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Environmental Monitoring of the Theistareykir High-Temperature Geothermal Field: Impacts on Groundwater in Northeast Iceland

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ABSTRACT

Environmental monitoring at the Theistareykir high-temperature geothermal field in Northeast Iceland has been conducted systemically since 2012 to assess potential impacts on groundwater quality and flow toward Öxarfjörður through Kelduhverfi. Groundwater boreholes and nearby cold and tepid springs show that arsenic and aluminum concentrations have remained stable and well below Icelandic environmental and drinking water standards (≤0.4 µg/L and 200 µg/L, respectively), as well as European Union and World Health Organization guideline limits. Other trace metals, including copper, zinc, cadmium, lead, chromium, nickel, are consistently near analytical detection limits, exhibiting only minor, non-systematic fluctuations. Stable isotope measurements (δD and $\delta^{18}O$) indicate that a meteoric origin for all waters, with no evidence of mixing with geothermal fluids. These results demonstrate that geothermal operations at Theistareykir have had negligible effects on surrounding groundwater systems, showing that high-temperature geothermal utilization can be environmentally compatible when appropriately managed. The findings align with UN Sustainable Development Goals 6 (Clean Water) and 7 (Clean Energy). Continued long-term monitoring provides an essential baseline for evaluating the environmental impact and guiding sustainable geothermal development in Iceland.

1 INTRODUCTION

Sustainable utilization of geothermal resources requires the protection of surrounding groundwater systems from potential thermal and chemical impacts. In Iceland, high-temperature geothermal development plays a key role in achieving carbon-neutral energy production. Thus, long-term groundwater observation provides an essential basis for assessing possible geochemical changes associated with geothermal exploitation.

The Theistareykir geothermal power plant, located in NE Iceland, began commercial operation in 2017 and currently has an installed capacity of 90 MWe with future plans to add another 45 Mwe. Its development followed geological, hydrological, and environmental investigations (e.g., Óskarsson, 2015 and references therein). A structured monitoring program was established in cooperation between Landsvirkjun (the National Power Company of Iceland) and Iceland GeoSurvey (ÍSOR) to evaluate the chemical composition of groundwater before, during, and after construction and operation. The program focuses on tracking chemical and isotopic trends in groundwater flowing northward from the Theistareykir geothermal field toward the Kelduhverfi region and Öxarfjörður bay.

The objectives of this study are to present groundwater monitoring results at Theistareykir from 2012 and Kelduhverfi from 2007 up to 2025, evaluate trends in chemical and stable isotopic composition, and assess whether geothermal operations have influenced groundwater chemistry. Together, these results provide an assessment of long-term trends in shallow groundwater quality and support the evaluation of potential environmental impacts associated with geothermal development at Theistareykir.

2 BACKGROUND

Theistareykir is a central volcano system that lies within the Northern Volcanic Zone (NVZ) of Iceland, approximately 30 km north of Krafla and 20 km south of Húsavík. The geothermal field is characterized by Holocene basaltic lavas and hyaloclastites that overlie older Pleistocene formations (Sæmundsson, 2007). The area is cut by numerous NE-trending normal faults and fissures belonging to the Tjarnarás and Ketilfjall systems, which control both geothermal upflow and regional groundwater flow (Khodayar et al., 2018). The geothermal reservoir is hosted mainly within fractured basaltic lavas of the Theistareykjahraun formation. Geochemical and logging data indicate a high enthalpy system with reservoir temperatures of ~270–290 ˚C (Óskarsson, 2015).

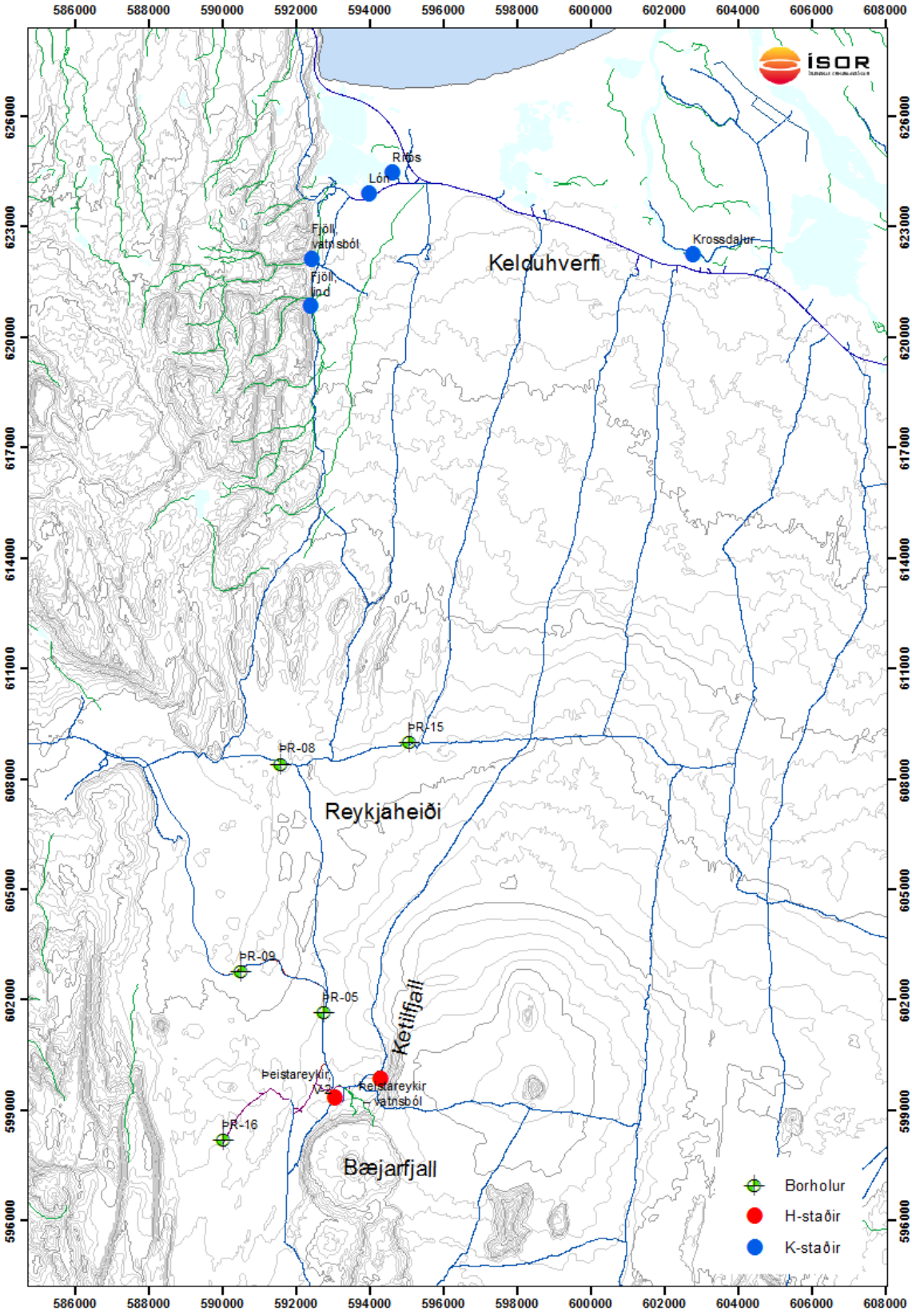


Figure 1. Sampling locations in Kelduhverfi and Theistareykir in N Iceland. Boreholes are shown in green with a cross. Warm springs are red and cold springs are blue.

The region has a subarctic climate typical of inland NE Iceland, with mean annual air temperatures of 2–3°C and annual precipitation of 400–500 mm (Icelandic Meteorological Office, 2025). Surface drainage is sparse, with precipitation and snowmelt providing the primary recharge. Groundwater boreholes were drilled primarily for monitoring and intersect shallow aquifers used also for cooling water supply. Regional heat flow in Iceland's neo-volcanic zone is elevated, typically 200–300 mW/m^2 compared with the global continental average of ~65 mW/m^2 (Hjartarson, 2015), with temperature gradients of 50–150°C/km (Flóvenz and Sæmundsson, 1993). Despite this, shallow groundwater in the study area remains cold, as shown by the monitoring results presented.

Geochemical investigations prior to power plant commissioning established that deep reservoir fluids are near-neutral, relatively dilute Na–Cl waters with low gas content, consistent with a high-temperature convective system hosted in fractured basalts (Óskarsson et al., 2013; Óskarsson, 2015). Stable isotope studies show that the circulating thermal water is largely of meteoric origin, sourced mainly from recharge south of the field and including a significant pre-Holocene component, as indicated by strongly depleted δD and $\delta^{18}O$ values in the deepest fluids (Sveinbjörnsdóttir et al., 2013). More recent analyses of downhole and surface fluids at Theistareykir and Krafla reveal that deep fluids are enriched in several semi-volatile and base metals, reflecting a magmatic-degassing source rather than crustal leaching (Saby et al., 2022). These metals remain confined to acidic fluids at depth with the geothermal system separated from the overlying shallower aquifers due to the caprock and other aquicludes. Follow-up work has confirmed the persistence of this pattern and the limited vertical transport of trace elements within the system (Saby et al., 2024). Together, these studies demonstrate that the deep geothermal reservoir at Theistareykir is chemically and hydrologically distinct from the overlying meteoric aquifer that is the focus of the present groundwater monitoring study.

3 MONITORING METHODS

3.1 Sampling locations

Groundwater monitoring at Kelduhverfi began in 2007 and Theistareykir in 2012 and continues under a coordinated program managed by Landsvirkjun and ÍSOR. The network is designed to detect possible migration of geothermal fluids into shallow aquifers and to track northward groundwater flow from the geothermal field toward the Kelduhverfi lowlands.

The monitoring sites include the groundwater boreholes at Theistareykir (ÞR-08, ÞR-09, ÞR-15, ÞR-16) together with the local freshwater supply (ÞR – vatnsból). In addition, five cold and tepid springs in the Kelduhverfi area are sampled: Fjöll – vatnsból, Fjöll – lind, Lón, Rifós, and Krossdalur. The combined dataset therefore provides both spatial and temporal resolution for evaluating potential changes related to geothermal production. Locations are shown in Figure 1.

3.2 Field and laboratory procedures

All sampling and field protocols follow ÍSOR's standard procedures (Ármannsson and Ólafsson, 2006) and Arnórsson et al. (2006). Temperature, pH, electrical conductivity, and dissolved hydrogen sulfide (H_2S) were measured on site. Filtered (0.20 µm) water samples were preserved for cation and trace element analysis by acidification with ultrapure nitric acid (HNO_3), while separate filtered aliquots were retained for anion and stable isotope determination. Additional untreated samples were taken in airtight bottles for dissolved carbon dioxide (CO_2) and pH analyses, which were shipped to the ÍSOR chemical laboratory within 24 hours of collection.

Major cations and trace elements as well as silica (SiO_2) were analysed by inductively coupled plasma – optical emission spectrometry (ICP-OES; Thermo iCAP 7400/Agilent 7900) at ALS Laboratories and ÍSOR (from 2019) and inductively coupled plasma – mass spectrometry (ICP-MS) at ALS Laboratories in Sweden. In 2007 to 2018, cations were measured by atomic absorption spectrometry (AAS) and SiO_2 by spectrophotometry. Anions were determined by ion chromatography (IC; Dionex ICS-21002100) at ÍSOR. Dissolved CO_2 was measured by titration following a modified alkalinity procedure by Arnórsson et al. (2006). Stable isotope ratios of hydrogen and oxygen (δD, $\delta^{18}O$) were measured at the University of Iceland by isotope mass spectrometry (Thermo Delta V Advantage). Results are reported in per-mille (‰) relative to V-SMOW. Tracers such as naphthalenesulfonates, used occasionally for reservoir connection studies, were analysed since 2017 at the ÍSOR laboratory using a high-performance liquid chromatography with fluorescence detection (HPLC-FLD; Thermo Ultimate 3000+).

4 RESULTS

Time series of chemical composition results are shown in Figures 2-7 from waters collected from boreholes and springs in Theistareykir and Kelduhverfi. When relevant, data are compared with Icelandic water pollution quality categories laid out by the Icelandic regulation on Prevention against Water Pollution (Ministry of the Environment, 2025)

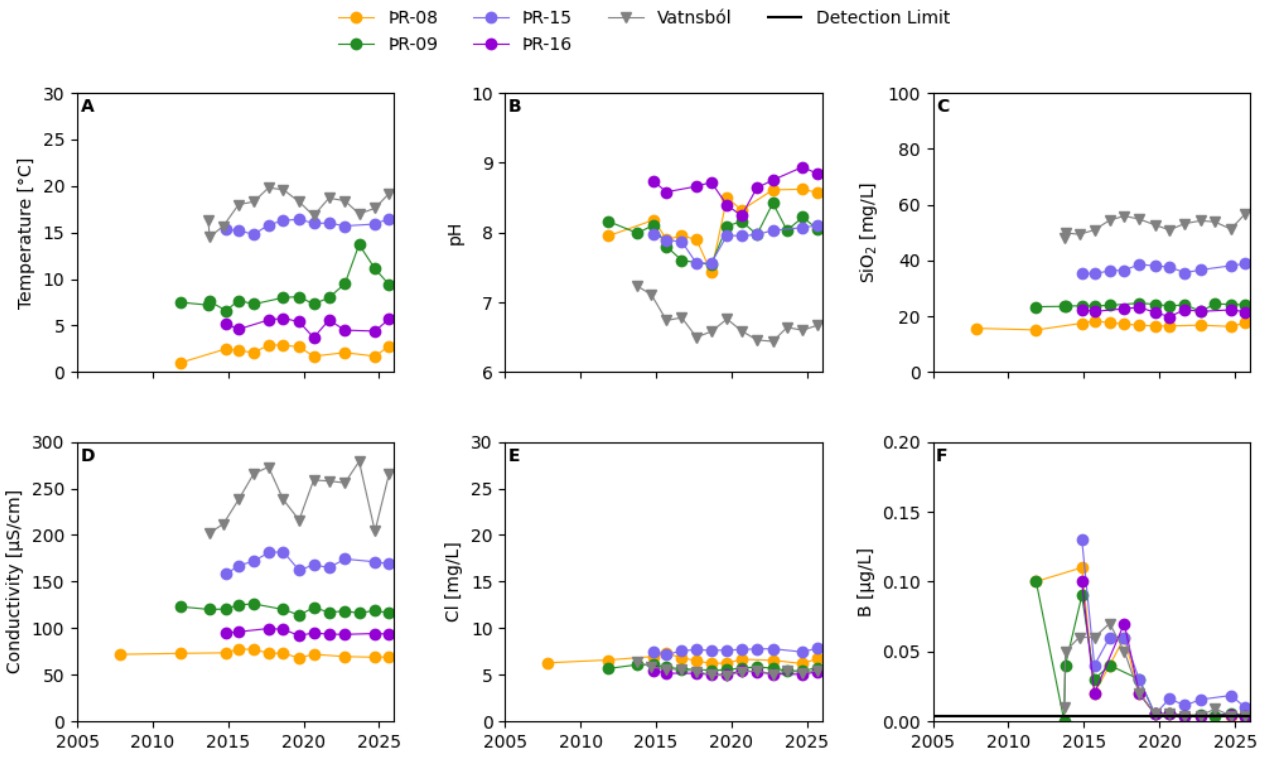


Figure 2. Temperature (A), pH (B), silica (C), conductivity (D), chloride (E), and boron (F) in water from boreholes and a tepid spring in Theistareykir.

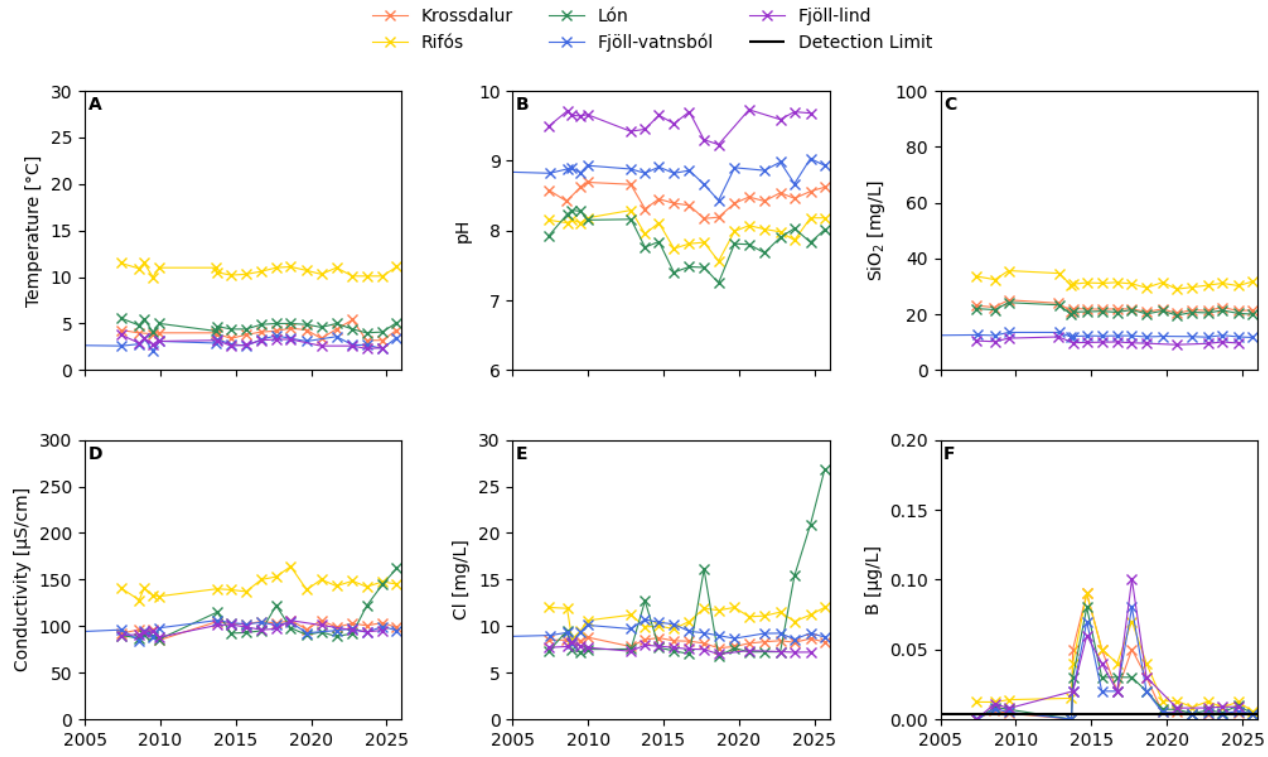


Figure 3. Temperature (A), pH (B), silica (C), conductivity (D), chloride (E), and boron (F) in water from springs in Kelduhverfi.

Groundwater in Theistareykir remains dilute and slightly alkaline (Figure 2). The warm spring at the Vatnsból shows the lowest pH values (6.5 – 7), highest temperatures up to 20 ˚C, and conductivity values up to 280 µS/cm. These temperatures and conductivities reflect shallow circulation and likely mixing with geothermal steam as dissolved CO_2 concentrations (not shown) are consistently high in these samples. Chloride (Cl) concentrations remain about 5-7 mg/L in all boreholes with no significant change after production began in 2017. Boron (B) concentrations decrease during the monitoring period and have been close to or at the analytical detection limit since 2019 that coincides when analytical methods were switched from AAS to ICP-OES.

Springs in Kelduhverfi are cold and alkaline (Figure 3), with the highest temperatures measured at Rifós (up to 11.5 ˚C) and the highest pH values at Fjöll-lind (up to 9.7). Conductivity and Cl have in recent years increased at the Lón spring. Like Theistareykir, B concentrations show fluctuations but remain close to or at the analytical detection limit from 2019 onward.

Arsenic (As) values shown in Figure 4 are consistently ≤ 0.4 µg/L, within Icelandic environmental water pollution limit I ('very low or no risk of effects' to aquatic biota) and well below Icelandic drinking water guidelines (Ministry of the Environment, 2018; 2025), the European Union (EU) Water Framework Directive (EU, 2020), and World Health Organization (WHO) guideline limits (WHO, 2023). Aluminium (Al) concentrations (Figure 4) are generally ≤ 20 µg/L, except for a single outlier observed at Fjöll-lind, which also has the highest values.

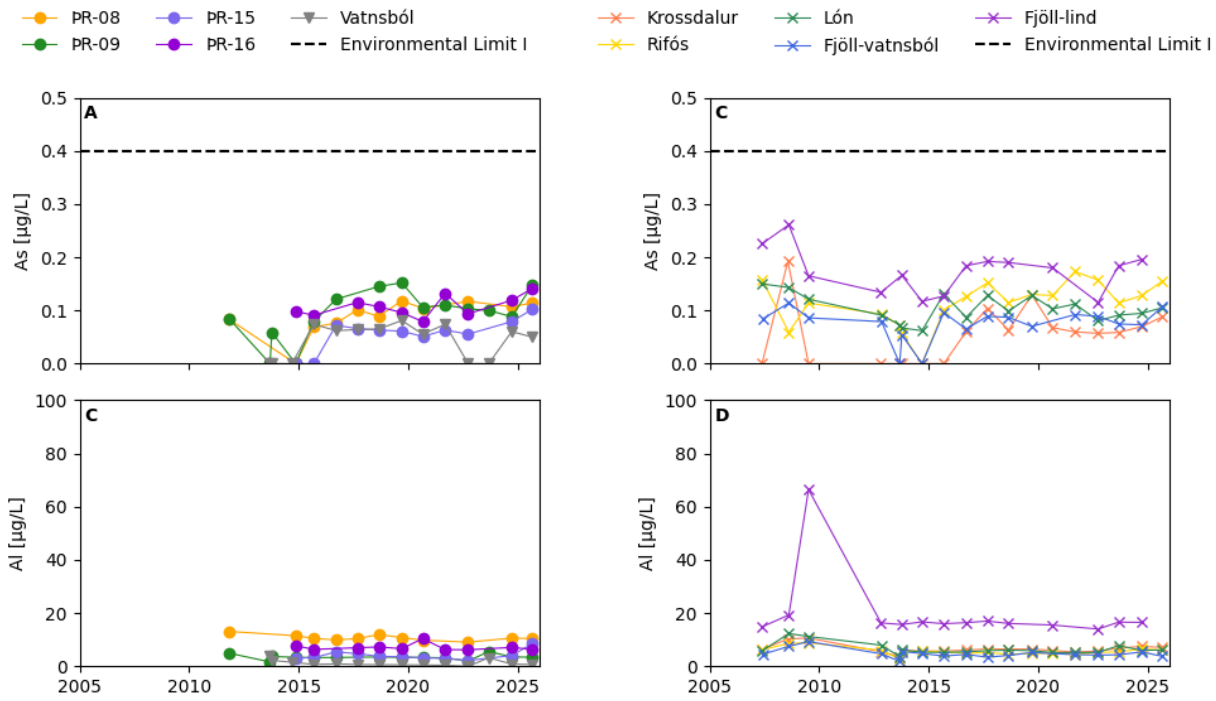


Figure 4. Concentrations of arsenic (A, B) and aluminum (C, D) in water from boreholes in Theistareykir and springs in Kelduhverfi along with environmental water pollution limit I. The Al limit for drinking water (200 µg/L) falls outside the scale of figures C and D.

Trace element concentrations in both Theistareykir and Kelduhverfi remain low and close to analytical detection limits (Figures 5 and 6). Copper (Cu), cadmium (Cd), lead (Pb), chromium (Cr), and nickel (Ni) are generally below 1–2 µg/L in all locations, while zinc (Zn) concentrations vary from >1 up to 8 µg/L in Theistareykir. These values fall within environmental limit I and, for Cu and Cr and occasionally Zn and Ni, within limit II ('low risk of effects' to aquatic biota). Minor fluctuations are observed (up to 3 – 5 µg/L for Cu, Cr, Ni), and a few isolated Cu and Ni measurements fall within environmental limit III ('effects expected on sensitive biota'). Nonetheless, all concentrations remain well below Icelandic, EU, and WHO drinking water guidelines.

Monitoring time-series plots (Figures 4-6) demonstrate that post-2017 variations remain within pre-operational ranges. When compared with background groundwater in neighbouring systems such as Mývatnssveit and Krafla (Kristinsson et al., 2024), trace element concentrations at Theistareykir are similarly low.

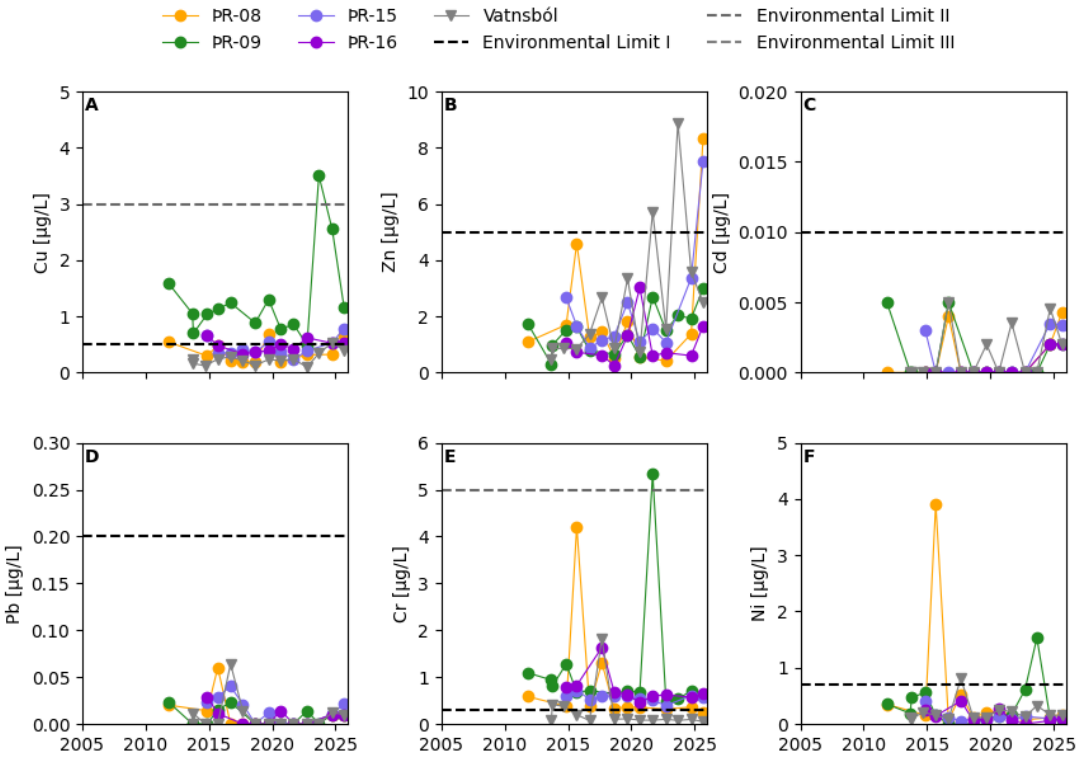


Figure 5. Concentrations of copper (A), zinc (B), cadmium (C), lead (D), chromium (E), and nickel (F) in water from boreholes in Theistareykir along with environmental water pollution limits I, II, and III.

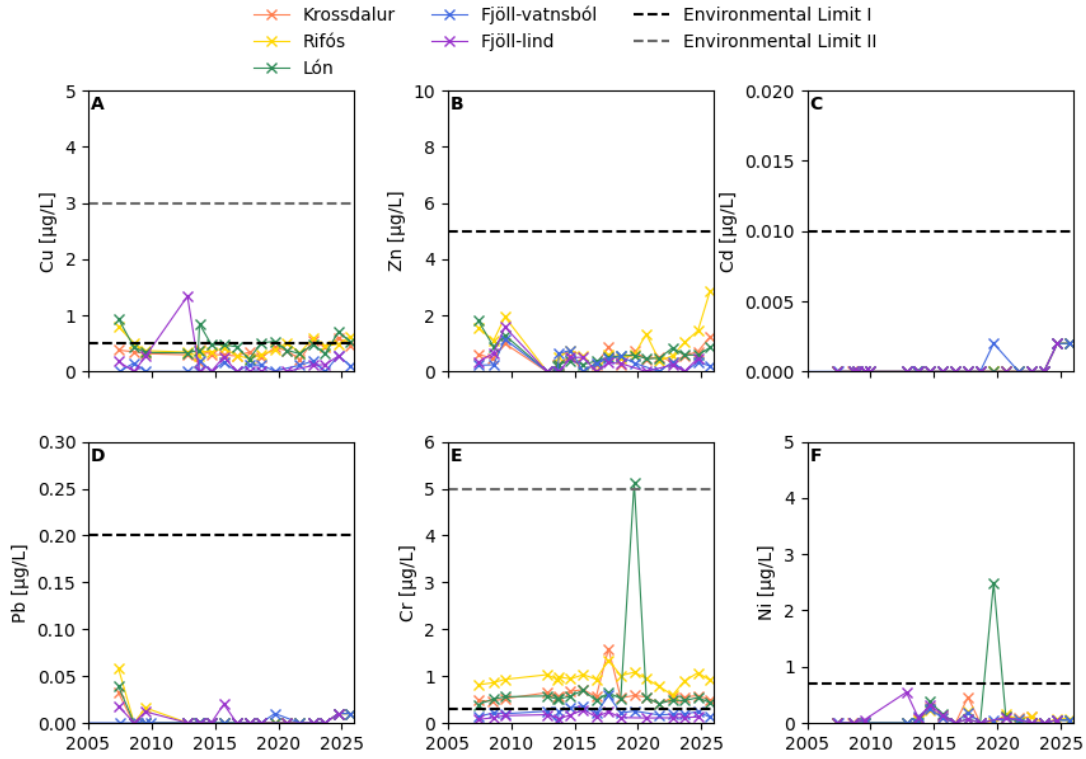


Figure 6. Concentrations of copper (A), zinc (B), cadmium (C), lead (D), chromium (E), and nickel (F) in water from springs in Kelduhverfi along with environmental water pollution limits I and II.

Stable isotope values (δD and $\delta^{18}O$) for all samples from Theistareykir and Kelduhverfi range approximately between –85 to –70‰ δD and –12 to –10 ‰ $\delta^{18}O$ (Figure 7). These values plot along or slightly above the Global Meteoric Water Line (GMWL; Craig 1961), indicating that all monitored waters are meteoric in origin. No samples show the more depleted isotopic signature of the Theistareykir geothermal reservoir (δD ≈ –140 to –105‰; Sveinbjörnsdóttir et al., 2013) and therefore do not show signs of significant mixing with the geothermal fluids.

Isotopic differences among Theistareykir boreholes are evident; ÞR-8 is the most enriched, followed by ÞR-15, with ÞR-9 and ÞR-16 (farther south) being more depleted. In Kelduhverfi, the two springs at Fjöll (vatnsból and lind) are also relatively enriched and align well isotopically with ÞR-8, which is also the closest Theistareykir borehole. The Rifós spring plots closer to the compositions of ÞR-9 and ÞR-16. These spatial-isotopic patterns suggest the presence of multiple shallow aquifers and potential groundwater flow connections between the Theistareykir and Kelduhverfi regions.

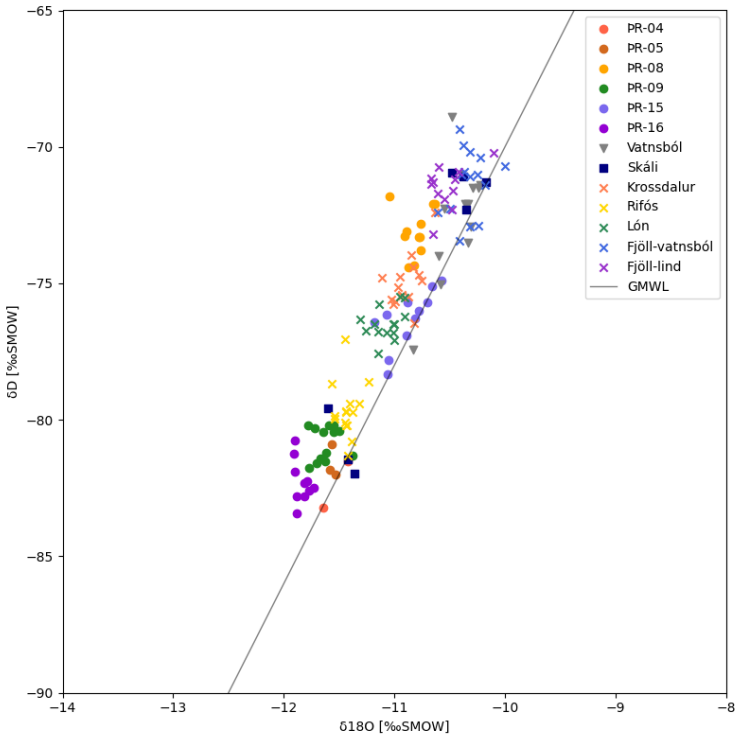


Figure 7. Stable water isotopes for all samples along with the GMWL (Craig 1961).

To complement the chemical monitoring, organic tracers (naphthalenesulfonates) that were used in an inter-well tracer test in the Theistareykir geothermal system were analysed since 2017. Two tracers (2,6-NDS and 2,7-NDS) were injected in 2020 and were subsequently detected in several production wells for at least three years following injection. In contrast, all results from the groundwater boreholes in Theistareykir and springs in Kelduhverfi were below the detection limit of 0.1 µg/L. These results suggest that the tracers from this, or any earlier, tracer test have not been detected in the monitored groundwater.

5 DISCUSSION

The Theistareykir and Kelduhverfi environmental monitoring programme spans close to two decades before and after plant commissioning of the power plant, enabling evaluation of both natural background variability and possible operational effects. The data show that trace metal concentrations have remained remarkably stable over the 2007–2025 period, with no statistically significant upward trends. These results indicate that the shallow groundwater system in the Theistareykir–Kelduhverfi area is effectively isolated from geothermal reservoir processes.

5.1 Absence of geothermal influence

A key objective of the monitoring programme has been to detect any evidence of mixing between deep geothermal fluids and the overlying meteoric aquifers. In high-temperature systems, such mixing is commonly

identified by increases in conservative constituents (e.g., Cl, B) or by oxygen-isotope shifts toward the depleted $\delta^{18}O$ values characteristic of geothermal fluids (Ármannsson et al., 2021). When groundwater monitoring in Mývatnsveit (south of Theistareykir) began to document any potential effects from the Bjarnarflagsvirkjun and Krafla power plants, As and Al were also selected as natural tracers of geothermal fluids, an approach equally applied here. None of these indicators are observed in the groundwaters and springs of Theistareykir and Kelduhverfi.

The isotopic distinction between the deep reservoir ($\delta D \approx -140$ to $-105‰$; Sveinbjörnsdóttir et al., 2013) and shallow groundwater ($\delta D \approx -80$ to $-70‰$; Figure 7) demonstrates a lack of hydraulic connection. Likewise, major elements typical of geothermal fluids (e.g., Cl, SiO_2) remain at low groundwater levels. Minor fluctuations observed in Cu, Cr, and Ni fall within analytical uncertainty and show no directional or sustained trends. An apparent decline in B concentrations corresponds with a change in analytical methodology rather than a hydrogeochemical shift, and values have remained at or near detection limits since 2019.

Across all parameters, no systematic shifts coincide with the start of geothermal production in late 2017. The absence of chemical anomalies, isotopic changes, or detected naphthalenesulfonate tracers therefore confirms that geothermal production and reinjection have not altered the regional groundwater system.

5.2 Comparison with other Icelandic geothermal systems

Similar environmental monitoring frameworks in Icelandic high-temperature fields, such as Krafla and Nesjavellir, have observed localized shallow aquifer perturbations near steam leakage zones or reinjection boundaries (Kristinsson et al., 2024; Hjartarson and Kristinsson, 2011). By contrast, Theistareykir shows no measurable deviations from natural baselines.

Several site-specific features can be attributed to hydrogeological rather than geothermal processes. Temperature, conductivity, and pH variations at the Vatnsból tepid spring are consistent with shallow circulation and some mixing with geothermal steam, unrelated to deep fluid input. The recent increase in conductivity and Cl at Lón in Kelduhverfi likely reflects its position at the outflow of a brackish coastal lagoon rather than geothermal influence. Trace element concentrations at Theistareykir are comparable to those observed in neighbouring systems such as Mývatnssveit and Krafla (Kristinsson et al., 2024), highlighting the geochemical stability of basalt-hosted aquifers.

This broader comparison suggests that Theistareykir's stability reflects both geological and operational factors. The reservoir lies within a relatively young and unaltered basaltic sequence with high permeability, promoting efficient deep circulation and limiting vertical transport of solutes. Reinjection is managed to maintain pressure equilibrium and prevent upward fluid migration. The absence of historical geothermal exploitation prior to 2017 also provides a clear pre-operational baseline for evaluating long-term change. Together, these characteristics illustrate that high-temperature geothermal development can coexist with clean groundwater systems when appropriate well siting, reinjection strategies, and long-term monitoring are implemented.

5.3 Environmental compliance and broader relevance

Trace elements (Al, As, Cu, Zn, Cd, Pb, Cr, Ni) remain well within Icelandic, EU, and WHO drinking water regulations (Ministry of the Environment, 2018; EU, 2020; WHO; 2023). Waters fall within environmental limits I to III of the Icelandic water pollution regulation (Ministry of the Environment, 2025), corresponding to no risk to low risk of effects on aquatic biota.

The multi-year records from both Theistareykir (13 years) and Kelduhverfi (18 years) underscore the importance of sustained monitoring beyond the initial development phase. Shorter studies (1–3 years) often fail to capture the full range of natural geochemical variability, particularly in Icelandic systems influenced by seasonal recharge and volcanic activity. Theistareykir therefore serves as a reference example showing that high-temperature geothermal utilization can be environmentally compatible with groundwater protection when supported by robust monitoring, careful well placement, and adaptive management.

Beyond Iceland, these findings contribute to the global discussion on geothermal sustainability. Concerns over groundwater quality often limit development of high-temperature resources; the Theistareykir case demonstrates that geothermal power generation can be operated with negligible impact on surrounding groundwater systems. This supports the broader role of geothermal energy as a low impact renewable resource aligned with the UN Sustainable Development Goals, particularly SDG 6 (Clean Water) and SDG 7 (Clean Energy).

6 CONCLUSIONS

The environmental monitoring programme at the Theistareykir high-temperature geothermal field documents groundwater chemistry before and after commissioning of the power plant in 2017. Groundwater composition across the Theistareykir–Kelduhverfi region remains stable, dilute, and within Icelandic environmental water quality standards throughout the monitoring period. Trace elements, such as arsenic, aluminium, and other metals, are consistently low with no increasing trends. Stable isotope data confirm a meteoric origin for all monitored waters, with no evidence of mixing with geothermal fluids.

The absence of chemical or isotopic change indicates that geothermal production and reinjection have not affected the regional groundwater system. This outcome reflects favourable geological conditions, careful well placement, and effective operational management. The Theistareykir case therefore represents a strong example of environmentally responsible geothermal development, aligning directly with SDG 6 (Clean Water) and SDG 7 (Clean Energy).

Continued long-term monitoring remains essential to maintain this environmental record and to provide early warning capability should conditions change. The experience gained at Theistareykir demonstrates that sustained, high-quality monitoring both safeguards local water resources and strengthens the evidence base for expanding geothermal utilization in Iceland and globally.

Acknowledgements

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