

ORIGINAL



Hydrogeoseismological variations in groundwater parameters in the bukhara region and their correlation with seismic activity

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ABSTRACT

Bukhara Region, one of the seismically active areas of Uzbekistan, is classified as a high seismic risk zone. Pre-seismic variations in groundwater levels and their chemical composition are often considered indicators of the onset or preparatory phase of seismic activity. The earthquake of magnitude $M=4.2$ that occurred on January 14, 2025, in the Karakul district of Bukhara Region, followed by another event of magnitude $M=4.0$ on January 23, 2025, in the nearby area, prompted an analysis of groundwater parameter anomalies observed in this region. This study analyzes variations in groundwater parameters prior to these earthquakes, based on hydrogeoseismological data obtained from a deep borehole in Bukhara Region. Identifying correlations between hydrogeoseismological anomalies and seismic events allows for associating seismicity with changes in groundwater gas composition, geochemical processes, and other physical parameters.

KEYWORDS

Hydrogeoseismology;
Earthquake prediction;
Geochemical anomalies;
Physical parameters;
Geomagnetic field; (CO_2 , He, Ph); Groundwater chemistry;
Hydrogeoseismological monitoring

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Introduction

Recent decades have witnessed increasing interest in hydrogeoseismology the study of groundwater responses to seismic activity as a promising approach to identify earthquake precursors. The discipline integrates hydrogeological, geochemical, and geophysical data to understand the behavior of groundwater systems before, during, and after seismic events.

Radon monitoring as an earthquake precursor

One of the earliest and most consistent indicators of seismic activity identified in hydrogeoseismology is radon gas. Studies such as those by Teng and Sun provided foundational insights into the use of groundwater radon anomalies as fluid-phase precursors to earthquakes [1]. Building on this, Negarestani et al. designed a continuous radon monitoring network for Tehran, demonstrating how such systems can effectively capture pre-seismic radon fluctuations [2]. Similarly, Negarestani et al. employed layered neural networks to correlate radon concentration changes with environmental parameters in the context of earthquake prediction [3]. Zoran et al. confirmed this approach in Romania's Vrancea region, where significant correlations between radon levels and local seismicity were established [4]. Namvaran and Negarestani further refined the methodology by applying Kalman filtering to reduce noise in radon data, enhancing its predictive utility [5].

Isotopic and chemical anomalies

In addition to radon, isotopic anomalies in groundwater have been extensively investigated. Onda et al. reported oxygen isotope anomalies preceding the $M6.6$ Tottori earthquake in Japan, suggesting isotopic ratios as reliable indicators of deep-seated fluid movements [6]. Sano et al. analyzed hydrogeochemical shifts related to CO_2 sequestration and a

subsequent earthquake, highlighting the complexity of anthropogenic and natural interactions in seismically active zones [7]. Liang et al. studied $\delta^{13}\text{C}$ - CO_2 -DIC isotopic signatures in geothermal springs along the Xianshuihe Fault in China, linking them with deep tectonic activity [8].

Groundwater level and pressure fluctuations

Changes in groundwater level and pressure have also been linked to seismic events. Matsumoto et al. explored the detectability of such anomalies using Japan's groundwater observation network, particularly in the context of the anticipated Tokai earthquake [9,10]. Nakagawa et al. employed self-organizing maps to analyze temporal variations in groundwater chemistry following the 2016 Kumamoto earthquake, revealing how machine learning techniques can improve anomaly detection [11].

Hydrochemical and multivariate anomalies

Hydrogeochemical indicators such as pH, Eh, ion concentration, and gas levels (CO_2 , He, CH_4) are central to many earthquake precursor studies. Martinelli reviewed hydrogeologic and geochemical precursors globally, while Martinelli et al. provided a 50-year overview of tectonic-related anomalies in Italy [12,13]. In another contribution, Martinelli et al. focused on recovering and processing hydrogeochemical parameters for short-term forecasting [14]. Their collaborative research emphasized multidisciplinary strategies in understanding pre-seismic fluid dynamics [15].

Integrated monitoring and modeling approaches

Advances in modeling and multi-parameter monitoring have expanded the scope of hydrogeoseismological research. Lai G et

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al. identified multiple mechanisms behind coseismic water level changes in China's Rongchang well, illustrating the complex interactions between seismic strain and fluid dynamics [16]. Yusupov et al. conducted a regional analysis in Uzbekistan's Bukhara region, documenting changes in pH, CO₂, and redox potential preceding moderate- magnitude earthquakes [17]. Their work contributes important local context to the growing global literature on pre-seismic hydrogeochemical anomalies.

Broader applications and trends

Research trends are increasingly moving toward real-time monitoring and the integration of hydrological, chemical, and geophysical data. Martinelli and Dadomo summarized ongoing research strategies in pre-earthquake processes, advocating for continuous, high-resolution, and interdisciplinary data acquisition [15]. These recommendations align with global efforts to operationalize hydrogeoseismological techniques for early warning systems.

Hydrogeoseismology has emerged as a vital interdisciplinary field, linking geophysics, geochemistry, and seismology to understand and forecast seismic activity through groundwater monitoring. Numerous studies have shown that hydrogeoseismological anomalies particularly changes in the chemical, gaseous, and isotopic composition of groundwater can serve as reliable precursors of earthquakes.

A primary mechanism behind these anomalies is the interaction between groundwater and host rock formations, which leads to gas-geochemical reactions. These processes are not solely a result of chemical disequilibrium but are fundamentally driven by disturbances in the thermohydrodynamic equilibrium of aquifer systems. Such disturbances often precede seismic events and manifest as measurable variations in groundwater parameters.

Research indicates that increases in CO₂ and helium (He) concentrations, pH shifts, groundwater level fluctuations, and even geomagnetic field anomalies are often observed in seismically active zones prior to earthquakes. For example, a decrease in pH and a rise in CO₂ concentration are frequently reported in pre-seismic periods, indicating systematic changes in the hydrochemical environment. These variations are believed to reflect subsurface geodynamic activities, such as fault movements or stress accumulation in the Earth's crust.

Helium and radon emissions, as well as methane and other gas concentrations, are also considered valuable indicators. Their anomalous behavior prior to seismic events is often attributed to increased rock permeability and fracturing, which facilitate gas migration toward the surface. Similarly, changes in the geomagnetic field have been linked to electrokinetic phenomena triggered by fluid movement in the crust, adding another layer of complexity to pre-seismic diagnostics.

The Bukhara Region of Uzbekistan, known for its seismic vulnerability, provides a significant case study. Prior to the

earthquakes on January 14 (M = 4.2) and January 23 (M = 4.0), 2025, researchers documented marked changes in various hydrogeoseismological indicators. These included alterations in gas concentrations, redox potential (Eh), pH levels, and geomagnetic field variations. Observations from monitoring boreholes showed a consistent pattern of decreasing pH and increasing CO₂ levels, aligning with previously documented pre-seismic anomalies in other global seismic zones.

These findings underscore the potential of hydrogeoseismological monitoring as a cost-effective and reliable tool for short-term earthquake forecasting. Continued research in this area, particularly in high-risk zones such as Bukhara, can contribute to the development of early warning systems and mitigate seismic hazards through improved preparedness [1-5].

Methods and Materials

Alongside changes in hydrogeoseismological parameters, simultaneous variations in the local geomagnetic field were also detected. This allows for the integrated analysis of the processes involved. Below, we will examine the analysis of groundwater samples collected from the Jongeldi and Gumbaz boreholes located in the Bukhara Region [6-12].

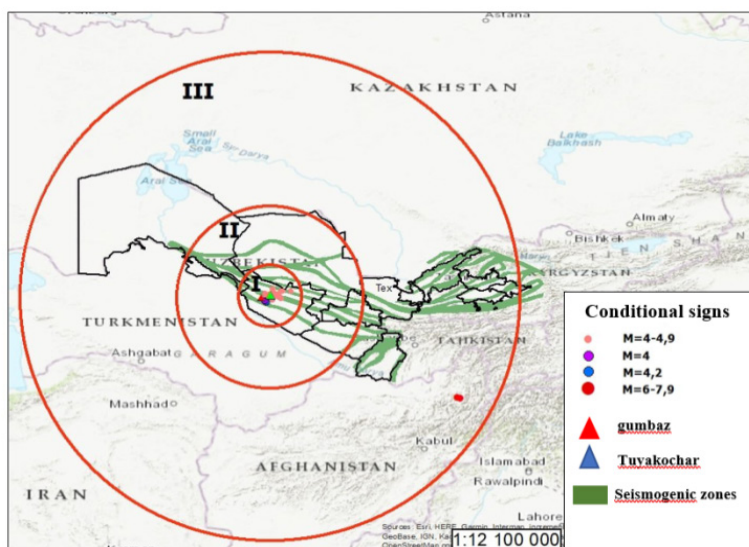


Figure 1. Location of Tuvakochar and Gumbaz Boreholes and Earthquakes with Magnitude Greater than M-4 (Source: Institute of Seismology, 2025)

This map illustrates (Figure 1) the earthquakes that occurred around the Jongeldi and Gumbaz observation boreholes, located in the Bukhara region. Earthquakes of varying magnitudes are marked with colored dots: yellow dots represent earthquakes with magnitudes ranging from M=4.0 to M=4.9; the earthquake of M=4.2 that occurred on January 14, 2025, is marked in light blue; the M=4.0 earthquake on January 23, 2025, is indicated with a blue dot; and strong earthquakes with magnitudes between M=6.0 and M=7.9 are shown in red. To monitor seismic activity, circular boundaries with radii of 100 km, 300 km, and 800 km have been drawn around the boreholes. These concentric circles help to assess the spatial impact of seismic events on the areas surrounding the observation sites [13-17].

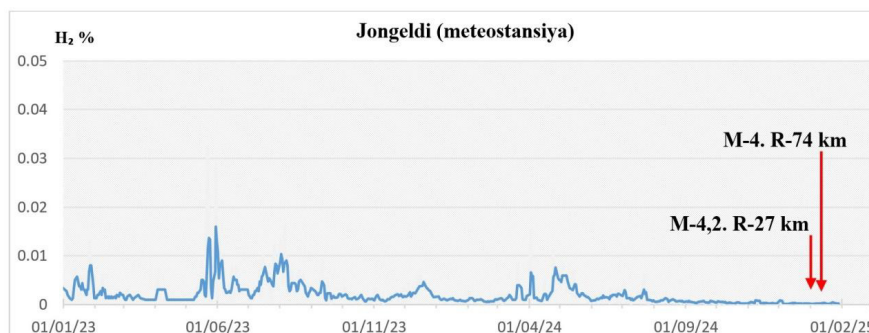


Figure 2. Two-Year Variation Graph of Hydrogen Concentration in Groundwater Samples from the Jongeldi (Meteorological Station) Borehole

Since the beginning of 2023 (Figure 2), the concentration of hydrogen (H_2) in groundwater has exhibited significant fluctuations. Particularly during May-June 2023, marked spikes in H_2 levels were observed, possibly associated with increased subsurface gas emissions linked to tectonic stress accumulation. In 2024, although hydrogen concentrations appeared relatively stable, slight increases were recorded at certain intervals. By the end of January 2025, H_2 levels had sharply declined, approaching near-zero values. The pronounced increase in hydrogen concentration during the spring and summer of 2023 may be indicative of pre-seismic degassing processes where tectonic strain facilitates the release of gases such as H_2 from fault zones into aquifers. Conversely, the drastic drop in H_2 levels prior to the $M=4.2$ (27 km depth) and $M=4.0$ (74 km depth) earthquakes in late January 2025 suggests a release of accumulated gas, followed by a pressure drop post-degassing. This behavior aligns with established models of geochemical precursors to seismic events, highlighting hydrogen as a potential early warning indicator in hydrogeoseismological monitoring.

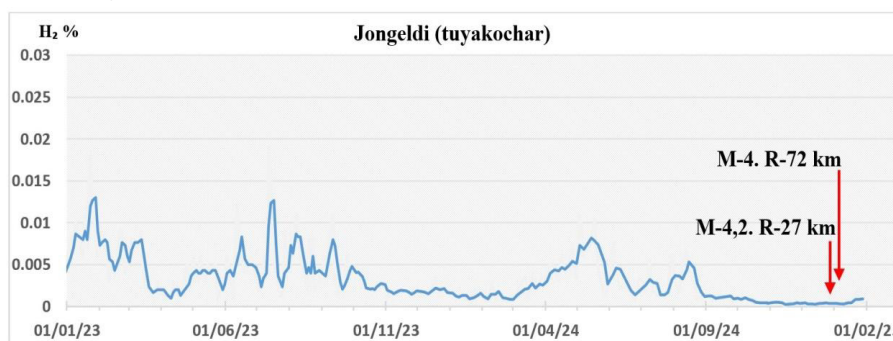


Figure 3. Two-Year Variation Graph of Hydrogen Concentration in Groundwater Samples from Jongeldi (Tuyakochar) Borehole

This graph also shows a sharp increase in hydrogen (H_2) concentration during the spring and summer months of 2023 (Figure 3). Although the values generally decreased in 2024,

intermittent fluctuations were still recorded. In January 2025, the hydrogen level dropped significantly. The variations observed in the spring of 2023 and throughout 2024 may indicate signs of seismic activity. Notably, just before the $M=4.2$ and $M=4.0$ earthquakes in January 2025, the hydrogen concentration dropped to a minimum. This may reflect a rapid degassing process preceding the seismic events, followed by stabilization as subsurface pressure conditions returned to equilibrium.



Figure 4. Two-Year Variation Graph of pH Levels in Groundwater Samples from Jongeldi (Meteorological Station) Well

The pH value was around 7.5 at the beginning of 2023 (Figure 4). Significant changes were observed during the spring and summer of 2023, especially with instances where the pH dropped below 7. Throughout 2024, the pH remained stable, though sharp fluctuations were recorded in certain areas. At the end of January 2025, the pH level sharply increased, rising above 8.0. The decrease in pH could be associated with the mixing of acidic gases from the Earth's crust with the groundwater. The sharp increase in pH at the end of January 2025, prior to the earthquake, indicates significant changes in the chemical composition of the water. Such abrupt changes

before an earthquake suggest the importance of hydrogeophysical processes related to groundwater, highlighting the geodynamic activity occurring in the subsurface. These changes are crucial indicators of hydrogeoseismological phenomena preceding seismic events.

The carbon dioxide (CO_2) level gradually increased starting from the spring of 2023 (figure 5). It reached a maximum level in the summer of 2023 and then slowly decreased. In 2024, the CO_2 level remained relatively stable, although

some sharp fluctuations were observed. At the end of January 2025, the CO_2 level sharply increased. The rise in CO_2 indicates the release of gas from underground before the earthquake. In

particular, the sharp increase in CO₂ levels before the earthquake in January 2025 suggests the presence of geochemical anomalies preceding the earthquake. The increase in such gases could be an important indicator that the seismic process is approaching.



Figure 5. Two-year change graph of carbon dioxide levels in groundwater samples from the Jongeldi (Tuyakochar) well

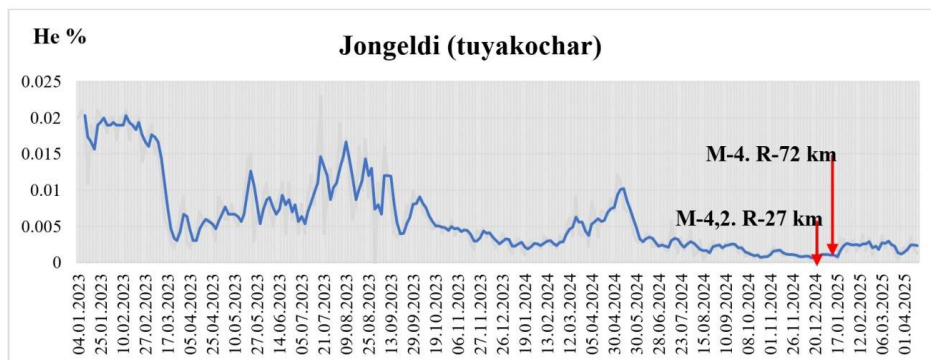


Figure 6. Two-Year Variation Graph of Helium Concentration in Groundwater Samples from the Jongeldi (Tuyakochar) Borehole

The helium concentration began to decrease in mid-2024 (figure 6) and continued to decline until the end of the year, reaching its minimum point by year-end. An increase was observed on January 13–14, followed by a gradual decline. Prior to January 23, another rise in helium concentration was recorded. The increase in helium levels before January 14 may indicate the opening of subsurface fractures or the accumulation of tectonic stress. The subsequent rise in helium concentration near January 23 could be a sign of another significant tectonic movement occurring in the region.

At the beginning of 2023 (figure 7), the helium concentration was high, followed by a decline. Fluctuations were observed in the middle and at the end of 2023. A sharp increase occurred at the end of January 2025. Such a sudden rise in helium concentration is likely

the result of underground gases escaping through fractures prior to an earthquake. This serves as a natural indicator that seismic activity may be approaching.

The methane (CH₄) concentration was relatively high at the beginning of 2023, followed by a decline. Fluctuations were observed throughout 2023 (figure 8). In January 2025, a significant increase in methane concentration was observed just before the earthquake occurred. The increase in methane gas could also be related to underground tectonic activity. In particular, the release of gases through deep fractures is closely linked to earthquakes.

The pH value was around 7.9 at the beginning of 2023 (figure 9). A decline was observed throughout the year, with a sharp drop occurring in mid-2023. In 2024, the pH level remained relatively stable, and in January 2025, just before the earthquake, a significant increase was recorded. Such a sharp rise in pH indicates

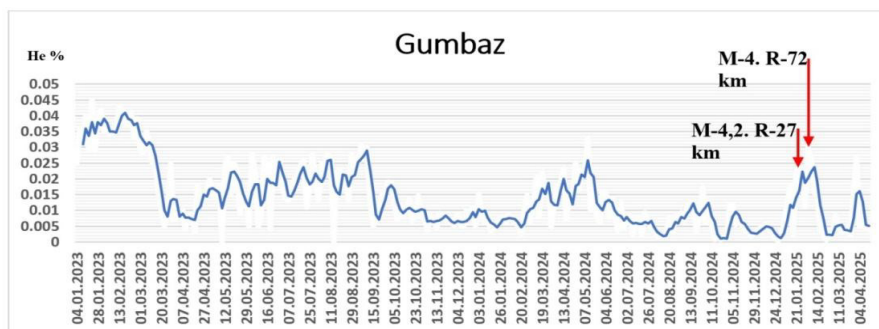


Figure 7. Two-Year Variation Graph of Helium Concentration in Groundwater Samples from the Gumbaz Borehole

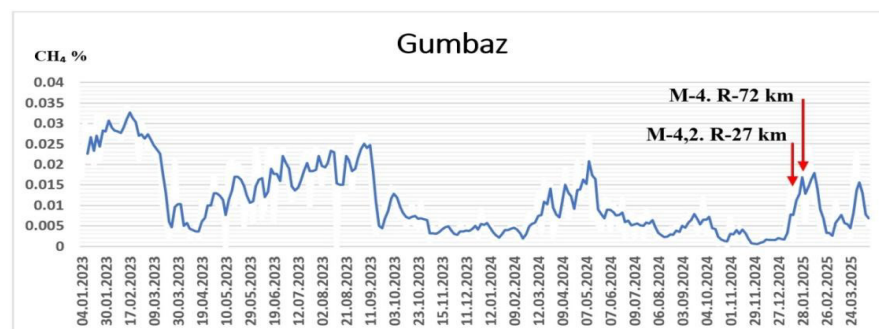


Figure 8. Two-Year Variation Graph of Methane Concentration in Groundwater Samples from the Gumbaz Borehole

alterations in the chemical composition of the groundwater. Changes in pH levels prior to seismic activity can result from the ingress of gases or the dissolution of minerals. The observed pH variations before January 14 and January 23 may be indicative of increasing tectonic stress.

Electrokinetic processes

The movement of underground liquids can cause the migration of electric charges, resulting in changes in the magnetic field. Deformation of magnetic minerals

As a result of tectonic stress, the state of ferromagnetic minerals in the Earth's crust changes, leading to disturbances in the magnetic field.

Gas release

The release of underground gases before an earthquake can lead to ionization processes, causing disturbances in the electric and magnetic fields.

Many scientists have studied the relationship between changes in the Earth's magnetic field and earthquakes, achieving significant results. Specifically, scientists such as Abdullabekov K.N., Maksudov S.Kh., and Tuychiev A.I. (Institute of Seismology, Academy of Sciences of Uzbekistan) have examined the duration of magnetic field anomalies in relation to earthquake magnitude and presented their results in tabular form (Table 1).

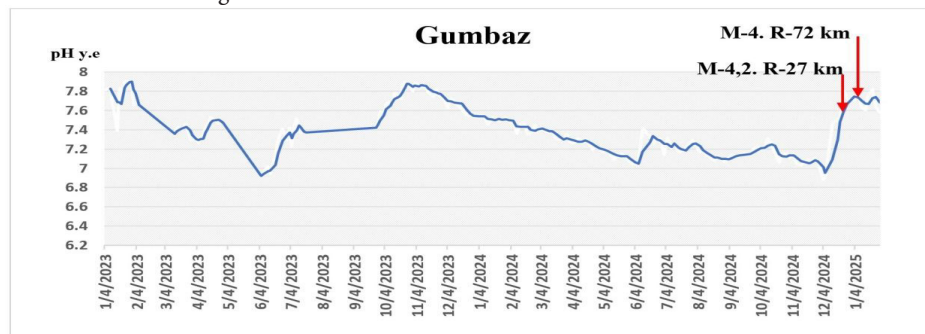


Figure 9. Two-Year Variation Graph of pH Levels in Groundwater Samples from the Gumbaz Borehole

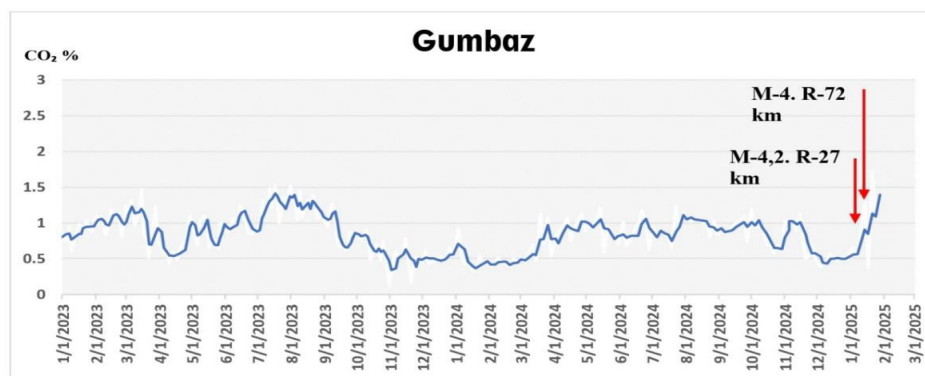


Figure 10. Two-Year Variation Graph of Carbon Dioxide Concentration in Groundwater Samples from the Gumbaz Borehole

Discussion of Results

The concentration of carbon dioxide (CO_2) varied throughout 2023 (figure 10) with both decreases and increases. In 2024, the changes were relatively stable, but in January 2025, just before the earthquakes, a sharp increase was observed. This is related to the activation of tectonic processes and the release of underground gases. After the increase before the first earthquake, the CO_2 concentration decreased, and during the second earthquake, a sharp rise was observed, suggesting a strong correlation between the sharp increase in CO_2 and seismic activity.

Along with hydrogeoseismological changes, anomalous variations were also observed in the data of the Earth's magnetic field recorded by the Jongeldi magnetometric station located in the region. The relationship between changes in the Earth's magnetic field and earthquakes has been studied in seismology for a long time. Research shows that during the strengthening of tectonic processes, when underground layers undergo deformation, local changes in the magnetic field can be observed. These changes could be associated with the following reasons:

Piezoelectric effect

Under tectonic pressure, certain minerals (such as quartz) can generate electric and magnetic fields.

Table 1.

M=4.0-4.9	M=5.0-5.9	M=6.0-6.9	M=7.0-7.9	M=8.0
4,0 – 45,3	5,0 – 171	6,0 – 624	7,0 – 2645	8,0-11200
4,1 – 52,3	5,1 – 188	6,1 – 700	7,1 – 2950	
4,2 – 58	5,2 – 205	6,2 – 800	7,2 – 3400	
4,3 – 66,5	5,3 – 230	6,3 – 920	7,3 – 3900	
4,4 – 74	5,4 – 280	6,4 – 1150	7,4 – 4500	
4,5 – 85,5	5,5 – 325	6,5 – 1270	7,5 – 5100	
4,6 – 97	5,6 – 350	6,6 – 1480	7,6 – 5800	
4,7 – 115	5,7 – 400	6,7 – 1600	7,7 – 6600	
4,8 – 121	5,8 – 450	6,8 – 1900	7,8 – 7800	
4,9 – 140	5,9 – 550	6,9 – 2150	7,9 – 9000	

This table provides data in the form of M-days, where M is the earthquake magnitude. It shows the average duration of anomalies observed before an earthquake with a magnitude equal to M. (4.2, 58 – The average anomaly duration before a 4.2 magnitude earthquake is 58 days). This table expresses the duration of anomalies in the Earth's magnetic field in relation to the magnitude of the earthquake. According to research findings, specific changes in the geomagnetic field are observed before earthquakes occur. This table shows the periods when magnetic field anomalies appear, depending on the earthquake's magnitude. For small-magnitude earthquakes ($M=4.0-4.9$),

geomagnetic field changes start to be noticeable 40–140 days before the event, while for larger magnitude earthquakes ($M=7.0-7.9$), this period is recorded to range between 2645–9000 days (approximately 7–25 years). For the strongest earthquakes ($M=8.0$ and greater), geomagnetic anomalies were observed up to 11,200 days (approximately 30 years) before the event. These results suggest that geomagnetic monitoring could potentially enable the long-term forecasting of earthquakes. At the end of the table, the average time values for each magnitude are presented. Changes in the Earth's magnetic field recorded by the Jomgeldi magnetometric station could be related to earthquakes. According to the graph data, significant changes in the magnetic field were observed before the $M=4.2$ ($R=27$ km) and $M=4.0$ ($R=72$ km) magnitude earthquakes that occurred in January 2025. These changes may be associated with geophysical processes before the earthquakes occurred. In particular, more significant changes in the magnetic field were observed closer to the epicenter of the earthquake. This demonstrates the potential importance of magnetometric observations in predicting seismic events. The findings confirm the need for further research on the connection between magnetic field anomalies and earthquakes (Figure 11).

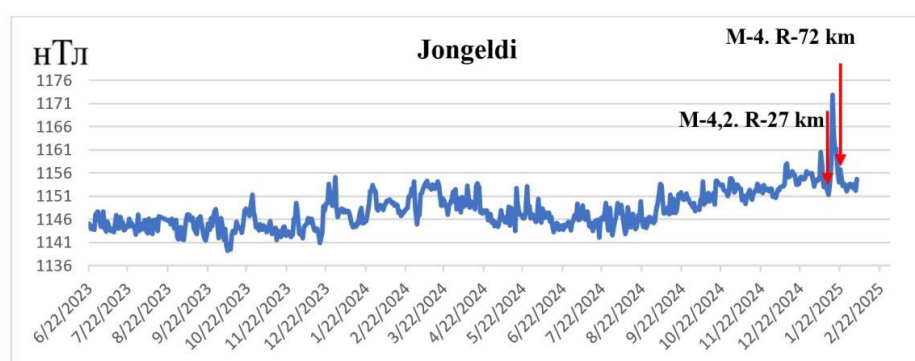


Figure 11. Two-year change graph of the Earth's magnetic field at the Jomgeldi magnetometric station.

Conclusions

Hydrogeoseismological observations show that significant changes occur in the composition of underground gases and water prior to earthquakes. Specifically, the concentration of helium and hydrogen decreased to minimal levels, while CO_2 , methane, and pH indicators sharply increased before the earthquake. These changes manifested in two stages: first, a significant rise in parameters before the earthquake, followed by a decrease, and then an increase again before the second earthquake. Importantly, these trends were consistent across the Jomgeldi (meteorological station), Jomgeldi (Tuyakuchar), and Gumbaz stations.

Additionally, variations in the Earth's magnetic field recorded at the Jomgeldi magnetometric station confirmed the connection of these geophysical processes with seismic activity. The simultaneous occurrence of changes in the Earth's magnetic field and sharp shifts in hydrogeoseismological parameters suggests a link between electromagnetic and gas dynamics resulting from tectonic processes. These findings highlight the importance of complex monitoring before earthquakes and emphasize the need to study geomagnetic field

changes alongside hydrogeoseismological parameters as seismic precursors.

Monitoring changes in groundwater parameters is crucial for accurate earthquake prediction. Hydrogeoseismological data from the Bukhara region's borehole helps in analyzing anomalies in underground water, which can aid in identifying physical and chemical processes that may begin before an earthquake. Monitoring and analysis provide a scientific foundation for assessing geological and seismic activity and thereby reducing potential hazards.

The hydrogeoseismological observations from the Bukhara region regarding the earthquakes of January 14 and 23, 2025, showed significant changes in the physical-chemical composition and gas content of underground waters. The analysis revealed increased concentrations of CO_2 and He gases, pH variations, geomagnetic anomalies, and other changes before the earthquakes. These changes could be linked to the activation of tectonic processes. Specifically, the rise in CO_2 concentration is hypothesized to be associated with increased pressure in the Earth's crust and the opening of fractures. The sharp increase in helium gas concentration before the earthquake and its decrease afterward may be attributed to the release of underground gases. pH changes may be explained by the mixing of gases in groundwater and the disruption of chemical equilibrium.

The hydrogeoseismological changes observed before the earthquakes can be considered potential indicators of seismic activity. The research results suggest that hydrogeoseismological monitoring could serve as an essential tool for predicting earthquakes. Such analyses could become one of the effective methods for future earthquake risk assessments.

During earthquake preparedness, changes in the composition of underground gases and chemical elements in groundwater might be associated with seismic activity. These changes, particularly involving gases like radon, carbon dioxide, hydrogen, oxygen, and nitrogen, as well as chemical elements such as chlorine, boron, and mercury, can lead to variations before and during an earthquake, creating opportunities for earthquake prediction.

Although Uzbekistan has achieved several successes in the field of hydrogeoseismology, much work remains to be done in earthquake prediction. Uzbekistan is located in seismically active regions, and the systems for monitoring and studying underground waters and geodynamic processes are still underdeveloped. There is a particular need to develop hydrogeoseismological monitoring systems in regions with high seismic activity, such as Bukhara, Samarkand, Tashkent, and other similar areas.

Research in hydrogeoseismology and earthquake forecasting continues at scientific institutions in Uzbekistan.

However, there is limited progress in consistently monitoring the chemical and gas composition of groundwater, implementing remote monitoring systems, and improving technologies for detecting radon gas. Currently, such systems have only been implemented in certain regions, and the data obtained has not yet been widely analyzed.

To address these issues, automated monitoring systems should be installed in seismically active regions of Uzbekistan. By integrating meteorological and hydrogeodynamic measurements, comprehensive scientific research should be conducted to identify the causes and risks of each variation. Uzbekistan's scientific teams and specialists should study the experiences of advanced countries like China and apply those technologies in the country.

Uzbekistan needs to introduce new methods in hydrogeoseismology and improve systematic monitoring to further develop and strengthen earthquake prediction capabilities. These efforts will not only contribute to the country's safety but also enhance international scientific collaboration.

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Disclosure statement

No potential conflict of interest was reported by the author.

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