-0.2=0.8;
- The *level of regional risk* of the region Simitli (r=7.8) is *Large* with degree of expert certainty μ_4=8.5–7.*8=0.7* and *Very large* with degree of expert certainty μ_5=1-μ_4=1-0.7=0.3;
- The *level of regional risk* of the region Dupnitsa (r=6.8) is *Large* with degree of expert certainty μ_4=1;
- The *level of regional risk* of the region Blagoevgrad (r=5.3) is *Medium* with degree of expert certainty μ_3=1;
- The *level of regional risk* of the region Sandanski (r=4.2) is *Low* with degree of expert certainty μ_2=4.5-4.2=0.3 and *Medium* with degree of expert certainty μ_5=1-μ_4=1-0.3=0.7.

The present results from the complex risk analysis of all natural hazards in the monitoring region are in accordance with the results obtained by the alternative fuzzy logic approach in [3].

IV. CONCLUSIONS

A fuzzy logic approach to complex risk analysis in regard to each of the natural hazard for given monitoring region is designed. This approach is based on the available statistical data and the expert knowledge. The calculations of complex risk are done for five regions in SW Bulgaria (Dupnitsa, Blagoevgrad, Simitli, Kresna and Sandanski). The proposed risk analysis is envisaged to be implemented as a part of a Web information system for risk management of natural disasters.

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