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DYNAMICS OF GEOCHEMICAL ANOMALIES IN GROUNDWATER BEFORE EARTHQUAKES

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Abstract

This study investigates hydrogeochemical anomalies in groundwater as potential precursors to seismic events in Azerbaijan. Long-term monitoring in the Shamakhi region, including data from the Baku (2000) and Shamakhi (2019) earthquakes, reveals consistent pre-seismic variations in sulfate, hydrogencarbonate, carbonate, and alkali metal ions (Na, K), along with shifts in redox potential and helium emissions. These anomalies typically emerged 1–16 days before earthquakes and were recorded at multiple stations. The findings support hydrogeochemical analysis as a valuable complement to traditional seismic forecasting and highlight the need for expanded monitoring networks to enhance spatial resolution and early warning systems. This work contributes to integrated seismic hazard assessment by combining geophysical, geochemical, and remote sensing methods.

Keywords: *Hydrogeochemical monitoring, geochemical anomalies, earthquake precursors, groundwater, seismic forecasting*

Introduction

Understanding earthquake precursors is essential for seismic hazard mitigation. Among various methods, groundwater geochemistry has shown promise for detecting pre-seismic changes. Previous studies have documented anomalies in ion concentrations, redox potential, and dissolved gases (e.g., helium) prior to seismic events, though the mechanisms linking these changes to tectonic stress remain debated (Ingebritsen et al., 2006).

The successful prediction of the 1975 Haicheng earthquake (M7.3), partly based on hydrological anomalies, contrasts sharply with the failure to forecast the 1976 Tangshan earthquake (M7.8), which caused over 240,000 fatalities despite similar signs (Wang et al., 2006). These contrasting outcomes underscore the challenges of reliable earthquake forecasting.

This study addresses such challenges through systematic hydrogeochemical monitoring in Azerbaijan, a tectonically active region at the Eurasian-Arabian plate boundary. Despite some progress in automated monitoring elsewhere (Japan, U.S., China, Turkey, Iceland), most geochemical data in Azerbaijan come from manual sampling (Roeloffs, 1988; Kissin & Grinevsky, 1990; Matsumoto & Koizumi, 2011). Given Azerbaijan's active fault zones and rich hydrothermal resources, the region offers a valuable natural laboratory.

The primary objectives are to identify pre-seismic hydrogeochemical anomalies, correlate them with seismic activity, and establish a framework for geochemical monitoring to support seismic hazard assessment.

Methods

From 2015 to 2023, groundwater samples were collected monthly – and more frequently during seismic swarms – from wells and thermal springs in the Shamakhi region. Major ions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, HCO_3^{-}) were analyzed via ion chromatography (Dionex ICS-6000). Oxidation-reduction potential (ORP) was measured in situ with a YSI Professional Plus multiparameter probe. Dissolved helium was analyzed using the INGEM-1 gas analyzer (detection limit: 0.1 ppm).

Cross-correlation functions identified pre-seismic anomalies. Principal Component Analysis (PCA) was used to filter background noise. Machine learning models (Random Forest, SVM) enhanced anomaly detection and forecasting. While this integrative approach improves understanding of groundwater behavior before earthquakes, seasonal changes, contamination, and dilution effects remain confounding factors. Sampling resolution may also limit detection of short-term precursors. Future efforts should prioritize real-time monitoring.

Hydrogeochemical Indicators for Seismic Monitoring

Long-term hydrogeochemical monitoring in Azerbaijan's seismogenic zones has involved observing variations in groundwater, mud volcanic waters, free and dissolved gases (e.g., Rn, He), and radioactive emissions (Keramova, 2004; Telesca et al., 2020). Key indicators include:

- **Ion concentrations:** pH, Eh, $\sum(Cl^{-}, Br^{-}, I^{-})$, HCO_3^{-}, CO_3^{2-}, SO_4^{2-}, Na^{+}, K^{+}, Ca^{2+}, Mg^{2+}, mineralization, Fe^{2+}/Fe^{3+};
- **Hydrogeodynamics:** Continuous measurements of groundwater level and flow rates in observation wells.

Real-time automated systems track daily variations and intensify during seismic activity or aftershocks.

Hydrogeochemical Characteristics of Seismic Observation Wells

The Shamakhi region is Azerbaijan's most active seismic zone. Notable wells include:

- **Shamakhi No. 8**
  – Kurlov formula: Cl_{43} $SO_{4\,40}$ $HCO_{3\,17}$;
  – Temp: 8–11 °C | pH: 6.9 | Eh: –10 mV | Mineralization: 1.2 g/L;
  – Cold, moderately mineralized chloride-bicarbonate sodium-type water in slightly acidic, weakly reducing environments.
- **Chukhuryurd No. 49**
  – Kurlov formula: $HCO_{3\,48}$ $SO_{4\,36}$ Cl_{16};
  – Temp: 18–21 °C | pH: 6.8 | Eh: –80 mV;
  – Subthermal, slightly mineralized water with dissolved H_2S under moderately reducing conditions.
- **Damirchi Mud Volcano**
  – pH: 6.2 | Eh: +25 mV;
  – Surface gryphon gases indicate atmospheric interaction.

Seismic Event Case Studies

- **Baku Earthquake (Nov 25, 2000; M6.8; depth 13 km)**

Anomalies in Shamakhi No. 8 began Nov 19.

Groundwater level drop, increased Ca^{2+}, Mg^{2+}, Fe^{2+}/Fe^{3+}; decreased Na^{+}, K^{+}, Cl^{-}, Br^{-}, I^{-}.

SO_4^{2-} rose from 440–480 mg/L to 640 mg/L, then dropped to 20 mg/L.

Eh dropped in Chukhuryurd No. 49; pH fell to 7.0.

- **Shamakhi Earthquake (Feb 5, 2019; M5.3; depth 8 km)**

Preceded by sharp water level drop and discoloration.

SO_4^{2-} peaked at 640 mg/L, then declined.

Na^+/K^+ dropped to 450 mg/L; Fe levels spiked to 48 mg/L.

CO_3^{2-} peaked at 220 mg/L.

Helium as a Seismic Indicator

Helium anomalies were strong and consistent. Before the 2019 quake, helium levels increased tenfold near the epicenter and spread to other sites. Levels rose from 0 to 100% in deep events; prior to the 2000 quake, from 1% to 3–4%. These patterns suggest helium as a robust precursor.

Correlation Between Anomalies and Seismicity

Precursor strength increased with earthquake magnitude and decreased with distance. Key correlations:

- **Helium:** $r = 0.82$ ($p < 0.01$), peaking 10–20 days before earthquakes;
- **Ca^{2+} and Mg^{2+}:** $r = 0.65–0.72$ ($p < 0.05$);
- **Eh anomalies:** Appeared ~1 month prior to events.

SO_4^{2-} anomalies were particularly reliable, occurring across multiple stations. However, sparse monitoring limits spatial analysis.

Practical Implications for Forecasting

Integrating hydrogeochemical data with seismic monitoring can enhance early warning systems. For instance, quasi-annual seismicity near the Mingechevir reservoir may be influenced by water-level changes, though data remain preliminary (Telesca et al., 2020).

Future recommendations:

- Expand real-time monitoring across fault zones;
- Integrate hydrogeochemical data with GPS strain and microseismicity;
- Apply machine learning to improve anomaly detection and forecasting.

These steps could substantially improve predictive accuracy in Azerbaijan and other tectonically active regions.

Conclusion

Hydrogeochemical monitoring – particularly ion fluctuations, redox shifts, and helium emissions – shows strong potential for earthquake forecasting in Azerbaijan. Consistent pre-seismic patterns support their value as geochemical precursors. However, environmental noise and predictive limitations remain challenges.

For robust seismic hazard mitigation, future research should prioritize high-resolution, real-time hydrogeochemical data, integrate geophysical measurements, and apply machine learning for anomaly validation. Such a multidisciplinary framework may significantly advance regional early warning systems.

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