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STATISTICAL AND SPATIAL EVALUATION OF MINING-INDUCED SEISMICITY USING GIS

Purpose. This study investigates the seismicity of North Rhine-Westphalia in western Germany, focusing on the tectonically active Lower Rhine Embayment and the surrounding Rhenish lignite mining district. It aims to characterize spatial, temporal, and magnitude-related patterns of seismicity and to assess the influence of both natural and anthropogenic factors. Methodology. A catalog of 626 earthquake events recorded between 1970 and 2026 was obtained from an open-access database, including information on earthquake magnitude, focal depth, geographic location, and occurrence time. The study applies descriptive statistical analysis, GIS-based spatial statistics, and frequency-magnitude analysis. Nearest neighbor analysis and kernel density estimation were used to examine spatial patterns, while temporal variations and the Gutenberg-Richter relationship were analyzed to assess seismic trends. Results. The findings indicate that seismic activity in the study area is dominated by low-to-moderate magnitude earthquakes, with a mean magnitude of 2.73 and with focal depths predominantly within the upper crust. Most events occur at depths between 0 and 15 km, reflecting predominantly shallow seismic processes. Spatial analysis reveals a clustered distribution of earthquake epicenters, with a nearest neighbor index of 0.73, and kernel density estimation identifies several zones of elevated seismic activity. Temporal analysis reveals fluctuations in earthquake occurrence, alternating between periods of increased and reduced activity. The Gutenberg-Richter frequency-magnitude relationship exhibits a clear linear trend with a b-value of 1.019, indicating a predominance of low-magnitude events. Originality. This study integrates long-term seismic records with GIS-based spatial statistical methods to provide a comprehensive assessment of seismicity in North Rhine-Westphalia, highlighting the combined effects of tectonic structures and mining-induced activities. Practical Significance. The results contribute to a better understanding of regional seismic hazards and provide valuable insights for risk assessment, land-use planning, and the management of mining-related seismic hazards.

Key words: GIS, mining-induced seismicity, kernel density, spatial assessment, Gutenberg-Richter, geostatistics.

Introduction

Earthquakes are usually associated with tectonic processes that occur along plate boundaries or active faults within the Earth's crust [Batur and Babii, 2024]. However, seismic activity can also be influenced by human activities. Processes such as mining, groundwater extraction, fluid injection, and reservoir construction can alter subsurface stress conditions and trigger earthquakes. These earthquakes are commonly referred to as induced or anthropogenic seismicity [Bommer 2022]. In recent decades, understanding such seismic events has become increasingly important, especially in regions with intensive industrial activity where even moderate earthquakes may affect infrastructure and populated areas.

One region where both natural and human-induced seismic processes occur is the Lower Rhine Embayment in western Germany. This area forms part of the European Cenozoic Rift System and is characterized by extensional tectonics and a network of normal faults [Roth et al., 2026]. Geological studies have shown that these faults remain active and can generate earthquakes within the upper crust [Schlogen et al., 2024]. Although Germany is generally considered a region of low to moderate seismicity, the Lower Rhine Embayment represents one of the most seismically active areas in the country due to its tectonic setting [Finger et al., 2022]. In addition to tectonic activity, the region is also strongly influenced by large-scale mining operations. The Rhenish lignite mining district in North Rhine-Westphalia contains several of the largest open-pit lignite mines in Europe, including the Garzweiler, Hambach, and Inden mines [Holtermann et al., 2025]. Mining operations in these areas involve large volumes of excavation and continuous groundwater pumping. These processes can significantly modify the stress distribution in the subsurface through mass removal, ground subsidence, and changes in pore pressure. As a result, mining activities may contribute to earthquake occurrence or influence their spatial and temporal distribution. Previous studies have suggested that in regions with intensive resource extraction, seismic events may occur due to both natural tectonic processes and human-induced stress changes [Chen et al., 2023; Zhang et al., 2024].

To better understand earthquake behavior in such environments, statistical analysis of seismic catalogs is widely used [Khan and Kumar, 2018]. These analyses help identify patterns in earthquake magnitude, depth, spatial distribution, and temporal occurrence. Basic descriptive statistics provide information on the general characteristics of seismicity, while spatial analysis techniques allow researchers to identify areas where earthquakes are concentrated.

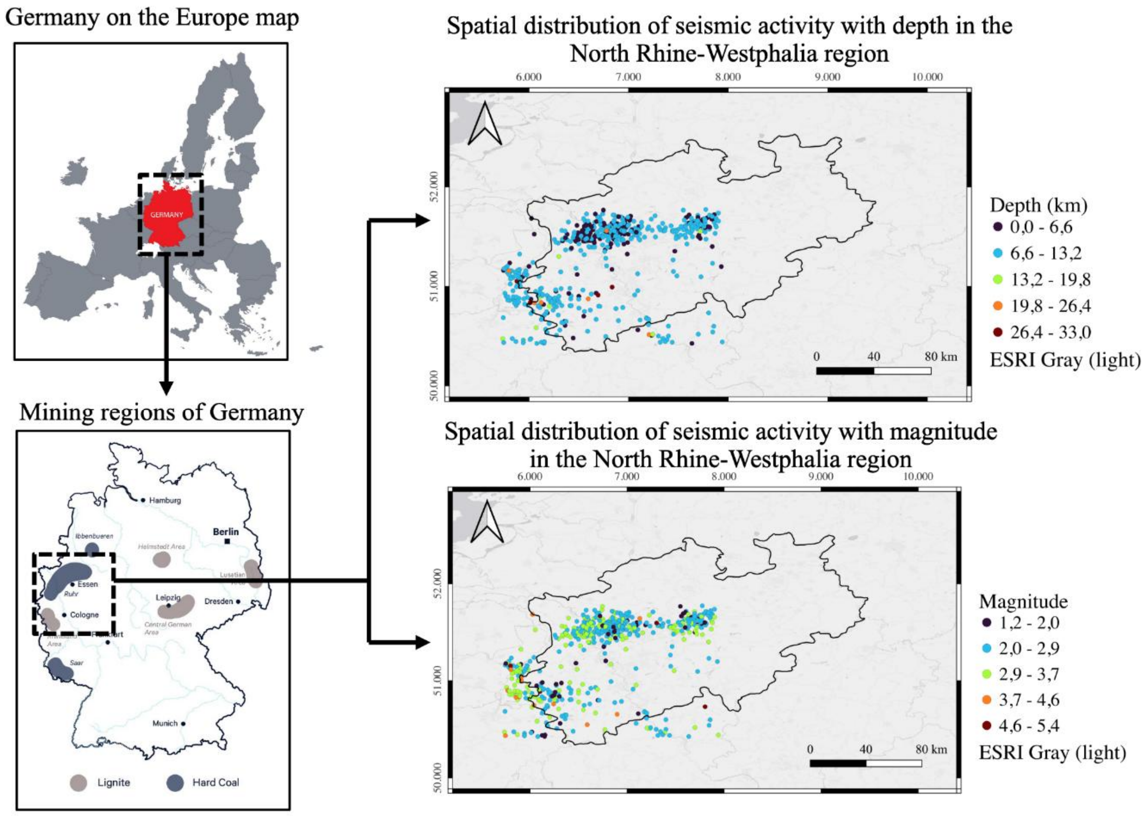

Fig. 1. Study area: spatial distribution of seismic activity within the mining area.

One commonly used spatial method is nearest-neighbor analysis (NNA), which assesses whether earthquake epicenters are randomly distributed or tend to form clusters [Peresan and Gentili, 2018]. A clustered pattern may indicate the influence of geological structures such as faults or localized stress changes related to industrial activity. Another useful technique is kernel density estimation (KDE), which transforms individual earthquake points into a continuous surface showing areas with higher concentrations of seismic events [Amador Luna et al., 2024]. This method helps to visualize zones of increased seismic activity within a study region. In addition to spatial analysis, the statistical relationship between earthquake magnitude and frequency can be described using the Gutenberg-Richter law. This relationship shows that smaller earthquakes occur much more frequently than larger ones. The parameters of this relationship provide useful information about the level of seismic activity in a region and the stress conditions within the crust. In particular, the b-value indicates the relative proportion of small and large earthquakes and is commonly used in studies of both natural and induced seismicity [Plourde 2023].

Several studies have investigated seismicity in the Lower Rhine Embayment. For example, [Hinzen et al., 2021] analyzed seismic activity in the Northern Rhine Area using instrumental earthquake records from 1995-2018. That study demonstrated that the region exhibits continuous low-to-moderate seismicity related to active fault systems within the rift structure and highlighted the importance of detailed seismic catalogs for understanding regional earthquake behavior. Similarly, [Pilz et al., 2021] investigated ground-shaking characteristics in the Lower Rhine Embayment using broadband simulations and found that the sedimentary basin structure significantly influences ground-motion amplification during earthquakes. More recently, [Najdahmadi et al., 2023] examined the potential for seismic monitoring and early warning in the Lower Rhine Embayment by optimizing the configuration of regional seismic networks. Their research demonstrated that improving the density and spatial distribution of seismic stations can significantly enhance earthquake detection and early warning performance in the region, which is characterized by scattered low-magnitude seismicity. In addition to instrumental observations, geological investigations have also revealed evidence of long-term tectonic activity along major fault systems in the region. Paleoseismological studies of structures such as the Feldbiss Fault indicate repeated surface-rupturing earthquakes during the Late Pleistocene and Holocene, suggesting that the Lower Rhine Graben remains an active tectonic zone capable of generating moderate to strong earthquakes [Steinritz et al., 2026]. Although these studies made significant contributions, further analysis of earthquake catalogs remains important for improving the understanding of seismic patterns in this region. Combining spatial statistical techniques with magnitude-frequency analysis can provide valuable information about how earthquakes are distributed and what factors may influence their occurrence.

Purpose

The main objective of this study is to analyze the spatial and statistical characteristics of earthquakes in North Rhine-Westphalia using a seismic catalog covering the period from 1970 to 2026. The study applies descriptive statistical analysis, GIS-based analysis including nearest-neighbor analysis and kernel density estimation, as well as Gutenberg-Richter frequency-magnitude analysis. These methods are used to evaluate the spatial distribution, temporal variability, and magnitude characteristics of seismic events in the study area. The results contribute to a better understanding of seismic processes in a region where tectonic activity and intensive mining operations coexist.

Study area

The study area is the North Rhine-Westphalia in western Germany, one of the most industrialized regions in Europe (see Fig. 1). The region lies within the western part of the North German Plain and includes parts of the Rhenish Massif, a geologically complex area characterized by Paleozoic basement rocks and sedimentary basins [Najdahmadi et al., 2023]. The study area is particularly influenced by the tectonic structures of the Lower Rhine Embayment, an active Cenozoic rift system that forms part of the larger European Cenozoic Rift System. This rift zone is associated with extensional tectonics and contains several normal faults that contribute to the occurrence of natural seismicity [Lehmkuhl et al., 2023]. In addition to tectonic influences, seismic activity in the region is also associated with intensive industrial activities, particularly large-scale lignite mining operations in the Rhenish lignite mining district [Dahmen 2024]. Surface mines such as Garzweiler Mine, Hambach Mine, and Inden Mine significantly modify subsurface stress conditions through excavation, groundwater lowering, and mass redistribution, which contribute significantly to induced seismicity [Dahmen 2024; Prinz et al., 2018]. As shown in Figure 1, the study area exhibits a clear spatial distribution of seismicity concentrated within and around the mining region. The seismic events, extracted from the available catalog, are considered representative of the overall seismic activity in the area during the study period. Notably, the spatial clustering of these events directly overlies the active mining zone. Based on this spatial coincidence, it is reasonable to infer a connection between the observed seismicity and mining operations, although the analysis focuses on characterizing the overall seismicity pattern rather than explicitly attributing causality.As a result, the region provides an important natural laboratory for studying both tectonic and anthropogenic earthquake processes.

Data and methodology

Seismic data

The seismic dataset used in this study was obtained from the open-access database of the Incorporated Research Institutions for Seismology (IRIS) [IRIS 2026]. Earthquake events in the study region of North Rhine-Westphalia, Germany, were extracted from the IRIS seismic catalog for the period 1970-2026. The dataset includes information on earthquake origin time, geographic coordinates (latitude and longitude), focal depth, and magnitude.

The IRIS catalog covers a multi-decadal period of observation and includes events of varying magnitudes recorded under evolving seismic network conditions. Catalog completeness is a critical factor in seismicity analysis, as the detection capability of seismic networks changes over time due to improvements in instrumentation, station density, and data processing techniques [Woessner and Wiemer 2005]. As a result, smaller-magnitude earthquakes are more likely to be underreported in earlier periods of the catalog, while more recent data generally provide a more complete record. To account for this, the frequency-magnitude distribution of the dataset was performed, and a magnitude of completeness was estimated based on the observed derivation from linearity in the Gutenberg-Richter relationship. Earthquakes with magnitudes below the magnitude of completeness are excluded from the statistical analysis to ensure the robustness of the calculated parameters. The magnitude of completeness was estimated using the maximum curvature method [Woessner and Wiemer 2005] and the estimated value was found to be 1.0 that is lower than the minimum magnitude in the catalog, indicating that the entire dataset used in this study falls within the complete part of the seismic record. Therefore, no additional magnitude filtering was required for the analysis.

GIS-based spatial analysis

To investigate the spatial characteristics and behavior of seismic events, two complementary spatial statistical techniques were applied: NNA and KDE. NNA was used to evaluate whether the spatial distribution of earthquake epicenters is random, clustered, or dispersed. This method measures the distance between each seismic event and its closest neighboring event and compares the observed mean distance with the expected mean distance for a randomly distributed dataset. The nearest neighbor ratio is defined as it is shown in equation (1) [Peresan and Gentili 2018]:

$$R = \frac{D_O}{D_e} = \frac{D_O}{2\sqrt{\frac{n}{A}}} \quad (1)$$

where ***Do*** is the observed mean nearest neighbor distance in km and ***De*** is the expected mean distance for a random spatial distribution in km, ***n*** is the number of earthquake events, and A is the area of the study region in square km. Values of R<1 indicate clustering, R=1 suggests a random pattern, and R>1 indicates dispersion.

This method is particularly useful for identifying localized concentrations of seismic activity associated with mining operations. In regions affected by large-scale resource extraction, stress redistribution due to excavation, groundwater withdrawal, or mass removal can lead to spatially clustered seismic events. Therefore, NNA provides an initial quantitative assessment of whether seismicity in the study area exhibits clustering that may be related to mining activities.

KDE is a spatial analysis technique used to identify areas with high concentrations of earthquake events. Instead of showing earthquakes as individual points, KDE creates a continuous surface that represents the density of events across the study region. This density at a given location is calculated using equation (2) [Amador Luna et al., 2024]:

$$f(x) = \frac{1}{nh^2}\sum_{i=1}^{n} K\left(\frac{x-x_i}{h}\right) \quad (2)$$

where *f(x)* is the estimated density at location x (earthquakes per km^2), n is the total number of earthquake events, h is the radius (km), and x_i represents the location of each earthquake. K is the kernel function that assigns higher weights to nearby events and lower weights to distant ones.

Gutenberg-Richter frequency magnitude analysis

To characterize the statistical relationship between earthquake magnitude and occurrence frequency, the Gutenberg-Richter frequency-magnitude relationship was applied to the seismic catalog. This empirical relation, originally developed by [Gutenberg and Richter 1944], describes how the logarithmic decrease in the number of earthquakes with increasing magnitude and remains a fundamental tool in seismology. It continuous to be widely used in contemporary earthquake studies to evaluate seismic activity and stress conditions in different regions [Taroni et al., 2021; Islam et al., 2023; Mitsui 2024]. The relationship is expressed as equation (3):

$$logN = a - bM \quad (3)$$

where N represents the cumulative number of earthquakes with magnitude greater than or equal to ***M***. Parameter a describes the overall level of seismic activity in the region, while b indicates the relative proportion of small to large earthquakes.

The a-value reflects the seismic activity in the study area: higher values indicate a greater number of earthquakes. In contrast, the b-value provides insight into the crust's stress conditions [Gutenberg and Richter 1944].

Results

Spatial and statistical characteristics of seismic events

Table 1 summarizes the descriptive statistics of earthquake magnitude and focal depth derived from a dataset of 626 seismic events, highlighting the main characteristics of local seismicity in terms of central tendency, dispersion, and range of the analyzed parameters.

Table 1

Descriptive statistical characteristics of earthquake magnitude and focal depth for the analyzed seismic dataset

	Magnitude	Depth
Mean	2.73	7.96
Median	2.70	10.00
Minimum	1.20	0.00
Maximum	5.40	33.00
Standard deviation	0.512	4.52

According to Table 1, the magnitude values range from 1.20 to 5.40, with a mean magnitude of 2.73 and a median of 2.70, indicating that the seismicity in the study area is dominated by low-to-moderate magnitude earthquakes. The close agreement between the mean and median values suggests a relatively symmetric distribution of magnitudes, with little skew toward extremely large events. The standard deviation of 0.512 further indicates that most earthquakes cluster within a narrow magnitude interval around the mean, reflecting relatively uniform seismic energy release within the analyzed catalog. The focal depth of the earthquakes varies from 0 km to 33 km, with a mean depth of 7.96 km and a median depth of 10 km. These values indicate that most events occur at shallow crustal levels, which is typical for induced seismicity [Foulger et al., 2018]. The slightly higher median compared to the mean suggests a minor skew toward shallower events, as several very shallow earthquakes lower the average depth. The standard deviation of 4.52 km indicates moderate variability in focal depths, implying that while most events occur within the upper crust, some earthquakes extend to deeper levels within the seismogenic zone. The ridgeline plots of earthquake magnitude and depth distributions shown in Fig. 2 and Fig. 3 further confirm it. Thus, Fig. 2 provides a temporal perspective on changes in seismic energy release throughout the study period.

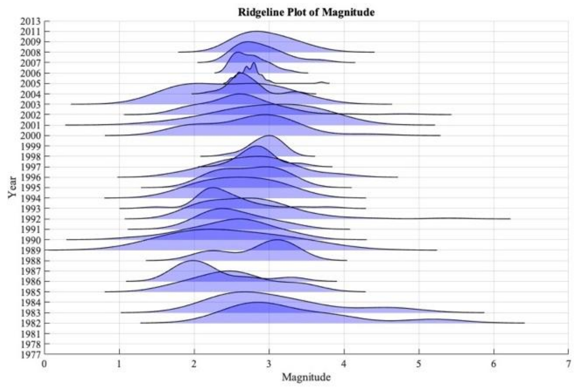

Fig. 2. Temporal distribution of earthquake magnitudes visualized with a ridgeline plot.

Across most years, the magnitude distributions exhibit peaks centered at 2.5–3.5, indicating that moderate-to-low magnitude earthquakes consistently dominate the seismic record. The distributions are generally unimodal and relatively narrow, suggesting stable magnitude characteristics through time. However, some years exhibit broader distributions or longer tails toward higher magnitudes, implying occasional occurrences of larger seismic events during those periods. For instance, several years show magnitudes exceeding 4.0 and even approaching 5.0, reflecting intermittent increases in seismic intensity. Despite these variations, the central tendency remains consistent, indicating that the overall seismic regime has not experienced significant long-term shifts in magnitude characteristics.

The ridgeline plot of earthquake depth distributions in Fig. 3 reveals the vertical structure of seismicity and its temporal variability across the study period. Most events are concentrated at shallow depths, generally between 0 and 15 km, reinforcing the interpretation that seismic activity predominantly occurs within the brittle upper crust. Several annual distributions show peaks around 5–10 km, suggesting recurring activation of similar crustal fault zones . In some years, the depth distributions appear wider, extending to 20 km or deeper, which may indicate episodic occurrences of deeper seismic activity possibly related to variations in stress transfer or localized tectonic processes.

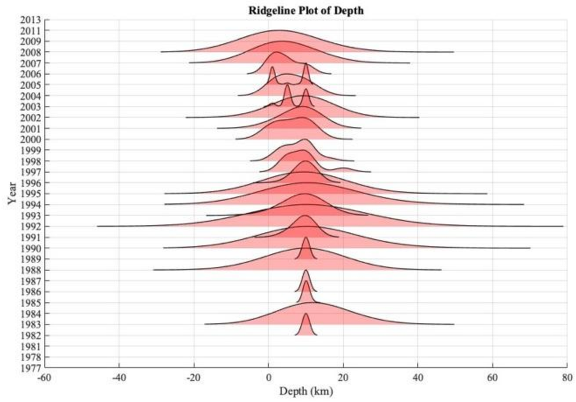

Fig. 3. Temporal distribution of earthquake depths visualized with a ridgeline plot.

The magnitude-depth scatter plot in Fig. 4 illustrates the relationship between earthquake magnitude and focal depth throughout the study period.

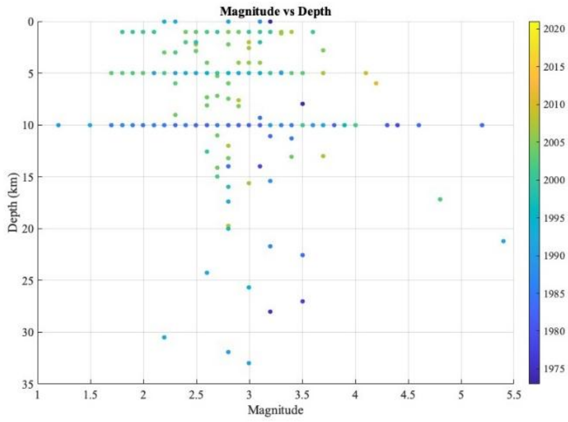

Fig. 4. Magnitude-depth distribution of earthquakes.

Several clusters of events are visible at depths of approximately 5 km and 10 km, reflecting the repeated activation of specific crustal fault zones or structural discontinuities. Higher-magnitude earthquakes exceeding 4.0 are comparatively infrequent and occur across a range of shallow to intermediate depths, indicating that larger events are not restricted to a particular depth interval. The temporal color gradient demonstrates that seismic events are distributed across the entire observation period without a pronounced concentration in specific magnitude-depth combinations.

Occasional earthquakes occurring at depths greater than 20 km also happen, although they remain relatively rare and generally exhibit moderate magnitudes. These deeper events reflect localized stress accumulation or rupture within the lower portions of the brittle crust. Therefore, in general, the scatter plot suggests that seismic activity in the study region is mainly influenced by shallow crustal processes.

Finally, the temporal distribution of earthquake occurrences in Fig. 5 demonstrates substantial variability in seismic activity throughout the observation period.

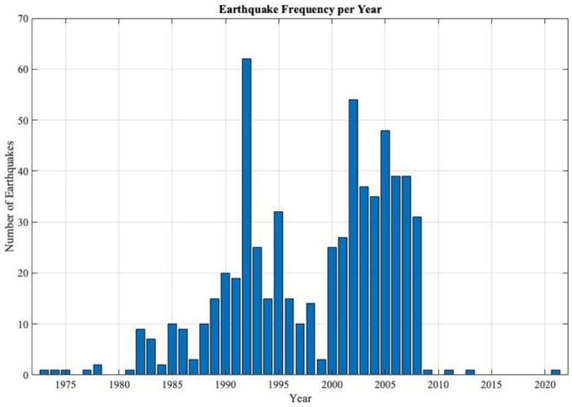

Fig. 5. Frequency plot of seismic events per year.

During the early years of the catalog, the number of recorded earthquakes remained very low, typically fewer than 2 per year. Beginning in the mid-1980s, the annual number of earthquakes gradually increased. A pronounced peak occured in the early 1990s, with the highest annual count exceeding 60 events. Following this peak, the frequency decreased during the mid-1990s but rose again during the early 2000s. Between approximately 2001 and 2007, earthquake counts remained consistently high, generally ranging between 30 and 55 events per year. This period represented a sustained phase of increased seismicity in the region. After 2008, the number of recorded earthquakes dropped sharply, with only isolated events occurring in subsequent years. Overall, the temporal pattern suggests that seismic activity in the study area is not uniform over time but occurs in clusters of elevated activity separated by periods. This episodic behavior is consistent with patterns observed in regions affected by anthropogenic seismicity [Chen et al., 2023].

Regarding the spatial analysis, NNA was conducted to assess the spatial distribution pattern of earthquake epicenters in the study area. The analysis compares the observed average distance between each earthquake and its closest neighbor with the expected distance assuming a random spatial distribution. The results indicate that the observed mean nearest neighbor distance (Do) is 2.30 km, while the expected mean distance (De) for a random distribution is 3.15 km. This yields a Nearest Neighbor Index (R) of 0.73. Since the calculated value R = 0.73 is less than 1, the spatial distribution of earthquakes in the dataset indicates a clustered pattern. The statistical significance of this pattern is further supported by a Z-score of –3.21, which exceeds the critical threshold of ±1.96 for the 95 % confidence level. This result suggests that the clustering of earthquake events is statistically significant and unlikely to be due to random processes. The kernel density map in Fig. 6 illustrates the spatial distribution of earthquake epicenters and highlights zones of concentrated seismic activity within the study region.

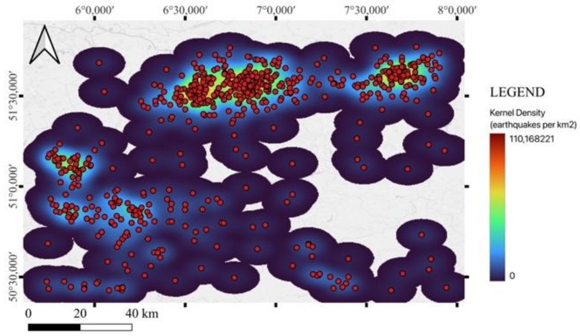

Fig. 6. Kernel density estimation of earthquake epicenters.

Therefore, several distinct areas of high seismic density are visible. The most prominent cluster is located in the central-northern part of the study area, where the highest density values are observed. This concentration suggests the presence of localized processes that promote earthquake occurrence. Additional clusters are visible in the western and northeastern parts of the region, although their densities are lower than those of the central cluster. These patterns indicate that seismic activity is not uniformly distributed but instead occurs in spatially localized concentrations.

Gutenberg-Richter seismic parameters

The observed data points display a generally linear trend on the semi-logarithmic plot shown in Fig. 7, indicating that the seismicity of the study area follows the Gutenberg-Richter frequency-magnitude relationship. The fitted regression line closely matches the observed data over most of the magnitude range, suggesting that the earthquake catalog is statistically consistent and that the Gutenberg-Richter model adequately describes the magnitude distribution of the recorded events. The calculated parameters of the relationship yield an a-value of 5.267 and a b-value of 1.019. The obtained b-value is very close to 1.0, which is typical for many tectonically active regions and indicates a balanced distribution of small and large earthquakes within the catalog. Such a value suggests that the seismic regime of the study area is characterized by a predominance of smaller-magnitude events, while still allowing for the occasional occurrence of moderate earthquakes [Geffers et al., 2022].

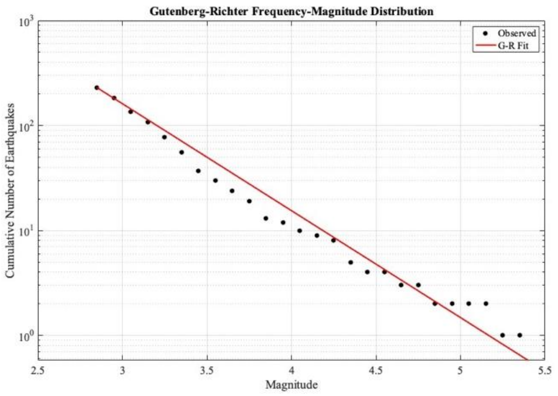

Fig. 7. Frequency-magnitude distribution of earthquakes based on the Gutenberg-Richter relationship.

Discussions

The results of this study offer insight into the spatial, temporal, and statistical characteristics of seismicity in the North Rhine-Westphalia region, particularly within the tectonically active Lower Rhine Embayment. The analyzed earthquake catalog indicates that seismic activity in the study area is dominated by low-to-moderate magnitude earthquakes, with a mean magnitude of 2.73 and relatively small variability. Such magnitude characteristics are typical for intraplate regions, where seismic activity occurs along pre-existing crustal weaknesses rather than major plate boundaries. Previous studies have similarly reported that seismicity within the LRE is generally moderate compared with Mediterranean plate boundary regions. Although it is one of the most seismically active areas in Germany due to active normal faults associated with the rift system [Pilz et al., 2021].

The predominance of shallow earthquakes observed in this study alligns with earlier investigations of seismicity in mining and rift environments. Most earthquakes in the analyzed catalog occur at depths between 0 and 15 km, suggesting that seismic deformation is largely confined to the brittle upper crust. Shallow seismicity is frequently associated with both natural tectonic processes and anthropogenic influences such as mining-related stress redistribution. Previous research has shown that large-scale lignite and coal mining operations in western Germany can trigger numerous shallow seismic events due to excavation, subsidence, and groundwater withdrawal, which modify the local stress field [Steinritz et al., 2026].

The spatial statistical analysis further supports the interpretation that seismicity in the study area is not randomly distributed. The nearest neighbor index of 0.73 indicates a statistically significant clustered spatial pattern. Such clustering is typical for regions where seismicity is controlled by localized structures such as faults or mining areas. Similar spatial clustering of earthquakes has been documented in mining districts in Germany, where seismic events tend to concentrate around active extraction zones or along pre-existing geological discontinuities [Bischoff et al., 2010]. The kernel density analysis performed in this study highlights several zones of elevated seismic density, suggesting that specific structural or anthropogenic factors may be controlling earthquake occurrence in these areas.

Temporal variations in the catalog further emphasize the episodic nature of earthquake activity in the region. Periods of increased seismicity, particularly during the early 1990s and early 2000s, indicate that seismic processes in the study area may be influenced by time-dependent stress changes. Such temporal clustering has also been observed in previous studies of induced seismicity, where variations in industrial activity or fluid extraction can lead to fluctuations in earthquake occurrence rates [Azari Sisi et al., 2025]. Although the present analysis does not explicitly correlate seismicity with mining production data, the temporal variability observed in the dataset is consistent with patterns reported in anthropogenic seismic environments.

The Gutenberg-Richter analysis performed in this study yielded a b-value of 1.019, which is close to the typical global average of approximately 1.0. This suggests a balanced distribution of small and moderate earthquakes within the analyzed catalog. Previous studies in the Lower Rhine Embayment have reported similar ranges of b-values, although variations of approximately 0.8 – 1.2 have been documented depending on the analyzed fault systems and datasets [Schmedes et al., 2005]. Higher b-values generally indicate a greater proportion of smaller earthquakes, which may reflect lower stress levels or the influence of induced seismicity mechanisms. In contrast, lower b-values are often associated with higher differential stresses within the crust.

Despite the insights provided by the present analysis, several limitations should be acknowledged. First, the seismic catalog used in this study is derived from a global open-access database; therefore, the completeness of the catalog may vary through time depending on changes in the seismic monitoring network and detection capabilities. Earlier decades of the dataset likely contain fewer recorded events due to lower instrumental sensitivity, which may influence the interpretation of temporal seismicity trends. Despite these inherent limitations, the dataset used in this study is considered sufficiently robust for the intended analysis. The frequency-magnitude distribution exhibits a stable and consistent behavior for the magnitude range of interest, indicating that the catalog adequately captures the dominant seismicity patterns in the study area. This is consistent with findings from previous studies, which demonstrate that global and regional catalogs such as IRIS provide reliable estimates of Gutenberg-Richter parameters when appropriate magnitude ranges are considered [Casey et al., 2018; Sumy et al., 2020; Chasanah and Handoyo, 2021]. Therefore, while minor temporal variations in completeness cannot be entirely excluded, they do not significantly affect the overall interpretation of seismic activity patterns presented in this study. The analysis is focused on statistically meaningful magnitude ranges, ensuring that the derived parameters remain representative and scientifically sound. Second, the study primarily relies on statistical and spatial analyses of earthquake occurrence without incorporating detailed geological, geomechanical, or mining-production data. As a result, the direct relationship between specific mining operations and individual seismic events cannot be definitively established. Future research could therefore address these limitations by integrating additional datasets and analytical approaches. For example, combining seismic catalogs with detailed information on mining activities, such as excavation volumes, groundwater extraction rates, and operational timelines, could help establish stronger correlations between industrial processes and seismic events. Furthermore, incorporating geological and fault-structure datasets would allow for a more comprehensive assessment of how tectonic features control the spatial distribution of earthquakes. Advanced statistical techniques, including spatiotemporal clustering analysis, machine learning and stress-field modeling, could also improve the identification of potential triggering mechanisms. Finally, high-resolution local seismic networks and moment tensor analyses would provide more precise information on earthquake source mechanisms, helping to distinguish between tectonic and mining-induced seismicity.

Originality

This study integrates long-term seismic records with GIS-based spatial statistical methods to provide a comprehensive assessment of seismicity in North Rhine-Westphalia, highlighting the combined effects of tectonic structures and mining-induced activities.

Practical significance

The results enhance understanding of regional seismic hazards and provide valuable insights for risk assessment, land-use planning, and managing mining-related seismic risks in the region.

Conclusion

This study investigated the spatial, temporal, and statistical characteristics of seismic activity in North Rhine-Westphalia, Germany, using an earthquake catalog containing 626 events recorded between 1970 and 2026. The results provide several important insights into the nature of seismicity within the Lower Rhine Embayment. The descriptive statistical analysis indicates that the seismic regime of the study area is dominated by low- to moderate-magnitude earthquakes with shallow focal depths. Most events occur within the upper crust, typically between 0 and 15 km depth. This is consistent with both tectonic fault activity and anthropogenic seismic processes associated with mining operations. Spatial statistical analysis revealed that earthquake epicenters exhibit a clustered distribution. The nearest-neighbor index (R=0.73) and the corresponding negative Z-score indicate that this clustering is statistically significant and unlikely to result from random spatial processes. Kernel density mapping further identified several localized zones of elevated seismic activity, suggesting that specific geological structures or mining areas may influence earthquake occurrence. Temporal analysis of the seismic catalog showed that earthquake activity is not constant through time but occurs in episodic phases characterized by increased seismicity followed by quieter periods. This behavior is typical for regions affected by stress redistribution related to mining and industrial operations. The Gutenberg-Richter frequency-magnitude analysis demonstrates that the seismic catalog follows a clear linear trend in the semi-logarithmic domain, confirming the applicability of the Gutenberg-Richter relationship to the study region. The calculated b-value of approximately 1.0 indicates a predominance of smaller-magnitude earthquakes while still allowing for occasional moderate seismic events.

Acknowledge

The earthquake data used in this study were obtained from the open-access database of the Incorporated Research Institutions for Seismology (IRIS). All statistical analyses and calculations were performed using MATLAB R2024a, while spatial processing, mapping, and geospatial analyses were conducted in QGIS 3.44 Solothurn. The availability of these open-source datasets and analytical tools greatly facilitated the implementation and competition of this research. This study was conducted as part of the graduate-level course ‘GIS in Mining’, taught by the author at Technical University ‘Metinvest Polytechnic’ LLC.

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СТАТИСТИЧНА ТА ПРОСТОРОВА ОЦІНКА ТЕХНОГЕННОЇ СЕЙСМІЧНОСТІ З ВИКОРИСТАННЯМ ГІС

Мета. Дане дослідження присвячене аналізу сейсмічної поведінки регіону Північний Рейн-Вестфалія (західна Німеччина) з акцентом на тектонічно активну Нижньорейнську западину та прилеглий Рейнський буровугільний гірничопромисловий район. Основною метою є характеристика просторових, часових і магнітудних закономірностей сейсмічності, а також оцінка впливу як природних, так і антропогенних чинників. Методика. Для дослідження використано каталог із 626 землетрусів, зареєстрованих у період з 1970 по 2026 рік, отриманий з відкритої бази даних. Набір даних включає інформацію про магнітуду, глибину землетрусу, географічне положення та час землетрусу. У роботі застосовано методи статистики та просторового аналізу з використанням геоінформаційних систем (ГІС), а також аналіз «частота-магнітуда». Для дослідження просторових закономірностей використано аналіз nearest neighborhood та kernel density, тоді як часові зміни та співвідношення Гутенберга-Ріхтера застосовано для оцінки сейсмічних тенденцій. Результати. Отримані результати свідчать, що сейсмічність досліджуваного регіону характеризується переважанням землетрусів малої та середньої магнітуди із середнім значенням 2.73, при цьому осередки переважно зосереджені у верхній частині земної кори. Більшість землетрсів відбувається на глибинах від 0 до 15 км, що вказує на переважно неглибокі сейсмічні процеси. Просторовий аналіз показав кластеризований розподіл епіцентрів землетрусів (індекс nearest neighborhood 0.73), а kernel density дозволила виділити декілька зон підвищеної сейсмічної активності. Часовий аналіз демонструє нерівномірність сейсмічної активності з періодами її зростання та зниження. Співвідношення Гутенберга-Ріхтера характеризується чіткою лінійною залежністю з b-значенням 1.019, що свідчить про домінування землетрусів малої магнітуди. Наукова новизна. У дослідженні поєднано довгострокові сейсмічні спостереження з методами просторового аналізу на основі ГІС, що дозволило комплексно оцінити сейсмічність регіону та виявити взаємодію тектонічних структур і техногенних факторів. Практична значущість. Отримані результати сприяють кращому розумінню регіональних сейсмічних небезпек і можуть бути використані для оцінки ризиків, просторового планування територій та управління сейсмічними ризиками, пов’язаними з гірничою діяльністю.

Ключові слова: ГІС, техногенна сейсмічність, просторова оцінка густини, просторовий аналіз, співвідношення Гутенберга-Ріхтера, геостатистика.

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