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Analysis and Mapping of Secular Geomagnetic Variations Based on Data from the INTERMAGNET Network and Magnetometric Stations in Uzbekistan

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Statistical Analysis of the Manifestation of Precursors of Strong Earthquakes in Hydrogeoseismological Parameters

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Abstract. This statistical analysis investigates scientific literature addressing hydrochemical anomalies in groundwater related to earthquake preparation processes across fourteen seismically active countries. The study is based on 379 peer-reviewed publications, including journal articles, conference proceedings, and books, sourced from the online Scopus database according to defined selection criteria. The data span research conducted in countries with high seismic activity, such as Japan, India, Germany, China, Turkey, Taiwan, Italy, the Russian Federation, and the United States. The statistical findings reveal a consistent association between hydrochemical changes in groundwater and seismic events. Across the analyzed publications, a total of 40 hydrochemical and physical parameters were reported to change in connection with 191 distinct earthquakes. Among these, anomalies in radon (Rn) gas concentrations were the most frequently observed, accounting for 18% of all reported anomalies. Changes in groundwater levels were observed in 8% of cases, followed by variations in sodium and chloride ion concentrations (7%), sulfate ions (6%), helium gas (5%), calcium ions (3%), and groundwater temperature (6%). Additionally, anomalies in the electrical conductivity of groundwater were reported in 3% of cases, with other individual parameters each contributing less than 2% to the total anomaly record. These results provide compelling statistical evidence that hydrochemical monitoring of groundwater can be a valuable tool in understanding and potentially forecasting seismic activity. The study emphasizes the need for continued interdisciplinary research to refine monitoring methods and improve early-warning capabilities for earthquakes based on geochemical precursors.

INTRODUCTION

Earthquakes are among the most devastating and unpredictable natural phenomena, often resulting in catastrophic loss of life, widespread destruction of infrastructure, and significant economic disruption. The sudden release of accumulated tectonic stress along fault lines can trigger seismic events that impact millions of people, particularly in regions located along active geological boundaries. Due to the scale of destruction caused by strong earthquakes, the need for reliable forecasting methods remains one of the most pressing challenges in modern geoscience.

In response to this challenge, a substantial body of research has emerged over the past several decades aimed at advancing our understanding of the physical processes that lead to earthquakes. These efforts are not only of academic interest but also of critical national, economic, and social importance, especially for countries situated in high-risk seismic zones. As a result, earthquake prediction and the identification of reliable precursors have become a central focus of multidisciplinary scientific investigation. Researchers from around the world — including the United States, Japan, China, Armenia, India, Russia, Italy, Uzbekistan, and others — have contributed significantly to this field [1–3].

A wide array of methodological approaches is currently employed to detect and interpret potential earthquake precursors. These include seismological and geophysical monitoring, geodetic and satellite-based observations, astrophysical modeling, and hydrogeochemical analysis. Among these, hydrogeochemical methods — which involve studying changes in the chemical composition and physical properties of groundwater — have shown promising potential for identifying early signs of seismic activity. Variations in parameters such as gas concentrations (e.g., radon, helium), ion composition (e.g., chloride, sulfate, calcium), groundwater level, temperature, and electrical conductivity have been reported as possible indicators of stress accumulation in the Earth's crust.

Given the increasing volume of data and the growing number of case studies in this area, there is a strong need for systematic analysis of the existing scientific literature. This study aims to statistically evaluate publications that report hydrochemical anomalies in groundwater associated with the preparation phase of earthquakes, based on data from fourteen seismically active countries. By synthesizing findings from 379 peer-reviewed sources indexed in the Scopus database, this work seeks to identify the most frequently observed hydrogeochemical precursors and assess their correlation with seismic events. The goal is to contribute to the broader effort of developing scientifically grounded and practically applicable methods for short-term earthquake forecasting.

In recent years, the problem of earthquake forecasting has attracted the attention of researchers to the various hydrogeochemical effects that precede and accompany catastrophic earthquakes. These effects in hydrogeological parameters were first discovered during the 1966 Tashkent earthquake. Studies conducted in the Tashkent Artesian Basin have revealed that hydrogeochemical and radiohydrogeological anomalies manifested themselves in changes in the chemical, gas and isotopic composition of groundwater during aftershocks before and after the Tashkent earthquake. Later, similar changes were observed during the Dagestan, Alai in 1978, Gazli in 1976 and 1984, and other earthquakes. At the same time, along with changes in the gas-chemical composition of groundwater, changes in their level, temperature, flow velocity, and reservoir pressure were observed. Seismic events can damage the Earth's crust and affect the physical and chemical properties of groundwater and geothermal waters. Currently, many researchers are trying in various ways through field research and scientific research to promote the connection of earthquakes with changes in the physico-chemical properties of groundwater [4-7]. Stillings et al. investigated how small earthquakes of magnitude 1 or less, which occur in nature more often than large earthquakes, can be caused by human activity and can affect groundwater. The authors note that with the spread of hydraulic fracturing, the development of geothermal energy and the use of underground coal mines, humanity is increasing the number of such earthquakes every year, and their impact on groundwater, especially in flooded areas, is increasing. The researchers conducted their study at the Grimsel landfill in Switzerland, which includes a series of tunnels and wells drilled into granite near Lake Raterichsboden. While the team was observing the site, the rise and fall of the groundwater level in the reservoir caused micro-earthquakes. Groundwater pulses spread from earthquake sites through a local fault network into tunnels. Observations from tunnel wells showed that the earthquakes did not change the groundwater pressure or the concentration of dissolved substances. However, they found that small earthquakes can temporarily make groundwater more acidic and lower the pH. According to the authors, the results obtained are the first field evidence of groundwater acidification caused by an earthquake. Researchers have studied this phenomenon in laboratory experiments by crushing and smashing rocks similar to those found in Grimsel. These experiments, in which the pH of the water decreased for several days, showed that the increase in acidity is caused by silanols and silica radicals formed on new mineral surfaces when hydrogen ions are concentrated in the water. The pH of groundwater affects many geochemical reactions underground. The new results, according to the authors, make a significant contribution to understanding the chemical interactions of groundwater. The purpose of this study is to evaluate the role of the hydrogeoseismological method in earthquake forecasting on a regional scale. Currently, there are several earthquake forecasting methods, and the hydrogeoseismological method is one of the most effective methods for detecting short- and medium-term earthquake precursors. Studies of the effects of earthquakes on groundwater were analyzed using the hydrogeoseismological method.

MATERIALS AND METHODS

his study presents a comprehensive statistical analysis of hydrogeochemical anomalies observed in groundwater in relation to earthquake activity across fourteen seismically active countries. The methodology was designed to synthesize global findings, identify the most frequently observed hydrogeochemical precursors, and evaluate their correlation with seismic events over the past four decades.

Data Sources and Selection Criteria. The primary source of data for this study was the Scopus online database, which provides access to a broad collection of peer-reviewed literature. A total of 379 scientific publications—including journal articles, conference proceedings, and monographs—were selected based on relevance to hydrogeochemical anomalies associated with earthquake preparation processes. Selection criteria included: Studies reporting observational or experimental data related to pre-seismic changes in groundwater; Publications focused on hydrogeochemical, geophysical, or interdisciplinary earthquake precursors; Reports from seismically active countries with a documented history of earthquake events.

Scientific contributions from China, Japan, India, the Russian Federation, Turkey, Armenia, the United States, Italy, Taiwan, Uzbekistan, and other regions were included in the review. Regional case studies were emphasized to assess patterns in specific geological and tectonic settings.

Analytical Tools and Visualization. Two software tools were used for data management and analysis: Zotero was employed for literature organization and citation tracking; VOSviewer was used to generate visual maps illustrating the frequency and co-occurrence of keywords, themes, and research collaborations across the selected literature.

These tools enabled effective data classification, thematic clustering, and visualization of global trends in hydrogeoseismological research.

RESEARCH RESULTS

Historical Context and Precedent Studies. The role of hydrogeochemical precursors in earthquake forecasting has been under scientific scrutiny since the 1966 Tashkent earthquake, where researchers first documented changes in the chemical and isotopic composition of groundwater during seismic activity. Similar anomalies were later observed during the Dagestan, Alai (1978), and Gazli (1976, 1984) earthquakes, establishing a precedent for using groundwater chemistry as a diagnostic tool in seismology. Contemporary research has expanded upon these findings. For instance, Stillings et al. [8-10] demonstrated that even micro-earthquakes ($M < 1.0$), triggered by anthropogenic activities such as hydraulic fracturing and geothermal energy extraction, can alter groundwater properties. Their study in Switzerland's Grimsel rock laboratory showed that seismicity caused minor acidification of groundwater through physical and chemical interactions between faulted rocks and infiltrating fluids.

Dataset Scope and Geographic Distribution. Earthquake-related hydrogeochemical anomalies were statistically compiled from reports spanning fourteen countries. The recorded number of earthquakes and corresponding anomalies includes: China: 51 events, Japan: 22, India: 16, Russia: 12, Armenia: 16, Turkey: 15, Taiwan: 9, USA: 19, Uzbekistan: 12, Italy: 8, Iceland: 7, Indonesia: 2, Korea: 2, Kyrgyzstan: 3. In total, 194 distinct seismic events were analyzed in which variations in up to 40 physical and chemical groundwater parameters were documented. The frequency of reported anomalies was as follows: Radon (Rn) gas: 18%, Groundwater level: 8%, Sodium and chloride ions: 7%, Sulfate ions: 6%, Helium gas: 5%, Calcium ions: 3%, Groundwater temperature: 6%, Electrical conductivity: 3%, Other parameters: <2%. These data reflect both natural and anthropogenically triggered seismic events and provide evidence of recurring hydrochemical responses associated with crustal stress accumulation [11].

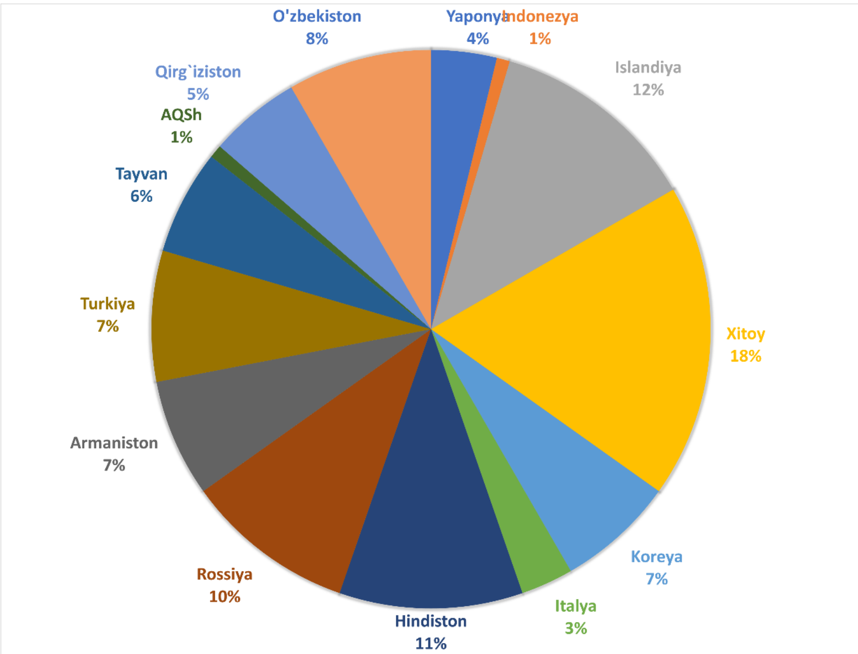

FIGURE 1. The use of hydrogeoseismological parameters in predicting national-scale earthquakes

Approach to Data Interpretation. The study employed a comparative approach, correlating the timing, magnitude, and depth of earthquakes with recorded hydrogeochemical anomalies. A regional perspective was applied to identify site-specific patterns, while cross-national synthesis allowed for generalization of global trends. By evaluating frequency, consistency, and lead time of the anomalies, the study contributes to the ongoing refinement of hydrogeoseismological methods for earthquake forecasting [12].

Figure 1 illustrates the distribution of hydrogeoseismological research efforts across various countries based on the percentage of studies or earthquake events analyzed using hydrogeochemical methods. The figure reflects the relative contribution or activity of each country in using groundwater anomalies for earthquake forecasting.

China (Xitoy) has the largest share, accounting for 18% of all documented cases. This reflects China’s long-standing and extensive investment in earthquake prediction, particularly through hydrogeochemical monitoring. The country has a well-developed earthquake observation network and has published numerous case studies involving radon, helium, and ion concentration anomalies.

Iceland (Islandiya) follows with 12%, a significant figure considering the country’s size. This highlights Iceland’s active tectonic setting along the Mid-Atlantic Ridge and its strong focus on geophysical and geothermal monitoring.

India (Hindiston) and Russia (Rossiya) account for 11% and 10%, respectively, showing their substantial engagement in hydrogeoseismological studies. Both countries have multiple seismically active regions where such research has been applied, especially in the Himalayas and the Caucasus.

Armenia, Turkey (Turkiya), and Korea (Koreya) each contribute 7%, underscoring their regional efforts in monitoring earthquake precursors through groundwater changes.

Taiwan (Tayvan) and Uzbekistan (O'zbekiston) contribute 6% and 8%, respectively, both notable given their seismic vulnerability and history of strong earthquakes.

Japan (Yaponiya), despite being a global leader in earthquake science, accounts for only 4% in this dataset. This may reflect the scope or selection criteria of the literature reviewed rather than actual activity levels.

Other countries like: Kyrgyzstan (Qirg’iziston) – 5%, USA (AQSh) – 1%, Indonesia (Indonezya) – 1%, Italy (Italiya) – 3%, show relatively lower shares. These figures suggest that while these countries have seismic monitoring programs, fewer studies may have been focused specifically on hydrogeochemical precursors or were included in the analyzed dataset.

Interpretation: The chart highlights global disparities in the application of hydrogeoseismological methods. Countries with: High seismic activity, Strong research infrastructure, And long-term groundwater monitoring programs are more represented. China's dominance suggests a strong institutional commitment to earthquake precursor research, while countries like the USA and Indonesia may rely more on geophysical or early warning systems not captured in this analysis.

This distribution emphasizes the importance of international collaboration and standardization in hydrogeoseismology. Expanding hydrogeochemical monitoring in underrepresented regions could improve the global understanding of earthquake precursors and enhance early warning capabilities on a broader scale.

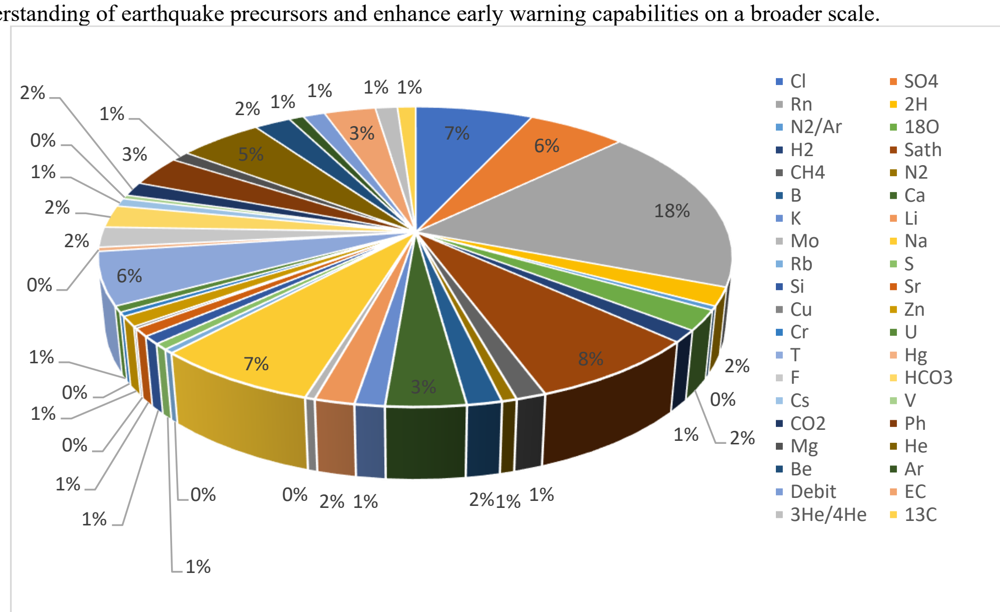

FIGURE 2. Anomalies of hydrogeoseismological parameters related to earthquakes.

Figure 2 presents a detailed pie chart illustrating the distribution of various hydrogeochemical and physical parameters that have shown anomalous behavior prior to earthquakes. These anomalies are based on the statistical analysis of 379 publications and 194 seismic events, as discussed in the study.

Key Observations: Most Frequently Reported Anomalies: Radon (Rn) – 18%. The most common anomaly, confirming radon's strong potential as an earthquake precursor. Its increase is typically associated with microcracks in rocks due to tectonic stress, allowing radon gas to migrate into groundwater. Groundwater Level (Debit) – 8%. Changes in groundwater level often result from crustal deformation or changes in aquifer pressure due to fault movement. Sodium (Na) and Chloride (Cl) Ions – 7%. Variations suggest increased water–rock interaction or mixing of different water sources triggered by seismic strain. Sulfate (SO_4^{2-}) – 6%. A common ion whose fluctuations may signal mineral dissolution or changes in groundwater flow paths. Groundwater Temperature (T) – 6%. Can rise due to increased permeability, geothermal flux changes, or mixing of waters from different thermal zones. Helium (He) – 5%. Indicates deep-seated fluid or gas migration, often from the mantle or fault zones. Calcium (Ca^{2+}) – 3%. Possibly caused by dissolution of carbonate rocks or cation exchange due to aquifer disturbance. Electrical Conductivity (EC) – 3%.

Reflects changes in ion concentration; a general indicator of groundwater chemistry variations. Less Frequently Observed Parameters (2% and below): These include a wide variety of chemical, isotopic, and physical parameters, such as: Stable Isotopes (^2H, ^{18}O, ^{13}C) – Indicators of water source mixing or evaporation. Gases: CH_4, CO_2, N_2, Ar, H_2, H_2S – May signal deeper gas influx or redox changes. Trace Elements: Cu, Cr, U, Hg, V, Sr, Rb, Mo, Be, Cs, etc. – Their changes can indicate geochemical mobilization from stressed rocks. Other: Mg, B, K, Si, pH (Ph), F, T, 3He/4He, Sath (saturation), HCO_3, and N2/Ar ratios – Reflect complex hydrogeochemical responses to seismic stress. Interpretation:The figure clearly shows that a small subset of parameters—especially radon, ion concentrations (Cl^-, Na^+, SO_4^{2-}), groundwater level, temperature, and helium—account for the majority of observed anomalies. These parameters likely respond more rapidly or sensitively to mechanical stress and crustal changes that occur before earthquakes.

Meanwhile, the broad distribution of lesser anomalies (most under 2%) suggests that while many hydrogeochemical indicators can respond to seismic precursors, they may be:Site-specific, Influenced by local hydrogeology, Or harder to detect without specialized instrumentation.

This underlines the importance of multi-parameter monitoring, which can increase the reliability of detection by capturing diverse signatures of seismic preparation processes.

Radon, major ions (Na^+, Cl^-, SO_4^{2-}), groundwater level, and temperature are the most promising hydrogeochemical indicators for earthquake forecasting. A multidisciplinary, region-specific approach is needed to interpret hydrogeochemical data correctly, given the variability and low frequency of many other parameters. These findings strengthen the case for incorporating hydrogeochemical monitoring into national seismic early warning systems.

DISCUSSION OF THE RESULTS.

The statistical analysis presented in this study reinforces the growing body of evidence supporting the role of hydrogeochemical anomalies in the short- and medium-term forecasting of earthquakes. The observed variations in groundwater parameters prior to seismic events across multiple countries indicate a consistent geochemical response to stress accumulation in the Earth's crust. These responses serve as potential precursors and can be used to enhance earthquake prediction models when combined with other geophysical and seismological data.

One of the most significant findings of this study is the high frequency of radon (Rn) gas anomalies, which accounted for 18% of all reported anomalies across 194 earthquakes. This is consistent with previous studies that have identified radon as a reliable geochemical indicator of seismic activity due to its mobility and sensitivity to microfracturing processes in rocks under tectonic stress. Radon emanation is often linked to increased permeability in fault zones, allowing this radioactive inert gas to migrate to the surface via groundwater systems. The repeatability of radon anomalies across diverse tectonic settings suggests its potential as a universal precursor, though local geological conditions must be considered for accurate interpretation.

Groundwater level changes, which comprised 8% of all anomalies, also demonstrate strong correlation with seismicity. Such fluctuations can result from strain-induced changes in crustal porosity, permeability, and aquifer pressure. Similarly, anomalies in major ion concentrations, including sodium, chloride, and sulfate, likely reflect stress-induced water–rock interactions, fluid mixing, or migration of deep fluids along activated fault zones.

The presence of helium anomalies (5%) further supports the hypothesis of deep fluid migration in seismically active regions. Helium, especially ^3He, is often associated with mantle-derived fluids, and its detection in groundwater prior to earthquakes suggests upward movement through crustal fractures. Additionally, calcium ion anomalies (3%) and temperature changes (6%) may indicate mineral dissolution, geothermal disturbances, or fluid mixing, all of which are common precursory processes.

Electrical conductivity anomalies (3%), though less frequently reported, are also notable as they may indicate increased ion content or changes in fluid pathways within aquifers. These shifts are typically linked to enhanced rock permeability or fracture formation due to tectonic loading.

The geographical distribution of research activity, with China being the most represented (51 documented events), reflects both the country's high seismic hazard and its longstanding investment in earthquake prediction research. The breadth of parameter monitoring in Chinese studies (up to 24 variables) also highlights a comprehensive approach to hydrogeoseismological analysis. Other countries, including Japan, India, Russia, and the United States, also contribute significantly to the global dataset, reinforcing the universal relevance of these findings.

The particular interest is the inclusion of anthropogenic micro-earthquakes, such as those studied by Stillings et al. in Switzerland. Their findings demonstrate that even low-magnitude seismic events can affect groundwater chemistry, notably by decreasing pH through the generation of reactive mineral surfaces. These results underscore the importance of monitoring hydrochemical parameters even in low-energy seismic settings, particularly those influenced by human activities such as hydraulic fracturing, geothermal energy development, or mining.

The study also confirms that hydrogeochemical anomalies are not uniformly distributed across all seismic events. Only 194 out of 379 reviewed publications reported identifiable precursors, suggesting that either not all earthquakes generate measurable hydrochemical signals, or that some signals go undetected due to limitations in monitoring infrastructure, data resolution, or the timing of observations. Therefore, continuous, real-time, and multi-parameter monitoring systems are essential to improve detection and interpretation of hydrogeochemical anomalies.

Furthermore, the observed variability in the type and timing of anomalies points to the importance of site-specific calibration of prediction models. Geological heterogeneity, aquifer properties, fault types, and regional stress regimes all influence the behavior of hydrochemical indicators. As such, no single parameter can serve as a definitive predictor; rather, a multivariate approach combining hydrogeochemical, geophysical, and seismological data is required for robust forecasting.

In conclusion, this study validates the hydrogeoseismological method as a valuable tool for earthquake precursor detection. The recurrence of specific anomalies—particularly radon, ion concentrations, and groundwater level—across different countries and tectonic environments strengthens their credibility as forecasting indicators. However, further refinement in data collection, standardization of methodologies, and international collaboration are needed to fully integrate hydrogeochemical monitoring into global earthquake early warning systems.

CONCLUSIONS

This study presents a comprehensive review and statistical analysis of hydrogeoseismological research based on scientific articles, dissertations, and monographs that examine earthquake precursors in seismically active regions. The findings confirm that geochemical anomalies in groundwater—such as variations in gas concentrations, ion composition, temperature, and electrical conductivity—are frequently observed prior to seismic events and may serve as valuable indicators of earthquake preparation processes.

The analysis of 379 publications across fourteen countries demonstrates that while hydrogeochemical changes are often linked to seismic activity, they can also result from natural seasonal processes or anthropogenic factors, including climate change, soil contamination, acid rain, and other atmospheric influences. Therefore, distinguishing between seismic and non-seismic causes of hydrochemical anomalies remains a key challenge.

Importantly, the manifestation of geochemical anomalies varies significantly from one earthquake to another. Factors such as earthquake magnitude, the depth and composition of the groundwater aquifer, and the distance from the epicenter all influence the nature, intensity, and timing of observable changes. This variability highlights the necessity of region-specific monitoring frameworks and supports the use of multi-parameter, continuous observation systems.

In conclusion, hydrogeoseismological methods show strong potential for contributing to short- and medium-term earthquake forecasting. However, to increase their reliability and applicability, further research is needed to improve monitoring technologies, standardize data interpretation methods, and account for local geological and environmental conditions.

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