ENHANCING SEISMIC ANALYSIS: A FUSION OF SMART VISUALIZATION AND CORRELATION TECHNIQUES

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In recent years, there has been a growing interest in examining the significance of radon concentration measurements in the field of earth sciences. Radon emissions, heightened by impending geophysical events like earthquakes, have been observed in specific areas around the globe. This study proposes a specific approach for analyzing and clarifying a pertinent correlation among radon concentrations, environmental factors, and seismic activity in Romania, by integrating correlation analysis techniques with smart visualization tools, aiming to enhance the interpretation and communication of relevant scientific findings. The findings of this study highlight both linear positive and negative moderate correlations between radon concentrations and various environmental factors. It also reveals only weak correlations between seismic activity and radon concentrations across different monitoring stations. It sheds lights on the peculiarities of some seismic areas in Romania and open avenues for further thoroughly investigations with smart visualization, advanced analytics techniques, and structural equation modeling.

Keywords: earthquake, radon, correlation analysis, smart visualization, advanced analytics

1. Introduction

Smart visualization techniques involves employing advanced visualizations [1] and interactive tools to understand seismic activity and its possible impact. Smart visualization approaches enable scientists and stakeholders to develop dynamic simulations [2] by integrating multiple data sources such as geological surveys [3], historical seismic records [4], and predictive models [5]. These models offer a comprehensive look at fault lines, stress distribution, and potential seismic occurrences.

Various earthquake-related studies have focused on **radon** [6], a naturally occurring radioactive gas, because of its possible relationship to seismic activity [7], [8]. Recent research [6] revealed that the radon series and the daily seismic

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activity rate have an *almost linear relationship* that sheds light on how the seismic activity in the study region behaves using simply the radon data. The development of radon-based monitoring is evaluated in [9], where anomalous radon variations discovered in soils and groundwater are discussed.

In [10] the detection of radon anomalies caused by earthquakes using machine learning techniques is approached, specifically for the classification of groundwater radon anomalies and their potential formation mechanisms, the effects of soil and rock structures on radon migration, and the effects of the environment on radon concentrations. Other research [11] explores the potential application of radon monitoring as a method to examine post-seismic crustal deformation following significant earthquakes at a regional level, alongside seismic precursors. Moreover, correlations have been identified between radon anomalies and earthquake occurrences in the soil of a site within the seismo-volcanic region of Phlegrean Fields (Naples, Italy) [12].

Within the scope of this work, it is intended to explore whether correlation analysis, improved with specific smart visualization techniques, may become an essential analysis component in facilitating the discovery of complex relationships and dependencies in seismic data, and with other environmental variables, focusing on radon data.

In this regard, this paper poses two research questions (RQs) to be explored using earthquake-related data from two seismic regions in Romania, Vrancea and Oltenia, aiming to elucidate pertinent radon and earthquake behaviors unique to each region:

- RQ1: Is there any correlation between radon concentrations and certain environmental variables?
- RQ2: Is there any correlation between radon concentrations and seismic events (earthquakes)?

The research methodology is presented in Section 2, the results are presented in Section 3, and the paper is concluded with a discussion and conclusion in Section 4 that highlights the contributions' significance and offers recommendations for future research.

2. **Research methodology**

Within the scope of this paper, an advanced analytics-based investigation of the relationship between radon concentrations, earthquake activity, and environmental variables is proposed. The proposed working methodology employs the following steps: a) collection of data related to environmental variables, such as temperature, relative humidity, and atmospheric pressure, as well as radon gas measurements; b) identification and extraction of the corresponding earthquake datasets; c) interrogate reliability of data and verification of accuracy; metadata review; d) discover meaning in data by identifying patterns in the dataset (exploratory data analysis); e) identify patterns in relationships between variables.

2.1. Data collection

2.1.1. *Environmental data collection.* This research uses data extracted from official national radon measurements in Romania, available at NIEP (National Institute for Earth Physics) [13], [14]. The data were collected from the radon monitoring network [14] in Romania, from various radon stations (Table 1), between January 01, 2023 and November 17, 2023. The radon and environmental variables dataset contains the following parameters: datetime (UTC), radon concentration (Bq/m^3), temperature (°C), relative humidity (%), atmospheric pressure (mbar).

TABLE 1. Radon monitoring stations from NIEP.

Rn station code	Location	County	Frequency in the dataset (%)
SAHRdd	Sahastru	Vrancea	18405 (15.8%)
DLMdd	Dâlma	Buzău	18975 (16.3%)
RMGVdd	Râmnicu Vâlcea	Vâlcea	19499 (16.7%)
PANCdd	Panciu	Vrancea	19592 (16.8%)
LOPRdd	Lopătari	Buzău	19900 (17.0%)
NEHRdd	Nehoiu	Buzău	20367 (17.4%)

2.1.2. *Earthquake-related data collection.* The earthquake-related data was extracted from the official up-to-date ROMPLUS catalog [15], available at NIEP, and it was synchronized with the radon data timeline, ensuring the necessary temporal alignment for the data analysis. The earthquake activity dataset contains the following parameters: datetime (UTC), location, magnitude, magnitude type, latitude, longitude, depth (km), modified Mercalli intensity scale (MMI).

2.2. Data preparation and validation

The radon information used in this study was obtained from six monitoring stations located in the counties of Vrancea, Buzău and Vâlcea (see Figure 1).

A total of 4625 earthquakes in Romania have been identified and extracted from the ROMPLUS earthquake catalog between January 01, 2023 and November 17, 2023. Out of these, 59 earthquakes had a magnitude of 3.5 or higher, and six of these were significant earthquakes that registered a magnitude of 4.7 or higher and a modified Mercalli intensity scale (MMI) greater or equal to IV (Table 2).

The radon and earthquake datasets have been imported, cleaned, validated, and then used to answer the research questions.

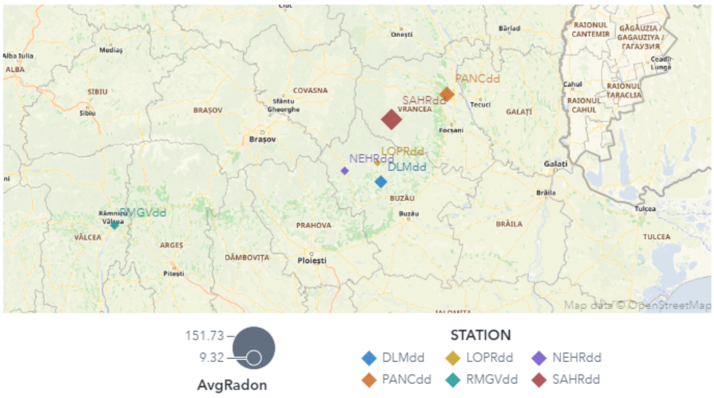


FIGURE 1. Radon stations by locations sized by Rn average values.

TABLE 2. Significant earthquakes in Romania between January 2023 and November 2023.

Origin time (UTC)	Region	Magnitude	Latitude	Longitude	Depth (km)	MMI
02/13/2023 2:58:00 PM	OLTENIA, GORJ	5.2	45.1199	23.1003	23.1	V
02/14/2023 1:16:00 PM	OLTENIA, GORJ	5.7	45.1164	23.151	6.3	VI
03/20/2023 2:02:00 PM	OLTENIA, GORJ	5.0	45.1029	23.067	14.7	V
05/22/2023 5:46:00 PM	BANAT, ARAD	4.8	46.1029	21.4432	8.7	VI
06/06/2023 5:26:00 PM	CRISANA, ARAD	5.2	46.1194	21.5303	7.2	VII
08/20/2023 9:39:00 PM	OLTENIA, GORJ	4.7	45.1475	23.2552	14.7	IV

2.3. Data analysis

To answer our research questions (RQ1 and RQ2), a correlation study has been employed further to evaluate the possible connections that may exist among geological events (earthquakes), radon emissions, and various atmospheric parameters (relative humidity, temperature, and atmospheric pressure). The following graphical representations have been used for the correlation analysis: a) *Bubble plots* - to visualize relationships and patterns among magnitudes, depths, and regional distribution of earthquakes in a single plot; b) *Correlation matrices* - to display the correlation coefficients (r) between multiple variables like radon concentrations and environmental variables, earthquake magnitudes and depths, earthquake magnitudes and radon concentrations. This analysis reveals the Pearson correlation coefficients that measures linear correlation between two sets of data, i.e. the strength and direction of the relationship between two variables; c) *Frequency heatmaps* - to provide a comprehensive understanding of the interdependencies among the variables under study; d) *Scatter plots* - to reveal and display visually whether there are patterns of linear dependency between two quantitative variables under study, i.e. the direction, form, and strength of the relationship.

3. Results

3.1. Evaluating correlation between radon concentrations and environmental variables in Romania

The correlation matrices presented in Figure 2 show the correlations between radon concentrations and environmental variables, such as temperature, relative humidity, and atmospheric pressure for each station.

The determined correlations between radon concentrations and environmental variables (Table 3), where r_{X_Y} denotes the Pearson correlation coefficient of the two variables X and Y (RH is the relative humidity, T is the temperature, P is the pressure, and R is the radon concentration): a) Station SAHRdd: strong negative r_{RH_T}, moderate positive r_{R_P}, moderate negative r_{RH_P}; b) Station DLMdd: moderate negative r_{RH_P}; c) Station RMGVdd: moderate negative r_{RH_T}, moderate negative r_{RH_P}, moderate negative r_{R_T}; d) Station PANCdd: moderate negative r_{RH_T}, moderate negative r_{RH_P}, moderate negative r_{R_P}, moderate negative r_{R_T}; e) Station LOPRdd: moderate negative r_{RH_T}, moderate positive $r_{R_{RH}}$, moderate negative r_{R_T}; f) Station NEHRdd: strong negative r_{RH_T}, moderate negative r_{R_T}, moderate positive r_{R_P}.

The frequency heatmaps of radon concentrations and environmental variables across multiple monitoring stations are presented in Figure 3.

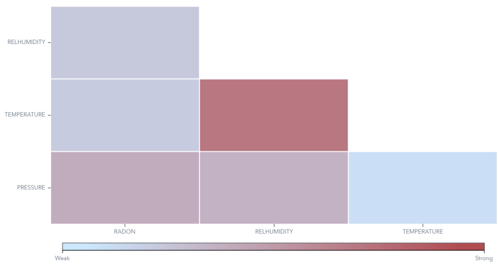
Radon concentration measurements corresponding to environmental variables are depicted by the scatter plots in Figure 4.

The scatter plots presented in Figure 4(b), Figure 4(e), Figure 4(f), Figure 4(g), Figure 4(h) indicate no clear relationships between the radon concentrations and environmental variables, as there is no distinct direction of the data. The scatter plots presented in Figure 4(a), Figure 4(c) and Figure 4(d) show that radon has a positive linear relationship with pressure at SAHRdd, a negative linear relationship with pressure at PANCdd, and a negative linear relationship with temperature at PANCdd.

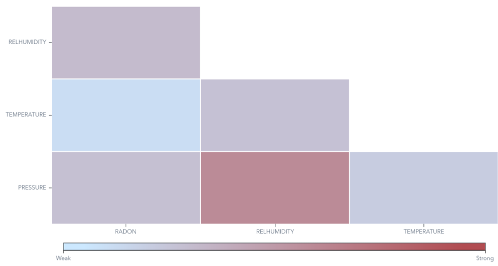
3.2. Evaluating correlation of radon concentration and earthquake activity in Romania

The investigation of the seismic activity across multiple regions in Romania over the observational time frame from January 01, 2023 to November 17, 2023 has indicated the presence of earthquakes with a magnitude of 3.5 or higher ($M \geq 3.5$), as presented in Figure 5.

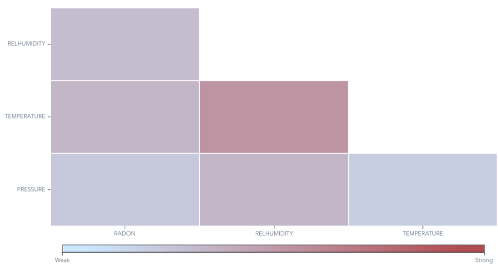
The confirmed earthquakes were spread over various geographical zones, with the Oltenia,Gorj region representing 40.7% of the total number of recorded



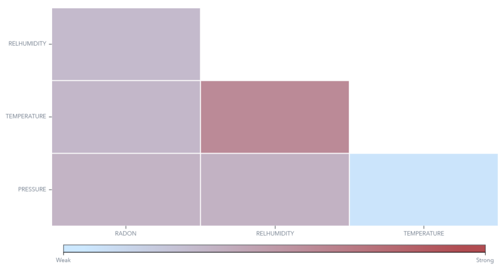
(a) SAHRdd station



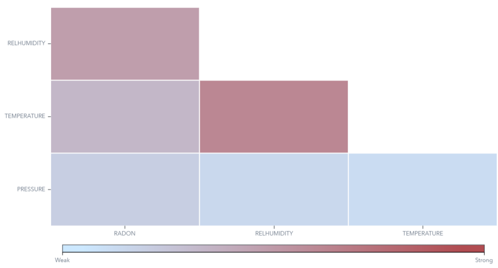
(b) DLMdd station



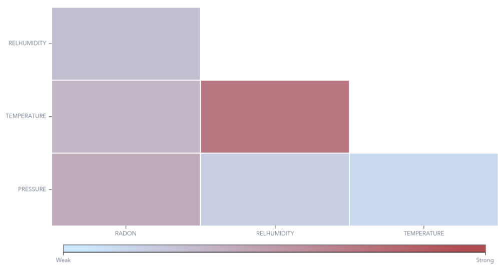
(c) RMGVdd station



(d) PANCdd station



(e) LOPRdd station



(f) NEHRdd station

FIGURE 2. Correlation matrices between radon concentrations and environmental variables across monitoring stations, based on Pearson correlation coefficient.

$M \geq 3.5$ earthquakes. Furthermore, the region of Buzău showed 33.9% of the recorded $M \geq 3.5$ earthquakes, 13.6% in Vrancea and 5.1% in Crisana,Arad region.

Figure 6 shows a distinct seismic pattern in Romania in the timeframe January 01, 2023 - November 17, 2023, emphasizing the country's seismicity in terms of the depths and magnitudes of the earthquakes. Notably, intermediate-depth earthquakes with depths exceeding 70 kilometers have been identified in Vrancea region, while for Banat, Oltenia and Crişana regions the map depicts

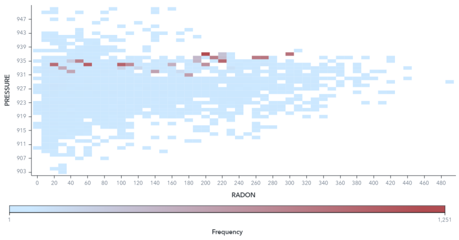
Table 3. Pearson correlation coefficients across environmental variables and radon concentrations at each monitoring station.

Station	**X axis**	**Y axis**	**Correlation (r_{X_Y})**	**Relationship**	**Strength**
SAHRdd	RADON	PRESSURE	0.379035729549136	Positive	Moderate
SAHRdd	RADON	TEMPERATURE	-0.181106423635523	Negative	Weak
SAHRdd	RADON	RELHUMIDITY	0.196116689045143	Positive	Weak
SAHRdd	RELHUMIDITY	PRESSURE	-0.341932335423341	Negative	Moderate
SAHRdd	RELHUMIDITY	TEMPERATURE	-0.723530017316493	Negative	Strong
SAHRdd	TEMPERATURE	PRESSURE	0.0560090717720016	Positive	Weak
DLMdd	RADON	PRESSURE	0.253634110227113	Positive	Weak
DLMdd	RADON	TEMPERATURE	0.0641101661278427	Positive	Weak
DLMdd	RADON	RELHUMIDITY	-0.282787341908559	Negative	Weak
DLMdd	RELHUMIDITY	PRESSURE	-0.595378432577678	Negative	Moderate
DLMdd	RELHUMIDITY	TEMPERATURE	-0.245063176911933	Negative	Weak
DLMdd	TEMPERATURE	PRESSURE	0.177798827627306	Positive	Weak
RMGVdd	RADON	PRESSURE	0.19980046661303	Positive	Weak
RMGVdd	RADON	TEMPERATURE	-0.316328174483852	Negative	Moderate
RMGVdd	RADON	RELHUMIDITY	0.275348689157252	Positive	Weak
RMGVdd	RELHUMIDITY	PRESSURE	-0.317924865316152	Negative	Moderate
RMGVdd	RELHUMIDITY	TEMPERATURE	-0.536411437752191	Negative	Moderate
RMGVdd	TEMPERATURE	PRESSURE	-0.164316838716268	Negative	Weak
PANCdd	RADON	PRESSURE	-0.329917219525031	Negative	Moderate
PANCdd	RADON	TEMPERATURE	-0.309162443002175	Negative	Moderate
PANCdd	RADON	RELHUMIDITY	0.290942754206632	Positive	Weak
PANCdd	RELHUMIDITY	PRESSURE	-0.34432995347709	Negative	Moderate
PANCdd	RELHUMIDITY	TEMPERATURE	-0.597543955214608	Negative	Moderate
PANCdd	TEMPERATURE	PRESSURE	-0.0204142483096821	Negative	Weak
LOPRdd	RADON	PRESSURE	0.161585989426937	Positive	Weak
LOPRdd	RADON	TEMPERATURE	-0.310722287767861	Negative	Moderate
LOPRdd	RADON	RELHUMIDITY	0.472609333299489	Positive	Moderate
LOPRdd	RELHUMIDITY	PRESSURE	0.100602791436543	Positive	Weak
LOPRdd	RELHUMIDITY	TEMPERATURE	-0.620137579742269	Negative	Moderate
LOPRdd	TEMPERATURE	PRESSURE	-0.0717946630455246	Negative	Weak
NEHRdd	RADON	PRESSURE	0.384211830436935	Positive	Moderate
NEHRdd	RADON	TEMPERATURE	-0.320463814725918	Negative	Moderate
NEHRdd	RADON	RELHUMIDITY	0.263535727750298	Positive	Weak
NEHRdd	RELHUMIDITY	PRESSURE	-0.165919690627774	Negative	Weak
NEHRdd	RELHUMIDITY	TEMPERATURE	-0.724481332431817	Negative	Strong
NEHRdd	TEMPERATURE	PRESSURE	-0.0896732380996727	Negative	Weak

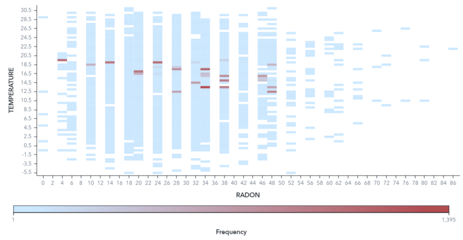
a prevalence of shallow-focus earthquakes, with seismic activity occurring at depths less than 25 kilometers (Figure 7).

The correlation matrices in Figure 8 reveal weak correlations ($|r_{M_R}| < 0.3$) between magnitude and radon concentrations as well as depth and radon concentrations, and moderate ($0.3 \leq |r_{M_D}| < 0.7$) to strong ($|r_{M_D}| \geq 0.7$) correlations between magnitude and depth in different seismic regions.

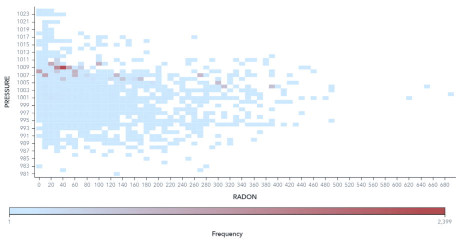
Further on, the following correlations between earthquake magnitude and depth have been determined in different regions (Table 4): a) Vrancea, Buzău region: strong positive $r_{M_D} \approx 0.8039$; b) Vrancea, Vrancea region: strong positive $r_{M_D} \approx 0.7145$; c) Oltenia, Gorj region: moderate negative $r_{M_D} \approx -0.3982$.



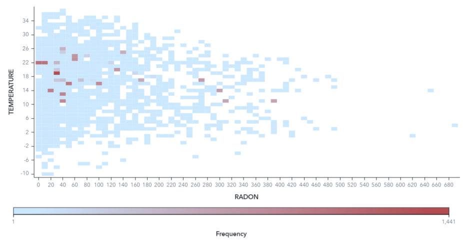
(a) radon and pressure at SAHRdd



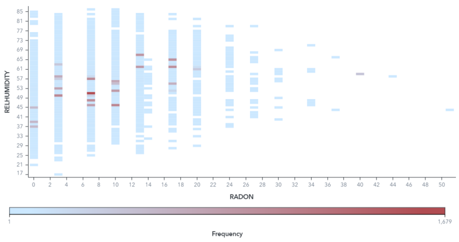
(b) radon and temperature at RMGVdd



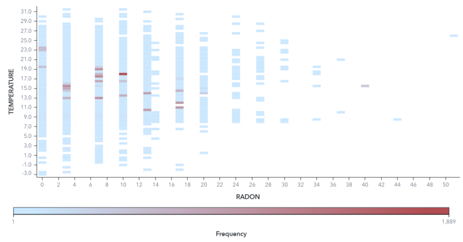
(c) radon and pressure at PANCdd



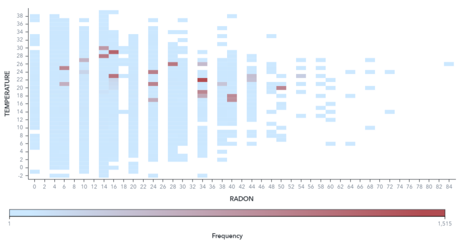
(d) radon and temperature at PANCdd



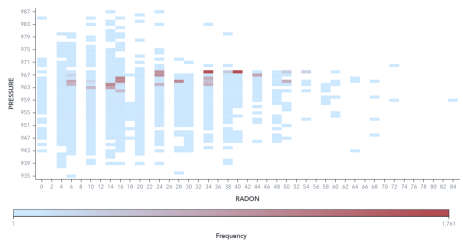
(e) radon and relative humidity at LO-PRdd



(f) radon and temperature at LOPRdd

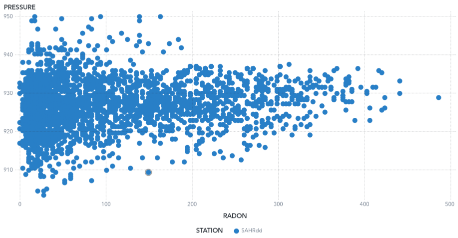


(g) radon and temperature at NEHRdd

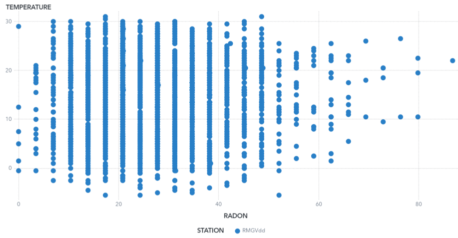


(h) radon and pressure at NEHRdd

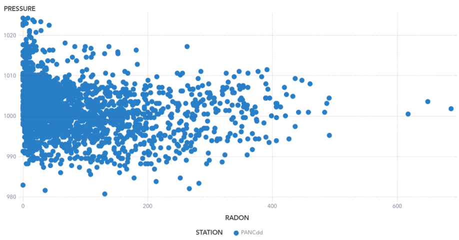
Figure 3. Frequency heatmaps: radon concentrations and environmental variables, selected monitoring stations.



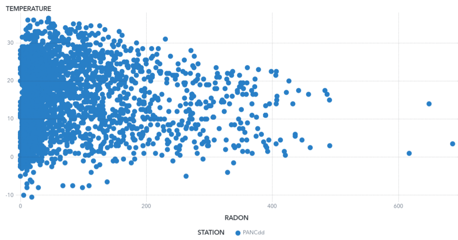
(a) radon and pressure at SAHRdd



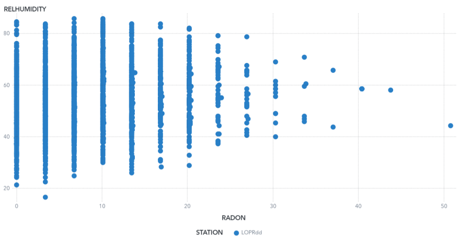
(b) radon and temperature at RMGVdd



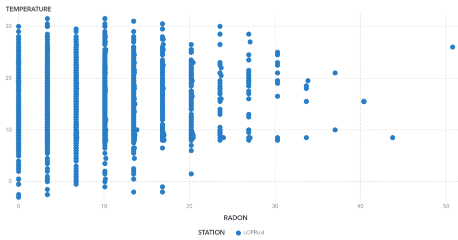
(c) radon and pressure at PANCdd



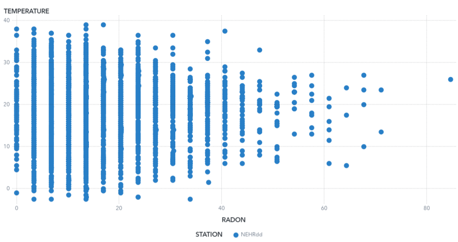
(d) radon and temperature at PANCdd



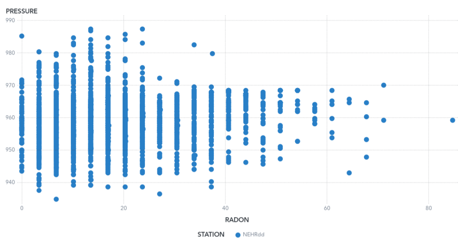
(e) radon and relative humidity at LOPRdd



(f) radon and temperature at LOPRdd



(g) radon and temperature at NEHRdd



(h) radon and pressure at NEHRdd

Figure 4. Radon concentration measurements corresponding to environmental variables, selected monitoring stations.

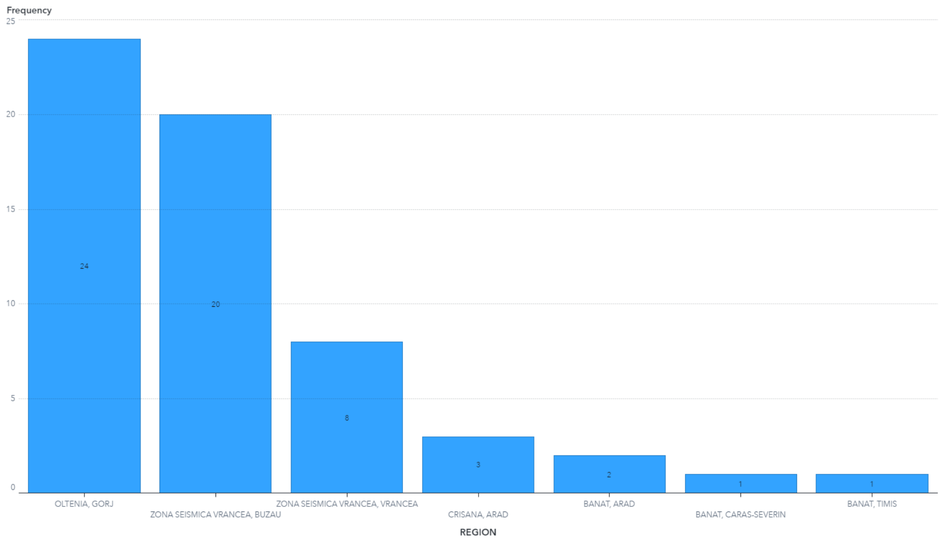


FIGURE 5. Frequency of earthquakes of magnitude $M \geq 3.5$ in different seismic regions in Romania.

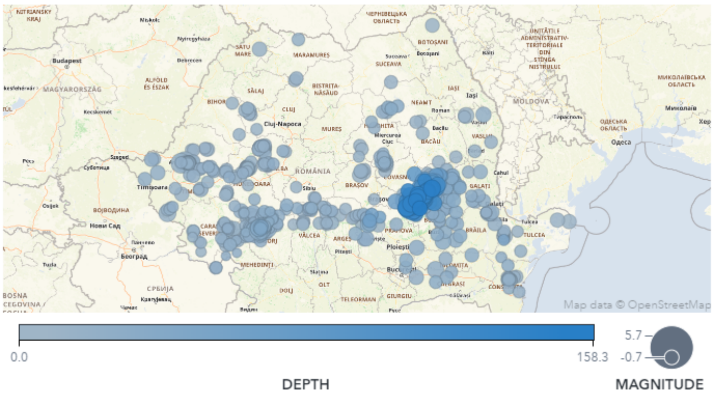


FIGURE 6. Earthquake locations by depth and magnitude.

TABLE 4. Pearson correlation coefficients between magnitude and depth across different geographic regions.

Region	**X axis**	**Y axis**	**Correlation** (r_{M_D})	**Relationship**	**Strength**
Vrancea,Buzău	Magnitude	Depth	0.803909791206619	Positive	Strong
Vrancea,Vrancea	Magnitude	Depth	0.714497286619886	Positive	Strong
Oltenia,Gorj	Magnitude	Depth	-0.398152393539662	Negative	Moderate

The set of frequency heatmaps in Figure 9 show how earthquake magnitude and depth relate to one another in different geographical areas by their frequencies.

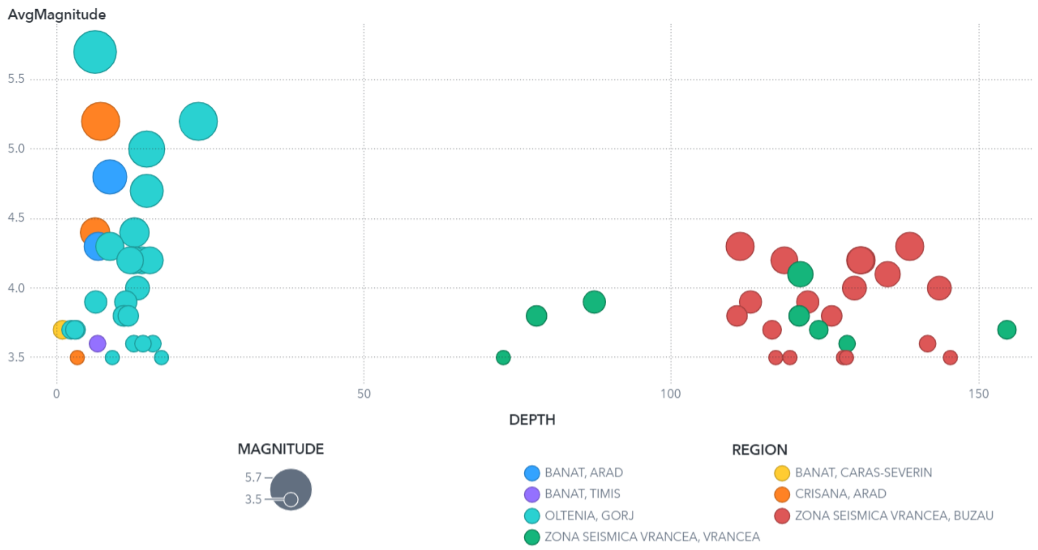
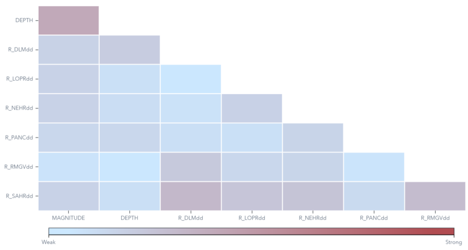
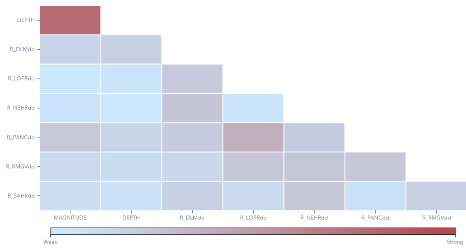


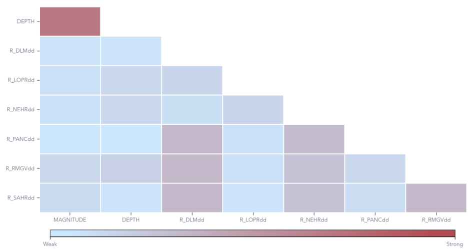
FIGURE 7. Magnitude, depth, and regional distribution for earthquakes with a magnitude $M \geq 3.5$.



(a) Oltenia, Gorj



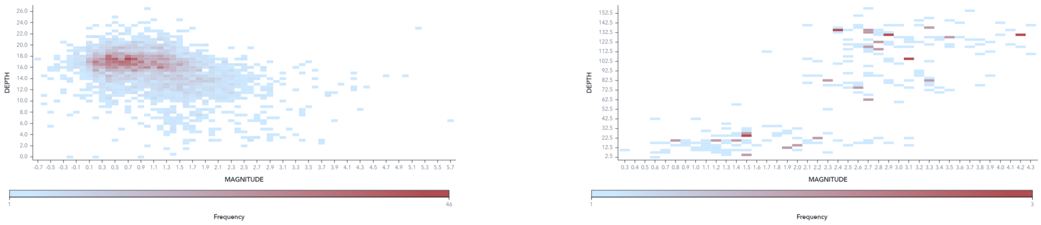
(b) Vrancea, Buzău



(c) Vrancea, Vrancea

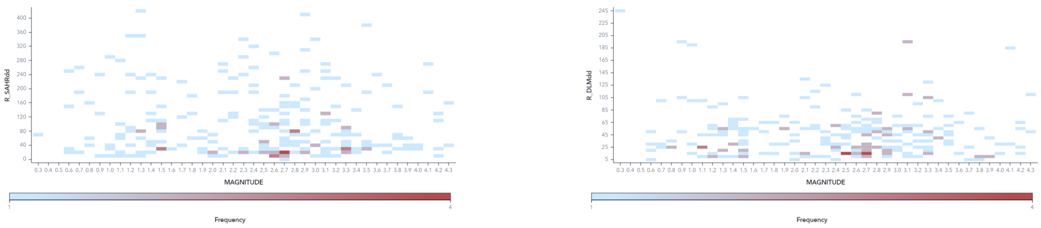
FIGURE 8. Correlation matrices of earthquake magnitude, depth, and radon concentrations across different geographic regions.

Each cell in Figure 10 represents a distinct combination of earthquake magnitude and depth on different stations, with color gradients reflecting the frequency.

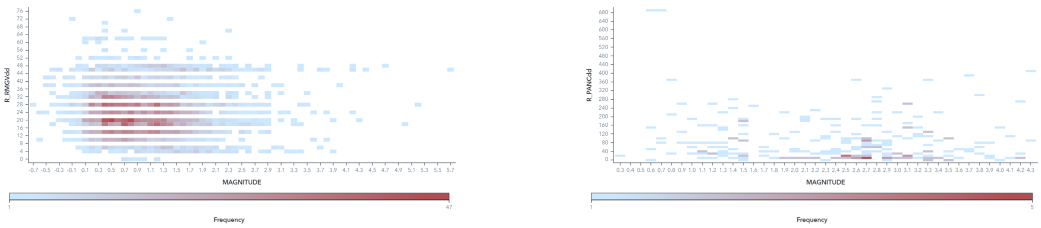


(a) Oltenia, Gorj region (b) Vrancea Region

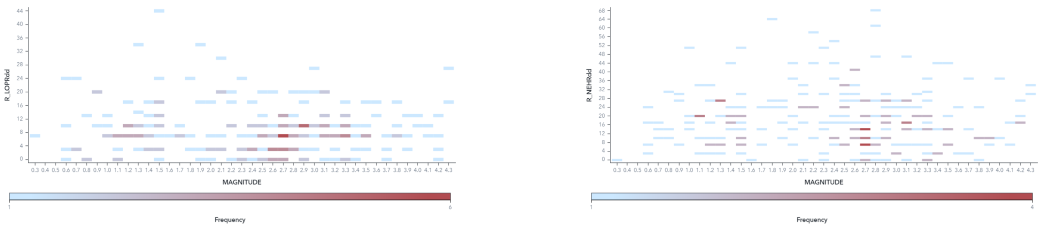
FIGURE 9. Frequency heatmaps of magnitude and depth at different geographic regions.



(a) SAHRdd station (b) DLMdd station

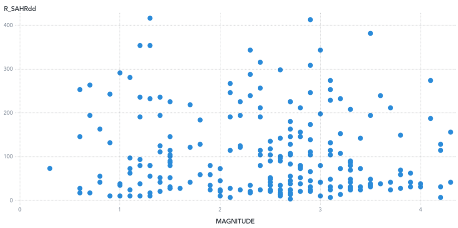


(c) RMGVdd station (d) PANCdd station

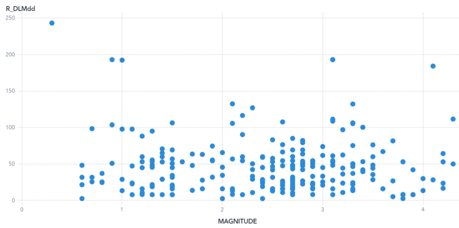


(e) LOPRdd station (f) NEHRdd station

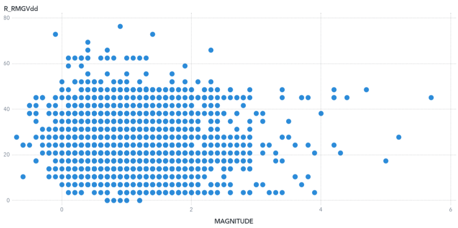
FIGURE 10. Frequency heatmaps of magnitude and radon concentrations at different monitoring stations.



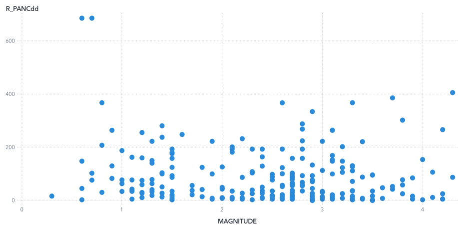
(a) SAHRdd station



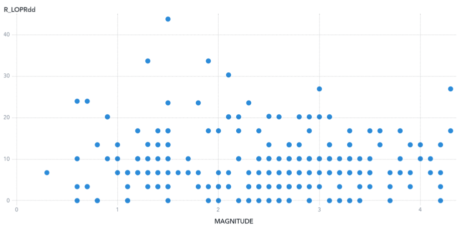
(b) DLMdd station



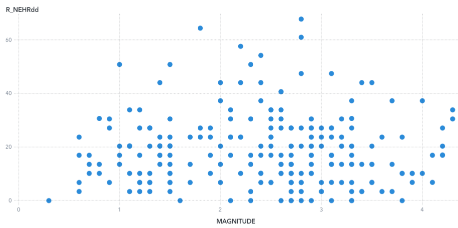
(c) RMGVdd station



(d) PANCdd station



(e) LOPRdd station



(f) NEHRdd station

Figure 11. Magnitude-radon relationships at different monitoring stations.

The scatter plots in Figure 11 suggest that there is no clear relationship between magnitude and radon concentrations at different monitoring stations.

4. Discussion and conclusions

This study examines the effectiveness of novel techniques, incorporating smart visualizations and visual analytics perspectives, in exploring complex natural environmental phenomena, specifically investigating potential correlations between radon levels, environmental factors, and seismic events, within a complex exploratory data analysis perspective. Specifically, this study investigates whether the correlations between radon concentrations, environmental variables, and seismic activity have a specific pattern in Romania that can be pertinently revealed based on effective visual techniques.

To determine whether there is a detectable, meaningful relationship between radon concentrations, environmental variables, and seismic activity in Romania, our study used correlation analysis as an initial exploration stage. The study has revealed both linear positive and negative moderate correlations between radon concentrations and some environmental variables (r_{R_P}, r_{R_T}, $r_{R_{RH}}$) in Vrancea, Buzău, and Vâlcea regions, but weak correlations between earthquake activity and radon concentrations.

Some limitations related to the context of this study have been identified: the unique geographical and timeframe criteria under consideration limit the scope of this analysis, potentially limiting the findings' generalizability to other places or longer timeframes; the complexity of environmental and geological factors, which were not investigated in this study, might include additional variables that influence the observed relationships or correlations; the available datasets and monitoring stations may introduce data limitations that could impact the robustness of the findings.

However, these limitations highlight the necessity for additional research studies, and there are several possible topics of research worth to mention: investigating the temporal dynamics of observed correlations; employing advanced time series analysis methods to find potential trends, periodicities, or anomalies in the relationships between radon and environmental variables, as well as radon and earthquake activity; extending the geographic area of the analysis to include a larger geographical spectrum could provide insights into regional variations in the identified correlations, allowing for a more comprehensive knowledge of the factors influencing radon concentrations in various environmental circumstances.

Within this respect, a thorough analysis to test and evaluate multivariate causal relationships on our dataset using structural equation modeling (SEM) multivariate technique [16] may provide relevant insights that can help stakeholders and advance future scientific research in evaluating earthquake behaviour, as PLS-SEM method is widely applied today in various domains, in testing hypothesized causal relationships between variables, including ecology [17], earthquake modeling [18], [19], and engineering [20], [21], [22], to name but a few examples. As well, considering the latest developments in AI technologies, integrating advanced machine learning methods may improve the prediction capacity of the data-intensive models by providing a deeper understanding of the possible complex or non-linear relationships.

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