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, Similiti, 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.

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”.

  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) \( H = \{ H_i \}, \ i = 1, \ldots, n \), which are typical for monitored regions, are determined.

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].

Index Terms—risk analysis, fuzzy logic, natural hazards, Europe, SW Bulgaria
• **Step 3:** The corresponding degree of importance in the risk analysis \( \lambda_i \) 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

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

If all indicators are equal importance, then

\[
\lambda_i = \frac{1}{n}, \quad i = 1, \ldots, n \quad (2)
\]

• **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 \( \mu_{ij}, \ j = 1, \ldots, 5 \) to the five fuzzy subsets.

The membership functions \( \mu_{ij} \) are defined with the following formulae:

\[
\mu_{11} = \begin{cases} 
1, & 0 \leq H_i < 1.5 \\
2.5 - H_i, & 1.5 \leq H_i < 2.5 \\
0, & 2.5 \leq H_i \leq 10
\end{cases}
\]

\[
\mu_{12} = \begin{cases} 
1, & 0 \leq H_i < 1.5 \\
4.5 - H_i, & 1.5 \leq H_i < 2.5 \\
0, & 2.5 \leq H_i \leq 10
\end{cases}
\]

\[
\mu_{13} = \begin{cases} 
1, & 0 \leq H_i < 1.5 \\
6.5 - H_i, & 1.5 \leq H_i < 2.5 \\
0, & 2.5 \leq H_i \leq 10
\end{cases}
\]

\[
\mu_{14} = \begin{cases} 
1, & 0 \leq H_i < 1.5 \\
8.5 - H_i, & 1.5 \leq H_i < 2.5 \\
0, & 2.5 \leq H_i \leq 10
\end{cases}
\]

(3)

It is carried out the calculation of the values of the five membership functions “severity of natural hazard” \( \mu_{ij} \) in regard to each of the natural hazard \( H_i \), \( i = 1, \ldots, n \) for each of the monitoring regions \( X_i, \ k = 1, \ldots, m \).

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**

<table>
<thead>
<tr>
<th>Risk value interval, ( r )</th>
<th>Classification of the risk level, ( R_i )</th>
<th>Membership function of the risk level, ( \mu_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 \leq r \leq 1.5</td>
<td>( R_1 )</td>
<td>1</td>
</tr>
<tr>
<td>1.5 \leq r &lt; 2.5</td>
<td>( R_2 )</td>
<td>( \mu_2 = 2.5 - r )</td>
</tr>
<tr>
<td>2.5 \leq r &lt; 3.5</td>
<td>( R_3 )</td>
<td>1</td>
</tr>
<tr>
<td>3.5 \leq r &lt; 4.5</td>
<td>( R_4 )</td>
<td>( \mu_4 = 4.5 - r )</td>
</tr>
<tr>
<td>4.5 \leq r \leq 5.5</td>
<td>( R_5 )</td>
<td>1</td>
</tr>
<tr>
<td>5.5 \leq r &lt; 6.5</td>
<td>( R_6 )</td>
<td>( \mu_6 = 6.5 - r )</td>
</tr>
<tr>
<td>6.5 \leq r \leq 7.5</td>
<td>( R_7 )</td>
<td>1</td>
</tr>
<tr>
<td>7.5 \leq r &lt; 8.5</td>
<td>( R_8 )</td>
<td>( \mu_8 = 8.5 - r )</td>
</tr>
<tr>
<td>8.5 \leq r \leq 10</td>
<td>( R_9 )</td>
<td>1</td>
</tr>
</tbody>
</table>

• **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

\[
r_k = \sum_{j=1}^{5} \alpha_j \sum_{i=1}^{n} \lambda_i \mu_{ij} = \sum_{j=1}^{5} \alpha_j q_j \quad \text{with} \quad q_j = \sum_{i=1}^{n} \lambda_i \mu_{ij} \quad (4)
\]

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**

<table>
<thead>
<tr>
<th>No</th>
<th>Monitor region, ( X )</th>
<th>Membership functions of ( H_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>( X_1 )</td>
<td>( \mu_1^{10}, \mu_1^{12}, \mu_1^{15}, \mu_1^{18}, \mu_1^{20} )</td>
</tr>
<tr>
<td>2.</td>
<td></td>
<td>( \mu_2^{10}, \mu_2^{12}, \mu_2^{15}, \mu_2^{18}, \mu_2^{20} )</td>
</tr>
<tr>
<td>3.</td>
<td>( X_3 )</td>
<td>( \mu_3^{10}, \mu_3^{12}, \mu_3^{15}, \mu_3^{18}, \mu_3^{20} )</td>
</tr>
<tr>
<td>4.</td>
<td></td>
<td>( \mu_4^{10}, \mu_4^{12}, \mu_4^{15}, \mu_4^{18}, \mu_4^{20} )</td>
</tr>
<tr>
<td>5.</td>
<td>( X_m )</td>
<td>( \mu_m^{10}, \mu_m^{12}, \mu_m^{15}, \mu_m^{18}, \mu_m^{20} )</td>
</tr>
</tbody>
</table>

• **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 classified 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 $\mu_i$.

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°C to 14°C 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°C. In very hot summers of 2000, 2006, 2007 and 2009 the absolute values over 40°C are reported, for example in Sandanski - 44.6°C (2007). In the last decade the average maximum temperature for this town is about 40.3°C [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.
The regions are assessed using quantity statistical data and quality expert evaluations as given in Table III. It is assigned to each natural hazard \( H_i, i = 1,...,5 \) the corresponding degree of importance in the risk analysis \( \lambda_i \). Here the hazards are arranged in decreasing importance as follows: Seismic > Landslides = Mud rock > Extreme temperature = Floods. The calculation of the values of the five membership functions are presented for each of the monitoring regions \( X_i \), \( i = 1,...,5 \) in regard to each of the natural hazard \( H_i, i = 1,...,5 \) and obtained results as follows: Seismic, Landslides, Mud rock, Extreme temperature, Floods.

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 \( H_i, i = 1,...,5 \) for each of the monitoring regions \( X_i \), \( k = 1,...,5 \) 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 \( H_i, i = 1,...,5 \) in the corresponding tables: from Table III to Table VIII.

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

\[
r_k = \sum_{j=1}^{5} \lambda_j \mu^k_{ij} = \sum_{j=1}^{5} \alpha_j \rho^k_j, \quad k = 1,...,5, \quad (7)
\]

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”, \( r_k k = 1,...,5 \) 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>
<thead>
<tr>
<th>No</th>
<th>Monitoring area</th>
<th>$r_j \equiv \sum_{i=1}^{j} \alpha_{ij}\mu_{ij}$; $j=VL, L, M, H, VH$</th>
<th>Level of regional risk</th>
<th>Order</th>
<th>Complex risk analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Dupnitsa</td>
<td>0.1 0.1 0.6 0.2</td>
<td>6.8 3</td>
<td>Large</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Blagoevgrad</td>
<td>0.05 0.15 0.4 0</td>
<td>5.3 4</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Simitli</td>
<td>0 0.05 0.35 0.55</td>
<td>7.8 2</td>
<td>Large - Very large</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Kresna</td>
<td>0 0 0.25 0.7</td>
<td>8.3 1</td>
<td>Large - Very large</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Sandanski</td>
<td>0.1 0.5 0.2 0.1</td>
<td>4.2 5</td>
<td>Low - Medium</td>
<td></td>
</tr>
</tbody>
</table>

- The level of regional risk of the region Kresna ($r=8.3$) is Large with degree of expert certainty $\mu=8.5-8.3=0.2$ and Very large with degree of expert certainty $\mu=1-\mu=1-0.2=0.8$;
- The level of regional risk of the region Simitli ($r=7.8$) is Large with degree of expert certainty $\mu=8.5-7.8=0.7$ and Very large with degree of expert certainty $\mu=1-\mu=1-0.7=0.3$;
- The level of regional risk of the region Dupnitsa ($r=6.8$) is Large with degree of expert certainty $\mu=1$;
- The level of regional risk of the region Blagoevgrad ($r=5.3$) is Medium with degree of expert certainty $\mu=1$;
- The level of regional risk of the region Sandanski ($r=4.2$) is Low with degree of expert certainty $\mu=4.5-4.2=0.3$ and Medium with degree of expert certainty $\mu=1-\mu=1-0.3=0.7$.

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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REFERENCES

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