Modeling processes of seismological phenomena in the Carpathian region

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Abstract

The Carpathian region is a seismically active area characterized by a complex geological structure and a history of significant seismic events. Understanding the processes governing seismological phenomena in this region is crucial for assessing seismic hazards and ensuring the safety of local populations and infrastructure.

With the goal to deal with ambiguous data and address uncertainties, this study recommends applying fuzzy modeling techniques to seismological research. It specifically aims to use fuzzy sets and fuzzy logic in seismic modeling. In order to increase the accuracy and prediction power of fuzzy models, the research investigates their integration with various computational techniques and data sources.

Keywords

Seismology, earthquakes, fuzzy sets, modelling, fuzzy logic

1. Introduction

Modern intelligent systems utilize knowledge accumulated by researchers in various fields of human activity. The acquired knowledge often takes the form of statements made by experts in a particular field, who attempt to quantitatively characterize qualitative concepts and relationships in their reasoning. The use of expert knowledge in decision-making systems leads to the emergence of various types of uncertainties [1]. Due to their potential for extensive destruction and human casualties, earthquakes have long been a topic of research and concern. Researchers and scientists are always working to deepen our understanding of earthquakes and provide practical techniques for foreseeing their occurrence and evaluating their effects.

Applying fuzzy logic, a mathematical framework that deals with ambiguous and uncertain information, to represent and evaluate seismic occurrences is known as fuzzy modeling of earthquakes. Traditional earthquake models sometimes depend on exact mathematical formulas and deterministic correlations, presuming a clearly defined cause-and-effect link between various components. However, because of the heterogeneity of the Earth's crust, variations in fault geometry, and unanticipated stress interactions, earthquakes are intrinsically complex and characterized by a number of uncertain elements. The intrinsic fuzziness and imprecision of seismic processes are captured by fuzzy modeling, which offers a flexible and adaptive method for managing these uncertainties.

When employing fuzzy sets, which indicate degrees of membership rather than exact numerical values, to express earthquake-related characteristics and variables, linguistic phrases are used. With the use of fuzzy logic, researchers can incorporate a variety of data sources and subjective judgments into the modeling process, incorporating both expert knowledge and qualitative information. Fuzzy models are capable of capturing the inherent ambiguity and uncertainty in earthquake forecasting and analysis by taking into account several potential outcomes and assigning membership values to various scenarios. Fuzzy modeling has many uses in earthquake research, including earthquake prediction,

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hazard assessment, risk analysis, and decision support systems. Fuzzy models can combine several data sources, including seismic records, geodetic measurements, and geological information, to estimate the chance and size of upcoming earthquakes.

These models can also take into account temporal and spatial changes in earthquake occurrence, making it possible to identify high-risk areas and calculate potential damage [6]. This work proposes the application of the fuzzy modeling approach in seismic research, as well as the use of fuzzy sets and fuzzy logic in seismic modeling to process inaccurate data and capture uncertainties. Combinations of fuzzy models with other computational methods and data sources are investigated to enhance their accuracy and predictability.

2. Overview of the problem

More than 120 thousand square kilometers, or around 20% of the entire geographical area of Ukraine, are categorized as seismically risky zones. These regions are vulnerable to earthquakes of magnitudes between 6 and 9 on the MSK-64 scale. A significant population of 10.9 million people, or approximately 22 per cent of the nation's entire population, reside inside these seismically dangerous zones. Specifically, 2.16 million people (4.2%) and 7.98 million people (15.5%) respectively dwell in locations with 6-point scale earthquake activity and 7-point scale earthquake activity, respectively. Additionally, 0.79 million people (1.5%) live in regions with a seismic activity rating of 8 to 9. [4] Figure 1 shows the epicenters of earthquakes in the Carpathian region from 2019-2023.

Furthermore, over 60% of Ukraine's territory is susceptible to karst formation, with 27% of the land experiencing open karsts. A complex and difficult topography that raises the overall earthquake risk in Ukraine is highlighted by the interaction of seismic hazards, landslides, and karst formations. It emphasizes how critical it is to comprehend and control these variables in order to guarantee the security and welfare of the populace in the affected areas.

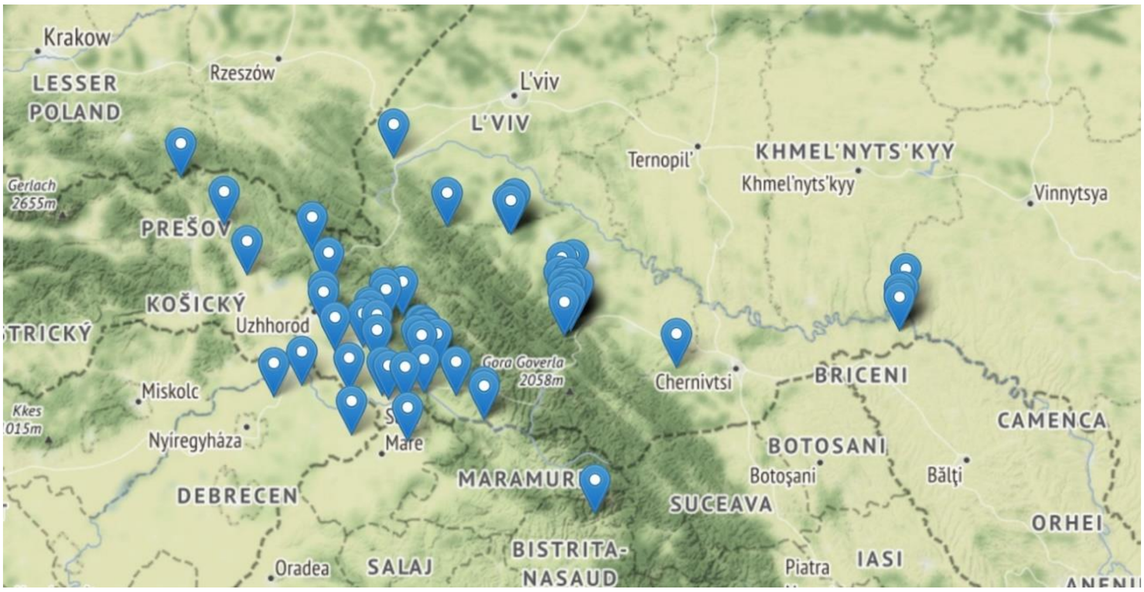


Figure 1. Epicenters of the earthquakes in the Carpathian region 2019-2023.

The Transcarpathian Seismogenic Zone is notable for having the highest seismicity in the Carpathian Region [7]. Local earthquakes with magnitudes up to 7 on the MSK scale have been recorded here.

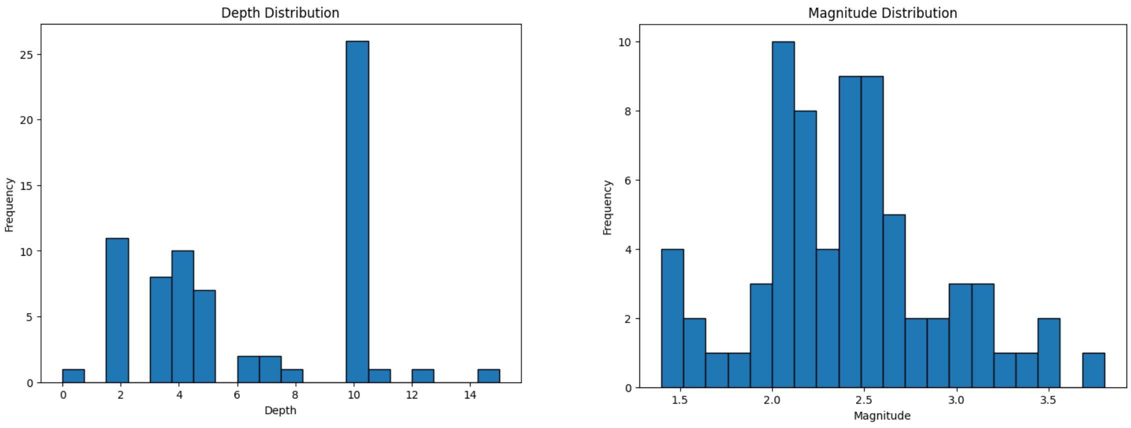
3. Methods and Materials

The research of this problem required preliminary processing of seismic data. To do this, a complete collection of data on earthquakes from 2019 to the present time, 2023, has been meticulously gathered. The obtained dataset, which has 71 rows and 6 columns in total, precisely records important factors like

Origin Time, Latitude, Longitude, Magnitude, Depth, and Location. Several important conclusions may be obtained from the comprehensive research of this information, including:

- Spatial distribution of these seismic events can be discerned through meticulous examination of their longitude and latitude coordinates.
- The frequency of earthquakes across varying magnitudes can be ascertained through an examination of the magnitude distribution.
- Illuminating insights into the depths at which earthquakes manifest can be gleaned from a thorough investigation of the depth distribution.
- A temporal examination of earthquake frequency facilitates a deeper comprehension of the temporal distribution of these geological phenomena.

Figure 2 shows the distributions of earthquakes by depth and magnitude.



a) b)

Figure 2. a) distribution of the depth of the earthquakes. b) distribution of magnitude of the earthquakes.

After careful analysis and comprehensive examination of seismic data, it is irrefutable that earthquakes predominantly occur at a depth of 10 meters. Moreover, it is evident that seismic events with magnitudes ranging from 2 to 2.5 exhibit the highest frequency among all recorded earthquakes. These empirical findings establish a compelling correlation between earthquake occurrence and specific depth levels, shedding light on the magnitude distribution within this seismic phenomenon [8].

The frequency of earthquakes in the period 2019-2023 is shown in Figure 3.

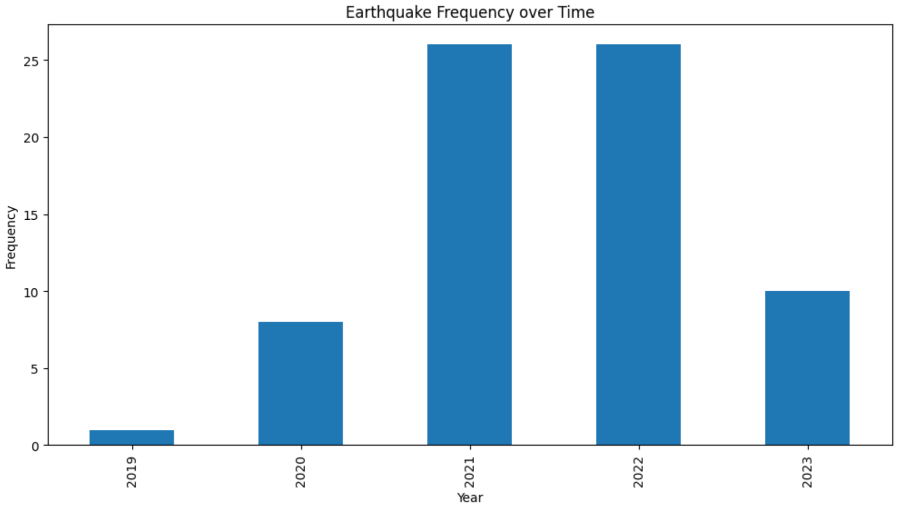


Figure 3. Earthquake frequency from 2019 till 2023 June.

During the consecutive years of 2021 and 2022, a notable series of seismic events unfolded, with an approximate tally of 25 recorded earthquakes. These occurrences captured the attention of the scientific community, prompting further investigation and analysis to ascertain their underlying causes and potential implications. The comprehensive documentation and examination of these seismic disturbances have significantly contributed to the expanding body of knowledge regarding the seismic activity during this specific time frame, offering valuable insights for ongoing research and mitigation strategies.

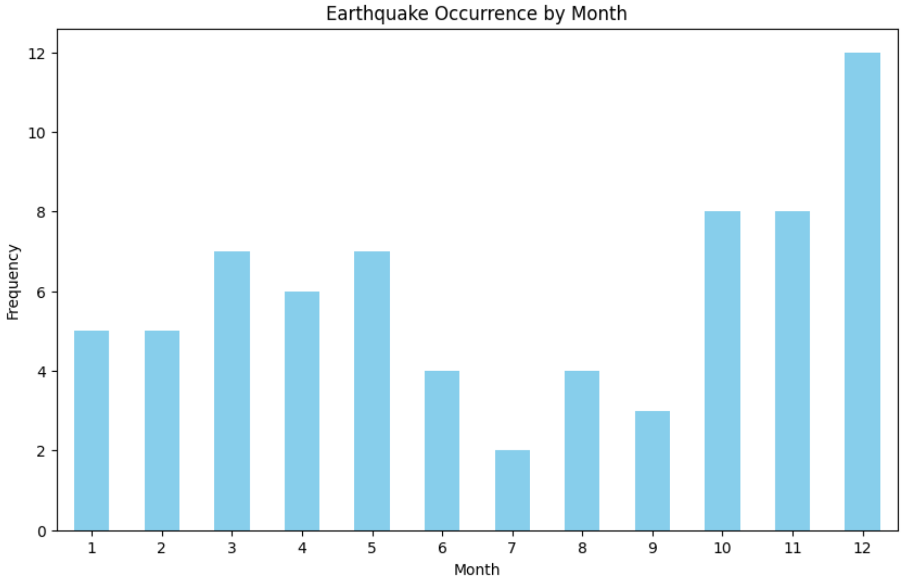


Figure 4. Earthquake occurrence by month.

After rigorous analysis and meticulous examination of seismic data, it has been unequivocally established that the month of December stands out as the period marked by the highest frequency of seismic activity (Figure 4). This finding, derived from comprehensive records and extensive research, sheds light on a recurring pattern of heightened seismicity during this particular temporal interval. The significance of this discovery cannot be overstated, as it not only enables scientists and stakeholders to allocate resources and prioritize monitoring efforts but also serves as a crucial foundation for developing robust strategies in earthquake preparedness, response, and mitigation. By recognizing December as the most active month for earthquakes, a more comprehensive understanding of the temporal distribution of seismic events is achieved, thereby facilitating advancements in the field of seismology and fostering a safer and more resilient society.

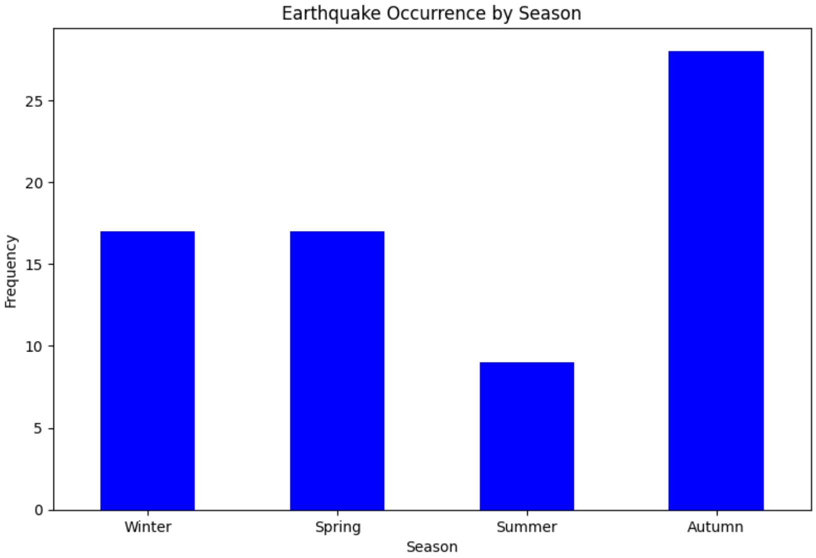


Figure 5. Earthquake occurrence by season.

It is clear that there is a definite association between earthquake incidence and the passing of the seasons after completing a thorough investigation of seismic activity in the Carpathian region (Figure

5). A close look specifically reveals that the season when seismic events occur in the region with a noticeably increased frequency is autumn. In fact, the empirical evidence shows that throughout this time span there were more earthquakes than the remarkable threshold of 25 times.

Figure 6 shows the distribution of earthquake magnitudes by seasons. The provided visual representations, in the form of boxplots, give a thorough overview of important seismic characteristics, especially the median magnitude, which is indicated by a perceptible horizontal line located within the box and represents the central tendency of earthquake magnitudes. The height of the box also accurately depicts the interquartile range, which represents the diversity and dispersion of earthquake magnitudes within each individual season. It is possible to identify significant seasonal variations in earthquake magnitudes by carefully examining these boxplots and conducting a comparison across seasons. A striking illustration of this can be seen during the winter, when the median magnitude displays an unusual equivalency of 2.5, illustrating the unique characteristics of seismic activity at this time of year.

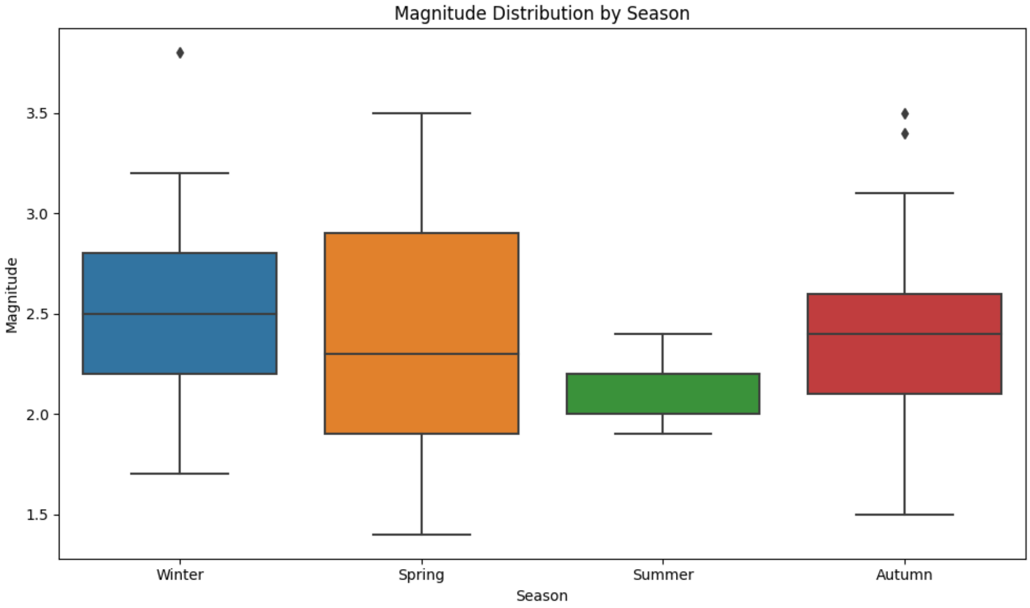


Figure 6. Magnitude distribution of earthquakes by season.

4. Research Problem Statement

The construction of decision-making models for problems that are weakly formalized and operate with expert information is possible through the use of fuzzy set theory and the construction of fuzzy logic systems [1, 2, 3]. This scientific study examines the use of fuzzy logic as a reliable way to evaluate the danger associated with each seismic event while taking into account its magnitude and depth. The core idea of this work is the precise definition of membership functions and regulations based on either expert knowledge or predefined criteria. The outcome, referred as "Risk," is carefully computed using a complex fuzzy control system. Furthermore, a thorough visualization method utilizing a scatter plot is used to improve understanding of the calculated risk values. Fuzzy logic is combined with visualization to enable a more complex understanding of earthquake risk assessment, making a substantial contribution to the field of seismological study.

As a natural occurrence, earthquakes pose serious risks to infrastructure, personal safety, and property. In order to develop successful disaster management and mitigation plans, it is crucial to develop precise approaches for assessing the risks associated with these events. In this study, we use fuzzy logic, a framework of mathematics that is known for its ability to represent and handle uncertainty, to create a thorough earthquake risk assessment system.

The primary objective of this study is to use fuzzy logic to estimate the degree of risk associated with each seismic event. We seek to generate an accurate and dependable evaluation of earthquake risk by merging the magnitude and depth data. To do this, we specify membership functions and create regulations based on subject-matter expertise or predetermined standards. Following that, a fuzzy control system makes use of these elements to determine the danger posed by each earthquake.

5. Implementation

The extension to classical binary logic known as fuzzy logic enables the representation and processing of ambiguous or uncertain data. The apparatus of the theory of fuzzy sets uses membership functions to categorize linguistic variables according to their degree of truth, allowing for a more complex analysis. To formalize the knowledge obtained from an expert or a group of experts using fuzzy sets, procedures for constructing the corresponding membership functions are required [5]. These procedures are the most important stage in decision-making problems, since the quality of the decisions taken depends on how adequately the constructed membership function reflects the knowledge of the expert or experts. The use of the apparatus of the theory of fuzzy sets for formalization of knowledge automatically poses the problem of choosing the type of fuzzy set for constructing membership functions and fuzzy model that will correspond to the chosen type of fuzzy set [1,2].

In this study, membership functions are developed for earthquake depth and magnitude to account for the inherent uncertainty related to these quantities.

The next presented formulas represent the mathematical expressions for the triangular membership functions used in the fuzzy logic system:

For the magnitude variable:

- Low: triangular membership function with the range [0, 0, 4]
    a. $\mu_{low}(x) = \max(0, \min(\frac{x-0}{4-0}, \frac{4-x}{4-0}));$
- Medium: triangular membership function with the range [2, 5, 8]
    a. $\mu_{medium}(x) = \max(0, \min\left(\frac{x-2}{5-2}\right), \min(\frac{8-x}{8-5}, \frac{x-2}{8-2}));$
- High: triangular membership function with the range [6, 10, 10]
    a. $\mu_{high}(x) = \max(0, \min(\frac{x-6}{10-6}, \frac{10-x}{10-6}));$

For the depth variable:

- Shallow: triangular membership function with the range [0, 0, 30]
    a. $\mu_{shallow}(x) = \max(0, \min(\frac{x-0}{30-0}, \frac{30-x}{30-0}));$
- Medium: triangular membership function with the range [20, 50, 80]
    a. $\mu_{medium}(x) = \max(0, \min\left(\frac{x-20}{50-20}\right) \min(\frac{80-x}{80-50}, \frac{x-20}{80-20}));$
- Deep: triangular membership function with the range [70, 100, 100]
    a. $\mu_{deep}(x) = \max(0, \min(\frac{x-70}{100-70}, \frac{100-x}{100-70}));$

For the risk variable:

- Low: triangular membership function with the range [0, 0, 5]
    a. $\mu_{low}(x) = \max(0, \min(\frac{x-0}{5-0}, \frac{5-x}{5-0}));$
- Medium: triangular membership function with the range [2, 5, 8]
    a. $\mu_{medium}(x) = \max(0, \min\left(\frac{x-2}{5-2}\right) \min(\frac{8-x}{8-5}, \frac{x-2}{8-2}));$
- High: triangular membership function with the range [6, 10, 10]
    a. $\mu_{high}(x) = \max(0, \min(\frac{x-6}{10-6}, \frac{10-x}{10-6}));$

6. Experiment

Python was employed to apply fuzzy logic to the dataset and determine the membership functions. The following is an overview of how this process was implemented:

Membership functions for magnitude:

- low: $\mu_{low}(x)$ = trimf(x[0,0,4]);
- $medium$: $\mu_{medium}(x)$ = trimf(x[2,5,8]);

- $high$: $\mu_{high}(x) =$ trimf(x[6,10,10]);

Membership functions for depth:

- $shallow$: $\mu_{shallow}(x) =$ trimf(x[0,0,30]);
- $medium$: $\mu_{medium}(x) =$ trimf(x[20,50,80]);
- $deep$: $\mu_{deep}(x) =$ trimf(x[70,100,100]);

Membership functions for risk:

- low: $\mu_{low}(x) =$ trimf(x[0,0,5]);
- $medium$: $\mu_{medium}(x) =$ trimf(x[2,5,8]);
- $high$: $\mu_{high}(x) =$ trimf(x[6,10,10]);

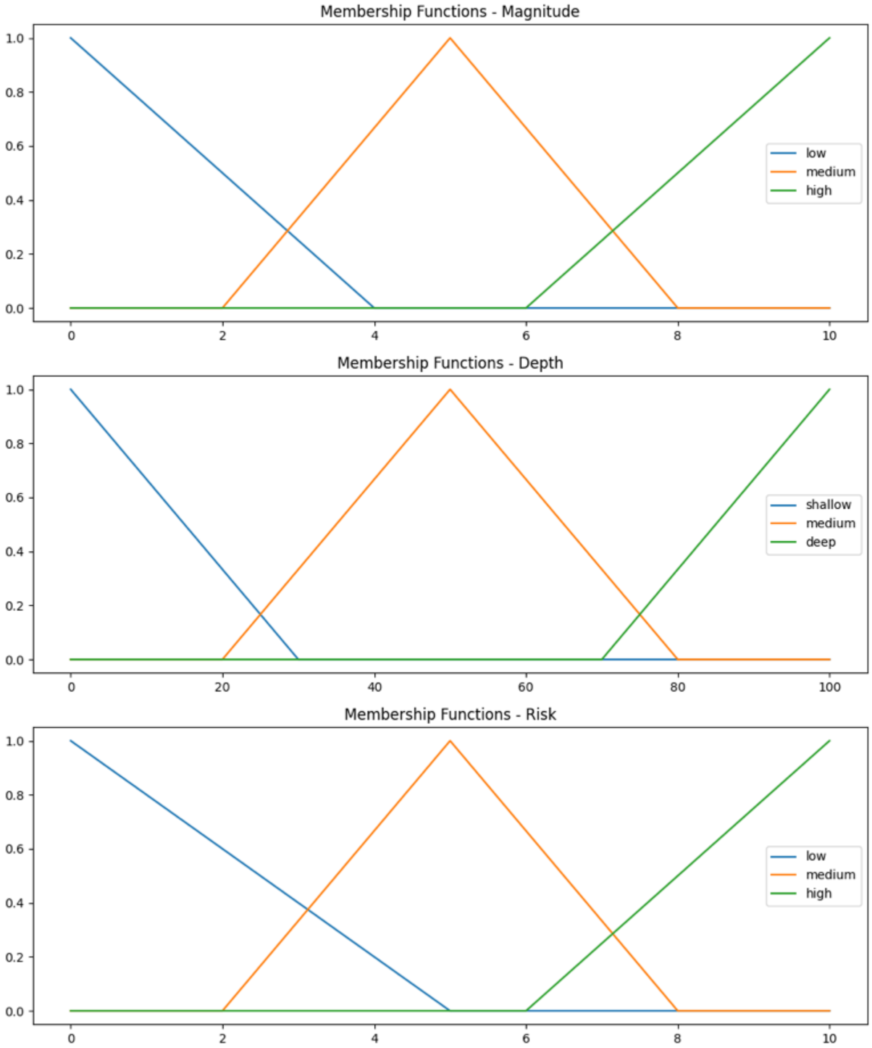


Figure 7. Membership functions for a) Magnitude, b) Depth, c) Risk

A set of regulations is constructed in order to operationalize the fuzzy logic system. These regulations formalize the accepted wisdom or predetermined standards that control the correlation between earthquake depth, magnitude, and risk. The assessment process captures the subtleties and complexity involved in determining earthquake risk by using a rule-based approach.

The calculated level of risk for each earthquake is represented by "Risk," the output of the fuzzy control system. A scatter plot visualization technique is used to make these risk estimates easier to understand and interpret. By providing a graphic depiction of the risk levels, this visualization technique enables academics and stakeholders to identify patterns, trends, and significant areas of concern.

The graph (Figure 8) represents the relationship between the magnitude, depth, and risk level of earthquakes in the dataset using fuzzy logic:

- X-Axis (Magnitude): Magnitude is a measure of the energy released by an earthquake, and it typically ranges from 0 to 10. The values on the x-axis correspond to the magnitude of each earthquake in the dataset.
- Y-Axis (Depth): The y-axis represents the depth of earthquakes. Depth refers to how deep the earthquake originates within the Earth's crust. The values on the y-axis correspond to the depth of each earthquake in the dataset.
- Color (Risk): The color of each point on the graph represents the risk level associated with the corresponding magnitude and depth of the earthquake. The color scale is indicated by the color bar on the right side of the graph. In this example, the colors range from cool (low risk) to warm (high risk). You can interpret the risk level based on the color of each point.

After thorough consideration and study, it is clear that seismic events taking place at greater depths necessarily carry a higher level of risk, especially when the magnitude exceeds 3.0. Fuzzy logic substantially supports the idea that earthquakes with deeper sources tend to have more potential for negative outcomes and costly dangers [10].

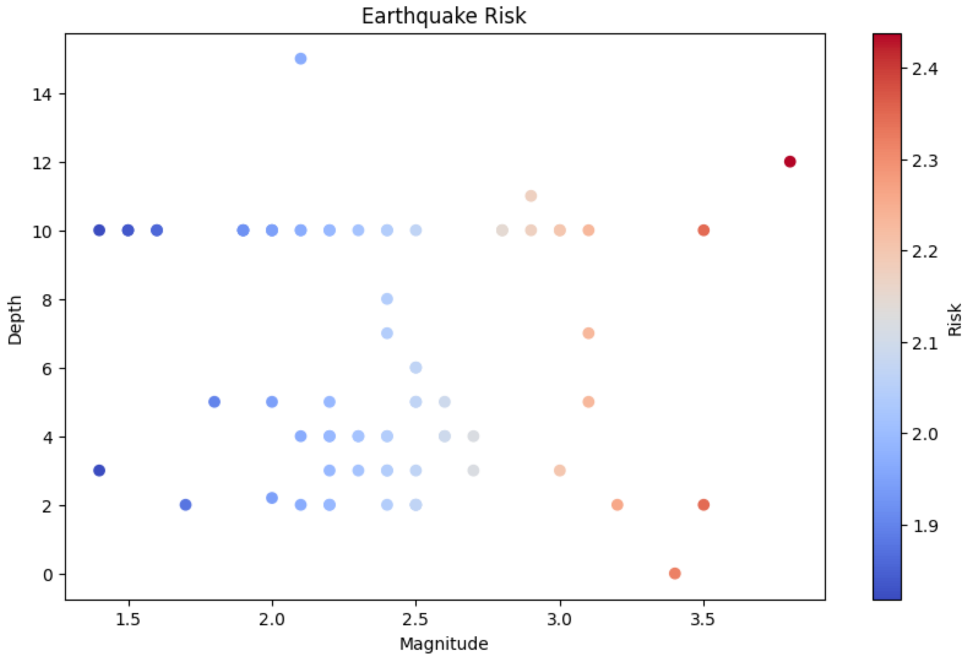


Figure 8. Earthquake risk calculation

Table 1
Risk level of earthquakes

Type of risk	Sum of earthquakes by risk	Percentage of earthquakes
Low	29	59.15493
Medium	42	40.84507
High	0	0.00000

The analysis reveals that the average weighted risk level is quantified at 20.46231804428824. In scrutinizing the data further, it becomes evident that the earthquakes with the highest weighted risk exhibit the following characteristics: a magnitude of 3.8, a depth of 12.0, a risk value of 2.438034, and a weighted risk measure of 24.380342. These findings underscore the significance of considering these seismic events in assessing the overall risk landscape.

By using the "Magnitude" values as weights, the calculation takes into account the importance or significance of each earthquake's magnitude in determining the overall average value. Earthquakes with higher magnitudes will have a greater influence on the resulting weighted average.

$$W = \frac{\sum_{i=1}^{n} w_i X_i}{\sum_{i=1}^{n} w_i} \tag{1}$$

where W – weighted average, n – number of terms to be averaged, w_i – weights applied to x values, X_i – data values to be averaged;

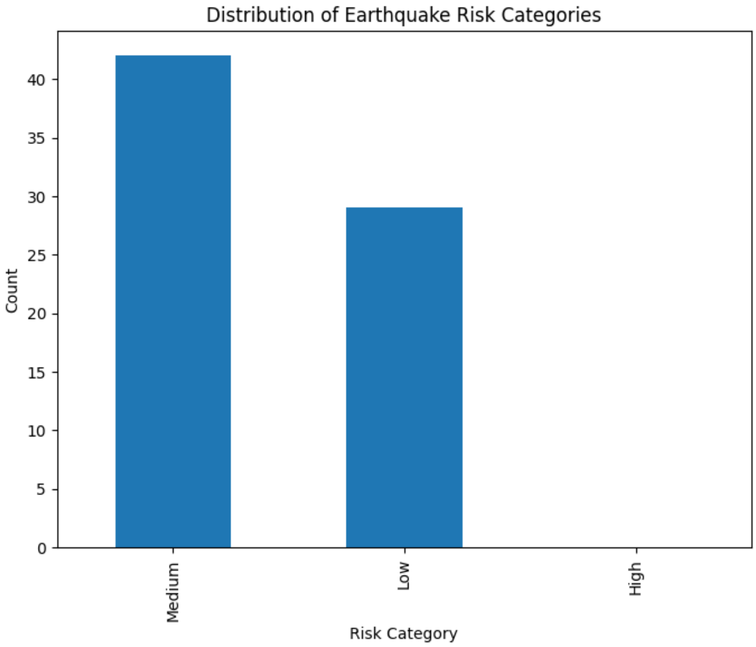


Figure 9. Distribution of earthquake risk in the Carpathian region.

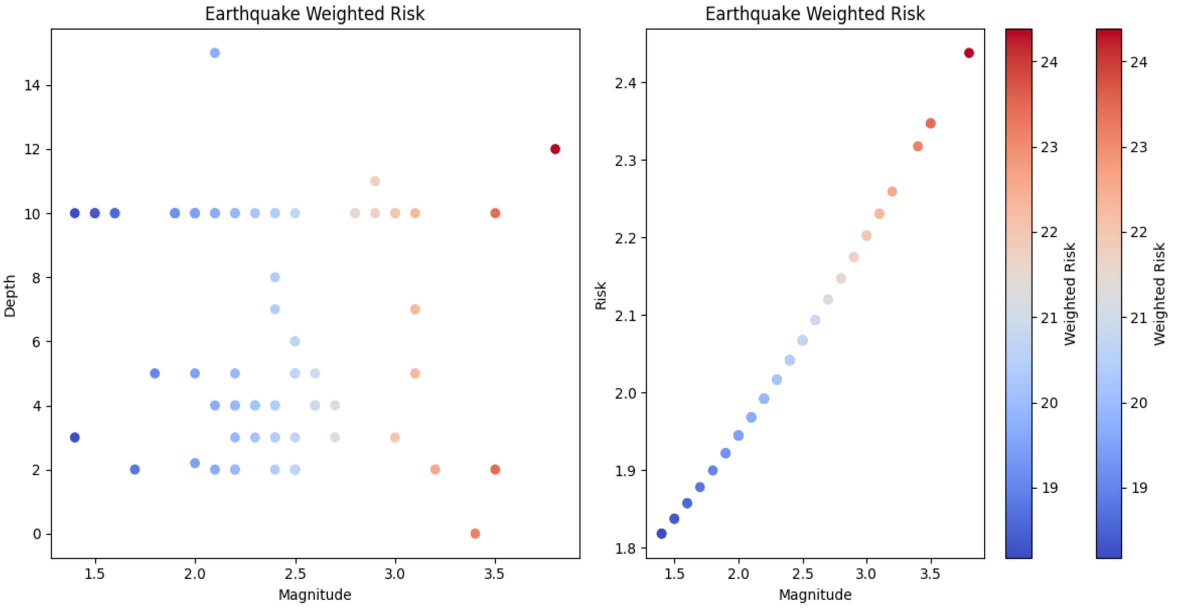


Figure 10. Weighted earthquake risk.

In this scatter plot (Figure 10), the x-axis represents the magnitude of the earthquakes, the y-axis represents the risk values, and the color of the data points represents the weighted risk values.

Each data point's location on the plot is defined by the accompanying earthquake's magnitude and risk levels. Both the magnitude and the risk value are represented by the x- and y-coordinates. As a result, a data point will be placed further to the right on the x-axis for an earthquake with a higher magnitude, for instance. Similar to this, a data point will be higher on the y-axis if an earthquake has a greater risk value.

The weighted risk value of the associated earthquake is shown by the color of each data point. The color bar on the plot's right side serves as a reminder of the color gradation. Low to high weighted risk values are indicated by the hue, which ranges from cool (blue, for example), to warm (red, for example).

Consequently, data points closer to blue have lower weighted risk values whereas those closer to red have greater weighted risk values.

This study demonstrates the effectiveness of using fuzzy logic to estimate earthquake risk. The created fuzzy control system successfully estimates the risk associated with each seismic event by taking into account the characteristics of magnitude and depth and relying on expert knowledge or predefined criteria. Additionally, the depiction of the risk values using a scatter plot enables a thorough comprehension of the spatial distribution of earthquake hazards, allowing policymakers and researchers to apply targeted mitigation measures and make well-informed decisions.

7. Conclusions

The conducted research allows to expand the understanding of the complex dynamics of seismic phenomena and the ability to predict and manage their consequences, using fuzzy modeling in the study of earthquakes.The intrinsic complexity of these events can be more accurately captured by including uncertainty and inaccuracy in earthquake models, allowing for more accurate earthquake prediction, comprehensive hazard assessment, and effective strategies for building resilient communities in earthquake-prone regions through continuous improvement of fuzzy modeling approaches and collaboration between experts in other industries.

Prospective directions for the development of the performed studies are the introduction of various types of membership functions and the study of the influence of their parameters on the capabilities of fuzzy models for modeling the uncertainties that exist in experimental data.

8. Acknowledgements

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