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Application of continuous radon gas concentration telemonitoring for predictive seismic hazard assessment in Manado, Indonesia

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ABSTRACT

Abnormal increases in radon gas (^{222}Rn) concentrations in soil, groundwater, and atmosphere have been consistently observed as precursors of seismic activity, especially near active faults. In this study, we focus on earthquake prediction using IoT-based radon monitoring near the active fault in Manado, North Sulawesi, Indonesia, where seismic activity is high due to interactions between the Eurasian, Pacific, and Philippine plates. Radon gas concentration telemonitoring collected in real-time every minute between October 2023 and August 2024 was analyzed along with seismic data above M4.5 to predict earthquakes with magnitude 4.5 and above. This telemonitoring system enables continuous data storage every minute, with data accessible on the dataalamdiy web server, despite radon concentration readings on the detector updating every 10 minutes to filter out emissions from Thoron and Actanium sources.The results showed that earthquake date prediction sensitivity was 84%, accuracy was 75%, and the average prediction time was 2.65 days before the earthquake. The prediction was based on statistical algorithms derived from the daily average of radon gas concentration fluctuations, which resulted in an effective early warning system. One of the largest earthquakes M6.7 on January 9, 2024, was predicted 2 days ago. These findings highlight the possibility of integrating radon gas concentration anomaly analysis into disaster prevention strategies and provide an important lead time for preparedness efforts in seismically active areas. This research will significantly contribute to earthquake prediction methodology in Indonesia, especially in less-studied areas such as North Sulawesi, improving regional disaster preparedness and resilience.

Keywords: Radon, monitoring, earthquake, prediction, early warning system, Internet of Things.

INTRODUCTION

Unusual increases in radon (^{222}Rn) concentration in soil, groundwater, and atmosphere have been reported before large earthquakes (Muto et al., 2021). Due to the statistically significant relationship between seismic events and variations in radon concentrations, monitoring radon dissolved in water near fault zones, such as in wells or springs, is of substantial observational value (Shuqi et al., 2022). Active tectonic faults, which enhance rock and soil permeability, are key geological sources of elevated radon emissions (Baubron et al., 2002; Chen et al., 2018; King, 1978; Seminsky and Bobrov, 2015). It is hypothesized that changes in stress and strain associated with seismic activity can induce the upward migration of fluids from the crust or mantle, particularly along fault lines (King et al., 1996). Anomalous radon concentrations are observed to be relatively high near fault zones and decrease with distance from the fault line (Khan et al., 2022).

Researchers (Ichedef et al., 2024) took measurements for two years, and two categories of radon anomalies were identified: in the first group, radon increased before the earthquake and decreased afterward, while in the second category, the opposite occurred. Groundwater radon fluctuations at six monitoring stations from 2009 to 2018 were analyzed by (Zhao et al., 2021). Seismic response zones were determined using historical seismic precursors. Low groundwater radon levels are due to the underground rock masses holding pressure and locking on some faults. According to A. Alam changes in radon (Rn) in groundwater caused by seismotectonic are a strong indication for monitoring the possibility of a major earthquake (Alam et al., 2020, 2021, 2023). Radon time series were statistically analyzed to identify radon anomalies that the Wenchuan earthquake may have caused.

Research on earthquake precursors based on radon gas concentration measurements in Indonesia has been conducted in Yogyakarta and Pacitan, located between the Eurasian and Indo-Australian plates. (Herlambang, 2018; Pratama, 2021; Pratama et al., n.d.; Sunarno et al., 2016, 2020). Herlambang examined the relationship between radon gas anomalies in Yogyakarta and the occurrence of earthquakes. The findings show that radon levels consistently rise two days before an earthquake. The most pronounced change was detected two days prior to the M5.8 earthquake in Malang on July 19, 2018. This pattern suggests that radon concentrations exhibit larger fluctuations when an earthquake is stronger and closer to the detector's location (Herlambang, 2018). Pratama's research results have stated that earthquake date prediction can be designed based on radon gas concentration and groundwater level measurements with more than 80% precision and sensitivity. While the prediction of magnitude based on radon cloud data at Pacitan station using machine learning (linear regression) has an evaluation: Standard Deviation: 0.4, MAE (0.30), MAPE (6%), RMSE (0.52), MSE (0.28), SMAPE (0.06), and cnMAPE (0.97). (Pratama et al., 2024).

Located at the meeting point of the Eurasian, Pacific, and Philippine tectonic plates, the Manado area is highly prone to frequent and often destructive earthquakes. The Pacific and Philippine plates move westward at an average rate of 11 cm per year, subducting beneath the Eurasian plate around Halmahera and North Sulawesi. This motion among the three plates creates a complex tectonic structure in North Sulawesi and its surrounding areas. Smaller plates have formed, specifically, fragments of the Eurasian plate's edge that the Pacific and Philippine plates compress. The Eurasian plate, being continental, is less dense than the oceanic Pacific and Philippine plates. Under this pressure, the Eurasian plate's edge fractured into three smaller plates: the Halmahera, Maluku Sea, and Sangihe plates, while North Sulawesi remains part of the Eurasian plate. This plate interaction has resulted in numerous faults across North Sulawesi, including the Gorontalo, Bolmong, Amurang, and Manado faults. (2021). However, despite its high seismicity, limited studies have been conducted in the Manado region. This study aims to predict earthquake date prediction by comprehensively analyzing radon anomalies near the active fault with earthquake occurrences using state-of-the-art IoT-based monitoring technology and advanced statistical methods.

METHOD

This study measured radon gas concentration using the Internet of Things (IoT) near an active fault in Manado. Figure 1 illustrates the schematic design of the telemonitoring system for radon gas concentration. The measurement has been placed at the office of the Provincial Council of North Sulawesi, Indonesia, since October 2023. Real-time cloud data consists of RD200 as radon transducer and ESP32 microprocessor to transmit data from transducer to server through internet network. Data in the server is stored in the database; measurement data can also be viewed on the dataalamdiy web server as in Figure 2.

This setup enables continuous data storage every minute, with data accessible on the Dataalamdiy web server, despite radon concentration readings on the detector updating every 10 minutes to filter out emissions from Thoron and Actanium sources (Cember and Johnson, 2009; Internationale Atomenergie-Organisation, 2013). Additionally, a timer resets the internet provider modem periodically to minimize technical errors. The measurement data of radon gas concentration at the server and earthquake data from USGS (United States Geological Survey) are then processed to obtain an earthquake date prediction algorithm. The characteristics of radon gas concentration towards earthquakes from one location to

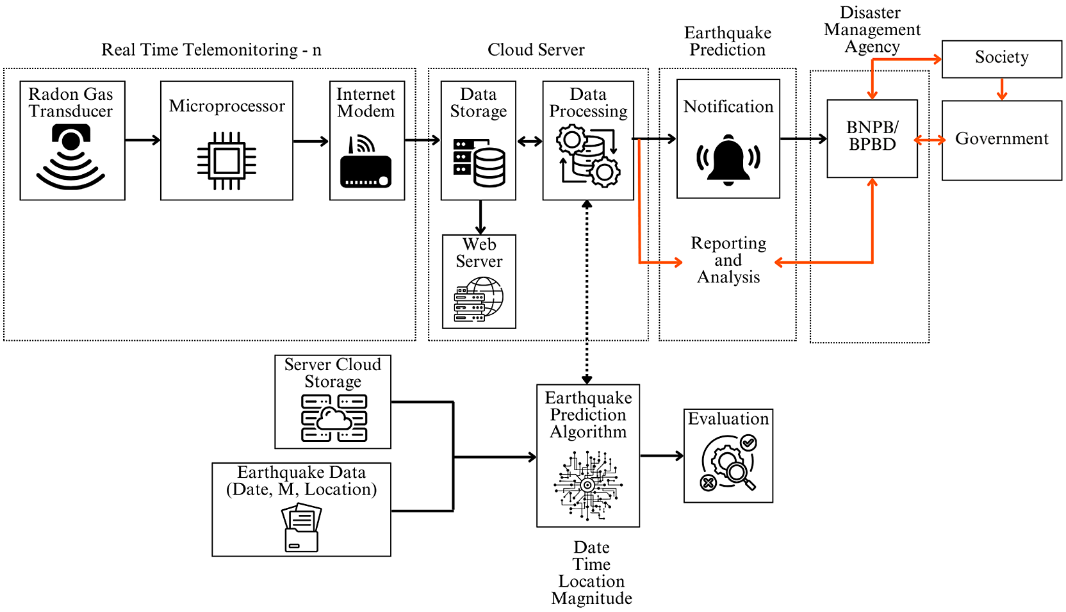

Figure 1. Design of earthquake prediction based on the radon gas concentration fluctuation monitoring systems

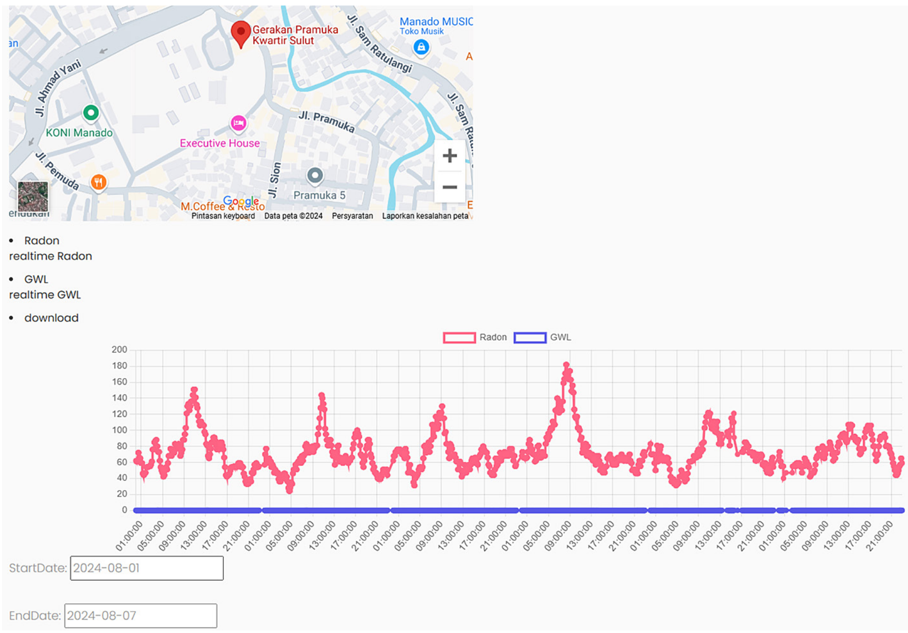

Figure 2. Radon gas telemonitoring in North Sulawesi Station

another are different, so it is necessary to analyze and predict the time of earthquakes based on fluctuations in radon gas concentration.

The daily radon gas concentration data and earthquake event data were sorted by date and then analyzed to determine if there was an anomaly in radon gas concentration before the Earthquake around Manado above M4.5 with confirm (C) or manual revised (M) status, as shown in the boundary map in Figure 3 with latitude: –5.8319 to 5.2395, longitude: 117.4978 to 129.1057. The statistical pattern of precursor fluctuations is generated by calculating the daily average. Using hourly or minute-based calculations would make establishing a clear statistical pattern challenging. Moreover, if predictions were made successfully hourly or minute-by-minute, evacuation efforts would become hurried and potentially chaotic. Figure 4 shows the methodology to find the earthquake date prediction based on the radon cloud data.

Calculate the daily average of precursor data and sort the data by the date. Then calculate v, which is a

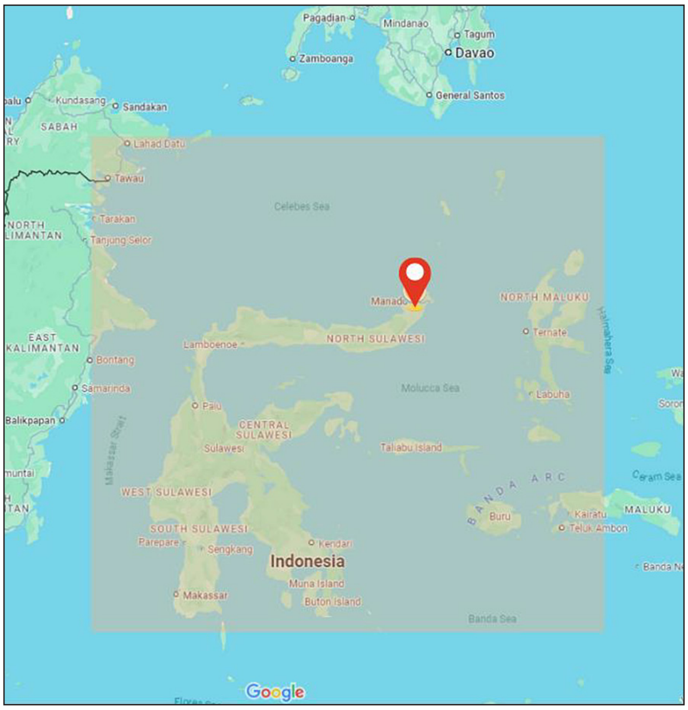

Figure 3. Earthquake regions zone (Google, 2024)

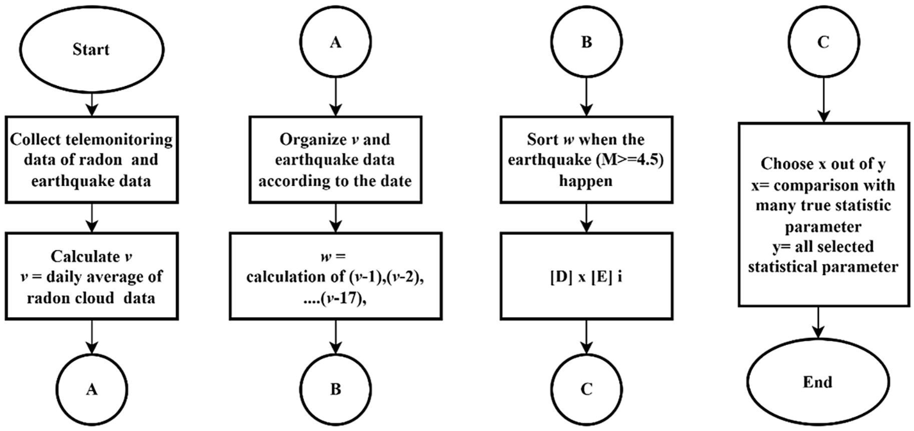

Figure 4. Earthquake date prediction algorithm flowchart (Oka Pratama, 2021)

daily average of measurement data (the detail can be shown in Table 1). Select earthquake data and pair it with the daily average measurement data by date. Use the matrix in Equation 1 to process the daily averages when earthquakes occur. Matrix D compares signal characteristics in matrix E, the radon daily average characteristic. The product of these matrices gives the statistical parameter. In matrix D, -1 negates the values after multiplying by matrix E. The resulting matrix is filtered by selecting statistical parameters that match the conditions of various earthquake events. The selected statistical parameters (x) are refined to find the minimum number (y) necessary for earthquake prediction. The station characteristic matrix represents x out of y from the station's statistical parameter matrix. Testing the station characteristics is essential to ensure high sensitivity and precision in earthquake prediction. The data is analyzed at weekly interval tests from October 2023 until August 2024, and the system's reliability against earthquakes will be recorded outside the system. The station characteristic can be considered an earthquake prediction algorithm if its sensitivity and precision are at least 75%. However, the statistical parameters must be adjusted if the sensitivity and precision are below 75%. The characteristics of radon gas concentration prior to seismic activity differ from one location to another, so they have their algorithm for earthquake date prediction (Oka Pratama, 2021).

Table 1. Radon daily average variables

Radon daily average characteristic	Description
$D(v)$	Radon daily average day v
$D(v-1)$	Radon daily average day $v-1$
...	...
$D(v-6)$	Radon daily average day $v-6$
$D(v-7)$	Radon daily average day $v-7$
$Dz(v-3)$	Radon daily average from $D(v-3)$ to $D(v-5)$
$Dz(v-7)$	Radon daily average from $D(v-3)$ to $D(v-9)$
$Dz(v-14)$	Radon daily average from to $D(v-3)$ to $D(v-16)$

$$[D] \times [E]\ i > 0 \text{ or } [D] \times [E]\ i < 0 \quad (1)$$

where:

$$[D] = \begin{bmatrix} 1 & -1 & 0 & 0 & 0 & 0 \\ 1 & 0 & \ddots & 0 & 0 & 0 \\ 1 & 0 & 0 & \ddots & 0 & 0 \\ 1 & 0 & 0 & 0 & \ddots & 0 \\ 1 & 0 & 0 & 0 & 0 & -1 \\ 0 & 1 & -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & \ddots & 0 & 0 \\ 0 & 1 & 0 & 0 & \ddots & 0 \\ 0 & 1 & 0 & 0 & 0 & -1 \\ & & \vdots & & & \\ 0 & 0 & 0 & 0 & -1 & -1 \end{bmatrix}$$

$$[E] = \begin{bmatrix} Dz(v-14) \\ Dz(v-7) \\ Dz(v-3) \\ D(v-7) \\ D(v-6) \\ \vdots \\ D(v-1) \end{bmatrix}$$

RESULT AND DISCUSSION

Statistical parameters are derived from analyzing the daily average radon measurements during earthquakes. The station characteristics are analyzed by multiplying the comparator matrix and the characteristic signal. The results of these matrix multiplications are filtered by selecting statistical parameters that match various earthquake events. The data used as training data is radon daily average characteristic from 23 earthquake events dated 16 November 2023 to 4 April 2024. From the comparison results, 10 radon daily average characteristics with a minimum correct value of 60% from the comparator matrix (Appendix 1) were obtained, then the data training was carried out until 24 August 2024.

Based on these statistical parameters, a minimum of 8 requirements is set to trigger an earthquake alarm for the best evaluation. The statistical parameter, detailed in Table 2, indicates the station characteristics. With the signal character of the average radon gas concentration fluctuations, there is also a certain pattern before the earthquake. The prediction algorithm relies on the statistical parameter before an earthquake occurs, which is obtained by multiplying the comparison matrix with the characteristic signal of the precursor's daily average measurements. Different locations yield different statistical parameters due to varying physical and meteorological factors.

The results of predicting the time of an earthquake based on radon gas concentration fluctuations at Manado station, North Sulawesi, show

Table 2. Earthquake prediction time algorithm based on the radon monitoring in Manado

Radon daily average signal characteristic	Algorithm requirement	Prediction time
$Dz(v-15) < Dz(v-3)$ $Dz(v-15) < D(v-3)$ $Dz(v-3) > D(v-6)$ $Dz(v-7) < D(v-3)$ $Dz(v-3) > D(v-6)$ $D(v-7) < D(v-3)$ $D(v-6) < D(v-5)$ $D(v-6) < D(v-3)$ $D(v-6) < Dz(v-2)$ $D(v-2) < D(v-1)$	The earthquake prediction algorithm activates when at least 8 out of 10 comparisons are correct.	1–5 days after the earthquake prediction is active.

Table 3. Previous research

Reference	Method	Prediction Result
(Pratama et al., n.d.)	Measure radon gas concentration near Grindulu Fault, in Pacitan, East Java, Indonesia	Time: 1–4 days Location: between the Eurasia and Indo-Australia plates. Magnitude: > M4.5 Precision: 70.27% Sensitivity: 78.79%
(Oka Pratama, 2021)	Measure radon gas concentration near active fault in Yogyakarta and Prambanan, Central Java, Indonesia	Time: 1–4 days (average 2.1 days) Location: between the Eurasia and Indo-Australia plates. Magnitude: > M4.5 Prambanan station: Precision: 91.67% Sensitivity: 88%
(Harahap, 2024)	Measure radon gas concentration near active fault in Padang, Indonesia	Time: 1–4 days Location: between the Eurasia and Indo-Australia plates, 5 clusters. Magnitude: > M4.5 Prambanan station: Precision: 78% Sensitivity: 90%
(Yanima Choirul Fikri, 2024)	Measure radon gas concentration near active fault in Serang, Banten, Indonesia	Time: 1–4 days Location: between the Eurasia and Indo-Australia plates, 5 clusters. Magnitude: > M4.5 Prambanan station: Precision: 75% Sensitivity:85%
(Alfiandiansyah, 2024)	Measure radon gas concentration near active fault in Kupang, Nusa Tenggara Timur, Indonesia	Time: 1–4 days Location: between the Eurasia and Indo-Australia plates, 5 clusters. Magnitude: > M4.5 Prambanan station: Precision: 78% Sensitivity: 87%
(Ichbal Fahriyanto, 2024)	Measure radon gas concentration near active fault in Bali, Indonesia	Time: 1–4 days Location: between the Eurasia and Indo-Australia plates, 5 clusters. Magnitude: > M4.5 Prambanan station: Precision: 76% Sensitivity: 97%
(Daffa, 2024)	Measure radon gas concentration near active fault in Kebumen, Central Java, Indonesia	Time: 1–4 days Location: between the Eurasia and Indo-Australia plates, 5 clusters. Magnitude: > M4.5 Prambanan station: Precision: 76.47% Sensitivity: 86.66%
(Tehseen et al., 2020)	Independent data test using seismic data processed by an expert system	Time: - Location: - Magnitude: M0.1–M5.9 Accuracy < 70%
(Hajikhodaverdikhan et al., 2018)	Process meteorological and seismic data by support vector machine	Prediction of the number of earthquakes in a month The average magnitude of an earthquake in a month Time: a month Location: -. Magnitude: mean magnitude Precision: 96% Accuracy: 78%
(Asim et al., 2017)	Process seismic parameter data by pattern recognition neural network, recurrent neural network, random forest, and linear programming boost ensemble	Time: 1 month Location: Hindukush Magnitude: > M5.5 Accuracy: 65%
(Asencio-Cortés et al., 2018)	The regression algorithm processes the cloud-based big data infrastructure	Time: 7 days Location: California Magnitude: M3–M7 Prediction Magnitude MAE: 0:59 ± 0:66 (M3–4) 0:25 ± 0:52 (M4–5) 0:27 ± 0:60 (M5–6) 0:28 ± 0:75 (M6–7) MSE: 0:79 ± 1:53 (M3–4) 0:34 ± 1:42 (M4–5) 0:43 ± 2:06 (M5–6) 0:63 ± 2:73 (M6–7)

that an earthquake will occur at the location under study 1–5 days after there is an alarm from the radon gas concentration fluctuation pattern recorded on the dataalamdiy.com server. Appendix 2 shows a recap of the predicted, unpredicted, and alarmed earthquake events without an earthquake. The number of earthquakes predicted is expressed as true positive (TP), prediction without an earthquake, false positive (FP), and earthquake without prediction with false negative (FN). Based on prediction evaluation using a confusion matrix, sensitivity and precision are expressed as TP/(TP + FN) and TP/(TP/FP), respectively.

Sensitivity measures the proportion of actual positive cases correctly identified by the model. Meanwhile, Precision measures the proportion of correct positive predictions. Based on the evaluation, TP (60), FN (11), and FP (19). The sensitivity and precision of the earthquake date prediction are 85% and 76%, which is fully complete with the requirements. A sensitivity of 84% indicates that the prediction model correctly identifies 85% of the actual earthquake dates. In other words, out of all the dates when earthquakes occurred, the model successfully predicted 84% of them. This shows the model is quite effective at detecting true earthquake events, with a relatively low rate of false negatives (missed earthquakes). A precision of 76% means that 76% of the dates predicted by the model to have earthquakes did have earthquakes. This indicates that out of all the dates the model predicted as earthquake dates, 76% were correct predictions, while 24% were false positives (dates predicted to have earthquakes but didn't). The earthquake date prediction is based on the fluctuation of radon cloud data in North Sulawesi station, which shows high sensitivity and is good at catching most of the actual earthquake dates, which is crucial for ensuring that potential earthquakes are not missed. Moderate Precision: While the model is fairly accurate, there is still a 24% chance that a predicted earthquake date might be a false alarm.

The average prediction time of earthquakes based on radon gas concentration fluctuations is 2.80 days. One of the largest earthquakes occurred on January 9, 2024, on Talaud Island M6.7 with coordinates 4.91N, 126.13E. There was an earthquake prediction on January 7, 2024, 2 days before the Earthquake occurred. It is about 408 km from the radon telemonitoring station in North Sulawesi.

Compared to the other studies in Table 3, this study adds value by focusing on North Sulawesi, a less explored area that contributes to regional disaster preparedness. Most Indonesian studies target Java or nearby regions, with Zaifudin (Bali) and Alfiandiansyah (Kupang) offering insights into Eastern Indonesia. Machine learning-based approaches (e.g., Hajikhodaverdikhan, Asim) show higher accuracy for broader timeframes but lack the granularity and immediacy needed for disaster preparedness. Regression algorithms (Asencio-Cortés) provide magnitude-specific predictions but are less effective for early warning systems. This study's 1–5 days prediction range and sensitivity (85%) position it as a practical tool for early disaster management, improving mitigation strategies in a highly seismic area. Although it is possible to predict the time of an earthquake based on radon gas fluctuations, it is necessary to develop future research to determine the number of earthquakes, time, magnitude, and location of earthquake predictions to have an ideal earthquake prediction so that it can be used as a mitigation measure for earthquake events to reduce the impact caused.

CONCLUSIONS

Earthquake date prediction can be designed based on the average daily radon gas concentration fluctuations in North Sulawesi, forming an algorithm that can successfully be used to predict earthquakes 1–5 days ahead with a magnitude greater than M4.5 in the study area with 75% precision and 84% sensitivity. This finding is important because it can improve disaster risk preparedness and mitigation, providing sufficient time for preventive measures and evacuation, especially in Sulawesi.

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