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Numerical Modelling of Environmental Impacts of Geothermal Wastewater Disposal from a Proposed Power Plant on a Shallow Groundwater Aquifer at Bjarnarflag, NE Iceland

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ABSTRACT

Landsvirkjun, the National Power Company of Iceland, owns and operates a 5 MWe geothermal power plant at Bjarnarflag in NE Iceland, targeting the western part of the Námafjall high-temperature geothermal reservoir. As part of the operational design of a proposed new power plant at Bjarnarflag, Vatnaskil provided Landsvirkjun with consultation relating to the disposal of geothermal wastewater from the plant with emphasis on minimizing environmental impacts on the shallow groundwater aquifer and nearby Lake Mývatn nature reserve. A numerical model was utilized to simulate several disposal scenarios, injecting the geothermal wastewater below the shallow groundwater aquifer to depths of 300-600 meters.

An existing regional watershed model of NE Iceland, developed by Vatnaskil and utilized as a tool for environmental related projects in the region, was used as a foundation for the modelling work. The watershed model covers an area of roughly 16,000 km^2 extending from the northern coastline of Iceland up to the Vatnajökull glacier and consists of a surface runoff model and a two-dimensional groundwater model simulating the shallow groundwater aquifer (upper 100 m of the groundwater system). In order to simulate the proposed disposal scenarios, it was necessary to expand the groundwater model vertically to take into account the deeper groundwater system, including the upper section of the Námafjall geothermal reservoir. A conceptual model of the local groundwater system and underlying reservoir was formulated utilizing data collected over decades of groundwater monitoring and geothermal exploration in the area. The conceptual model was then used to construct an integrated three-dimensional numerical model of a 20x30 km area centered around Bjarnarflag, extending to a depth of 900 meters, using iTOUGH2 modelling software in conjunction with the regional groundwater model.

The integrated three-dimensional model was used to simulate several disposal scenarios to analyze the sensitivity of key model input parameters as well as the effect of variations in the injection parameters. Model results revealed that enhanced permeability along vertical faults is a major control on groundwater flow paths connecting the shallow groundwater aquifer with deeper sections of the groundwater system. In all scenarios, a significant amount of the injected geothermal wastewater migrates upward through the Krummaskarð fault and into the overlying shallow groundwater aquifer. From there, the geothermal wastewater plume is carried southwest in the direction of regional groundwater flow. The Grjótagjá fault acts as a hydrologic barrier, preventing further plume migration west towards Lake Mývatn. Enhanced groundwater flow in the vicinity of the Grjótagjá fault significantly dilutes and cools the geothermal wastewater, forcing much of it downward through the fault into deeper sections of the groundwater system.

The integrated modelling approach utilized in the project proved effective for simulating groundwater flow and transport processes within a complicated geological environment. The approach is transferable to other geothermal fields where characterization of environmental impacts from wastewater disposal is required. An integrated three-dimensional model is a valuable management tool for use by geothermal developers during all phases of field development, including determining optimal disposal methods in the planning phase and mitigating existing impacts during the production phase.

1. INTRODUCTION

Landsvirkjun, the National Power Company of Iceland, owns and operates a 5 MWe geothermal power plant at Bjarnarflag in NE Iceland, targeting the western part of the Námafjall high-temperature geothermal reservoir. The Bjarnarflag power plant was brought online in 1969 and has therefore been in operation for over 50 years. In addition to electricity generation, the power plant also provides steam and geothermal water for the local district heating system, industrial use, and the Mývatn Nature Baths. Landsvirkjun also operates nearby geothermal power plants at Krafla and Theistareykir.

As part of the operational design of a proposed new power plant at Bjarnarflag, Vatnaskil provided Landsvirkjun with consultation relating to the disposal of geothermal wastewater from the plant with emphasis on minimizing environmental impacts on the shallow groundwater aquifer and nearby Lake Mývatn nature reserve. A numerical model was utilized to simulate several disposal scenarios, injecting the geothermal wastewater below the shallow groundwater aquifer to depths of 300-600 meters.

2. CONCEPTUAL MODEL

A wealth of data has been collected from over 50 years of hydrological and geothermal monitoring and exploration in the vicinity of Lake Mývatn and Námafjall. Vatnaskil has decades of modelling experience in the area, including modelling of the regional shallow groundwater aquifer (Vatnaskil, 2015) and modelling of geothermal wastewater disposal in the deep aquifer at the nearby Krafla (Vatnaskil, 2009a) and Theistareykir (Vatnaskil, 2009b) geothermal fields. Furthermore, Iceland Geosurvey (ÍSOR) have developed a conceptual model of the Námafjall geothermal reservoir and have used it to construct a numerical model of the reservoir (Halldórsdóttir et al., 2010).

All available data, including the above-mentioned research and existing conceptual models, were utilized in the construction of a comprehensive conceptual model of the groundwater system and underlying geothermal reservoir at Námafjall (Figure 1). The groundwater system at Námafjall is characterized by two main aquifers, a shallow aquifer in the upper 100 meters of the groundwater system and an underlying deep aquifer which extends down to the caprock of the geothermal reservoir. The existing regional watershed model developed by Vatnaskil (2015) represents the shallow aquifer. Less data has been collected from the deep aquifer, as it lies in the transition zone between the shallow groundwater aquifer and the underlying geothermal reservoir, which have been the main focal points of research to-date. The hydrogeology of the Námafjall area is rather complex, as the underlying geothermal reservoir has a significant effect on the overlying groundwater system.

The underlying heat source of the Námafjall geothermal reservoir lies below Námafjall and Jarðbaðshólar. Upflow of geothermal fluids is focused at these two locations. The caprock overlying the geothermal reservoir is not impermeable and allows geothermal fluids and gases to escape into the overlying groundwater aquifers, causing an increase in groundwater temperature and alteration of the chemical composition of the groundwater. Some of the geothermal gases and fluids eventually reach the surface, as evidenced by the prevalence of geothermal surface manifestations between Námafjall and Jarðbaðshólar. A regional fault zone striking NE-SW extends through the area just west of Bjarnarflag and has a strong influence on groundwater flow. Although regional groundwater flow is from east to west, enhanced hydraulic conductivity and anisotropy in the bedrock within the fault zone creates preferential horizontal pathways for groundwater in the NE-SW direction. The two main faults which border the fault zone to the east (Krummaskarð) and west (Grjótagjá) have a major effect on vertical groundwater flow patterns. The Krummaskarð fault penetrates the caprock and allows for upflow of geothermal fluids through the fault. Cold groundwater flows down the Grjótagjá fault and through the caprock, cooling and providing recharge to the underlying geothermal reservoir.

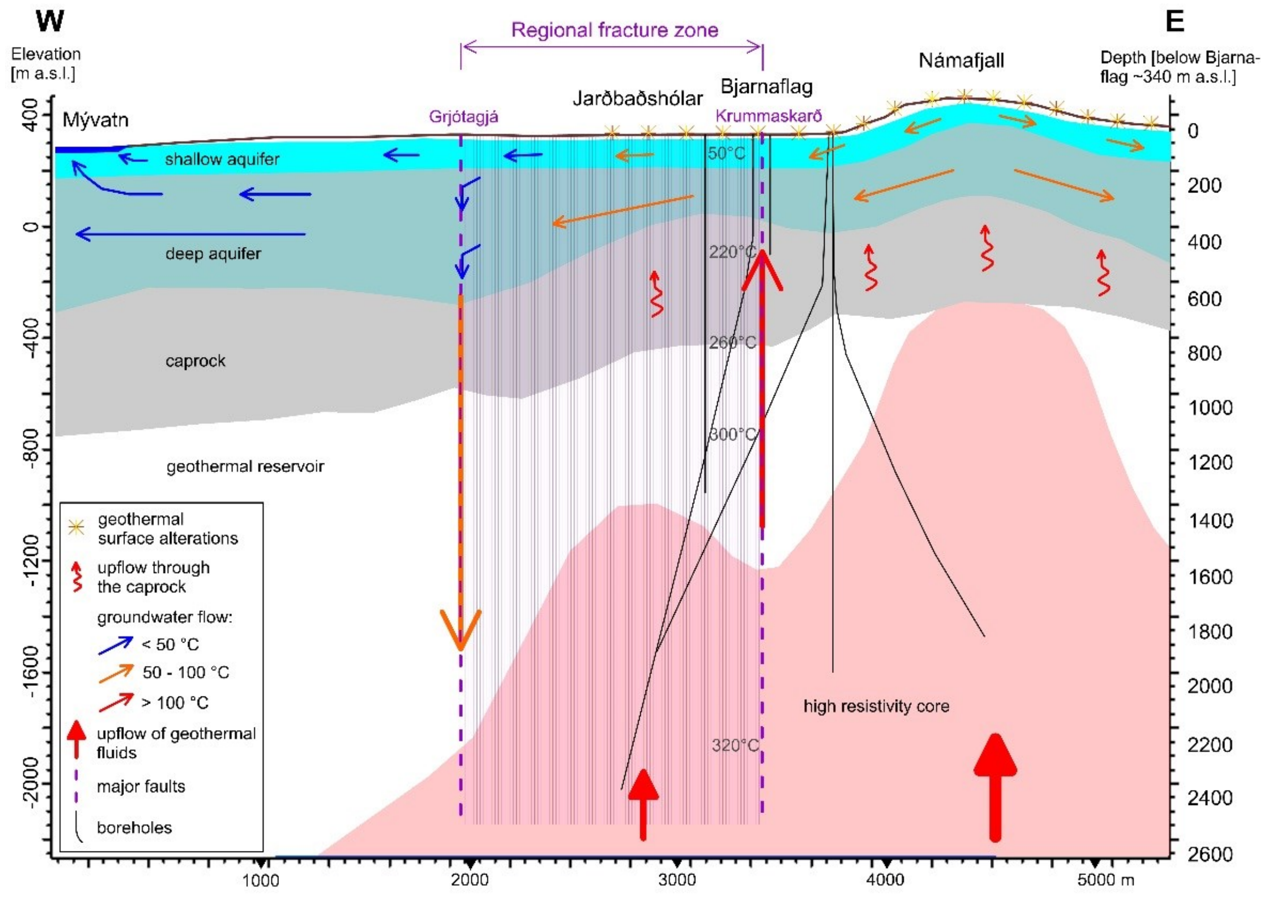

Figure 1: Conceptual model of groundwater system at Námafjall.

3. NUMERICAL MODEL

An existing regional watershed model of NE Iceland, developed by Vatnaskil and utilized as a tool for environmental related projects in the region, was used as a foundation for the modelling work. The watershed model covers an area of roughly 16,000 km^2 extending from the northern coastline of Iceland up to the Vatnajökull glacier and consists of a surface runoff model and a two-dimensional groundwater model simulating the shallow groundwater aquifer. In order to simulate the proposed disposal scenarios, it was necessary to expand the groundwater model vertically to take into account the deeper groundwater system, including the upper section of the Námafjall geothermal reservoir.

The conceptual model was used to construct an integrated three-dimensional numerical model of a 20x30 km area centered around Bjarnarflag, extending to a depth of 900 meters, using iTOUGH2 modelling software (Pruess, 1991; Finsterle, 1999) in conjunction with the regional groundwater model (Figure 2). Geological and geophysical data supplied by ÍSOR from their PETREL database (Schlumberger, 2010) were used to discretize the model vertically into 18 layers based on rock lithology and location of the caprock.

Boundary conditions (pressure and temperature) were defined to the top and bottom model layers, as well as the outer model boundary in all layers, using calculated groundwater levels from the regional groundwater model and temperature data from the PETREL database. The model was calibrated on measured temperature profiles from boreholes within the model area.

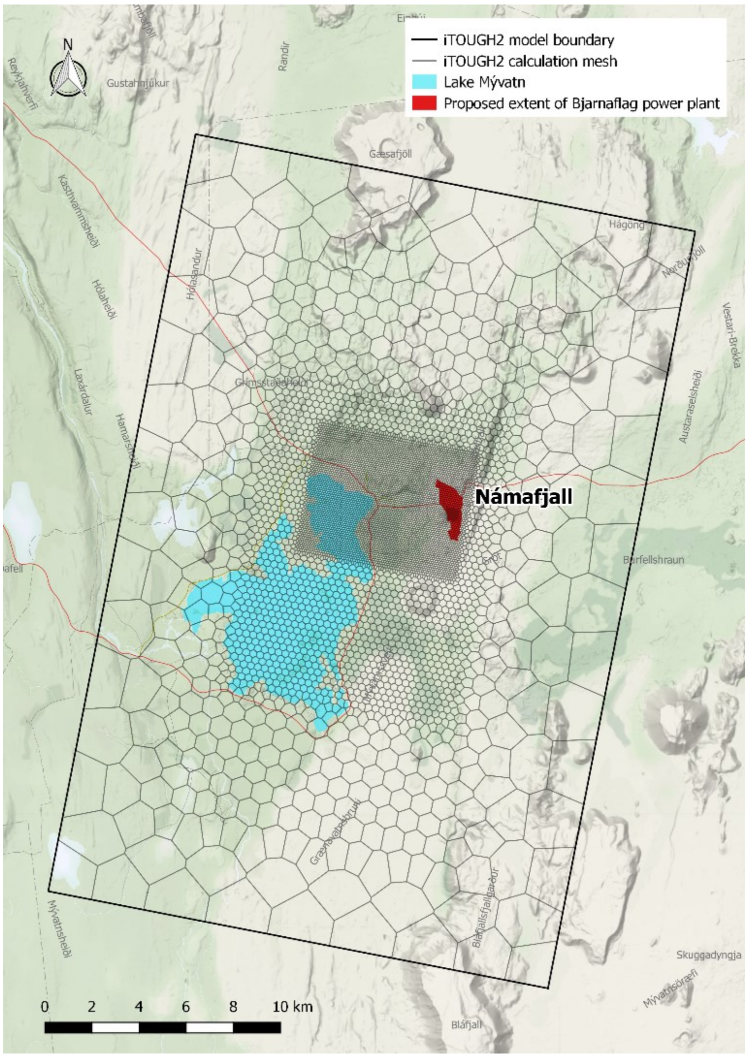

Figure 2: iTOUGH2 numerical model boundaries and calculation mesh.

The calibrated numerical model was used to simulate the injection of geothermal wastewater from the proposed new power plant at Bjarnarflag. The main goal of the modelling was to predict the effect of the proposed injection on the shallow groundwater aquifer and determine whether changes to the quality and temperature of the groundwater discharging into Lake Mývatn are likely. Multiple disposal scenarios were simulated at the request of Landsvirkjun in order to analyze the effects of variations in the injection parameters and assist in determining optimal operational specifications for the new power plant. Two injection depths were simulated, 360 m and 560 m, and several injection rates ranging from 94-260 kg/s with varying temperature of injected wastewater (117-178 °C) were also simulated. Additional disposal scenarios were simulated as part of a sensitivity analysis on key model parameters such as hydraulic conductivity and anisotropy.

4. RESULTS

In all scenarios, a significant amount of the injected geothermal wastewater migrates upward through the Krummaskarð fault and into the overlying shallow groundwater aquifer. Lateral migration of the wastewater is limited in the deep aquifer due to relatively low horizontal hydraulic conductivity. Once the wastewater reaches the shallow aquifer, the plume is carried southwest in the direction of regional groundwater flow. The Grjótagjá fault acts as a hydrologic barrier, preventing further plume migration west towards Lake Mývatn. Enhanced groundwater flow in the vicinity of the Grjótagjá fault significantly dilutes and cools the geothermal wastewater, forcing much of it downward through the fault into deeper sections of the groundwater system. The results from disposal scenario 1 (260 kg/s injection of 136 °C fluid at 360 m depth) are shown in Figures 3 and 4, where the calculated wastewater concentration is plotted as a percentage of the original concentration of the injected wastewater.

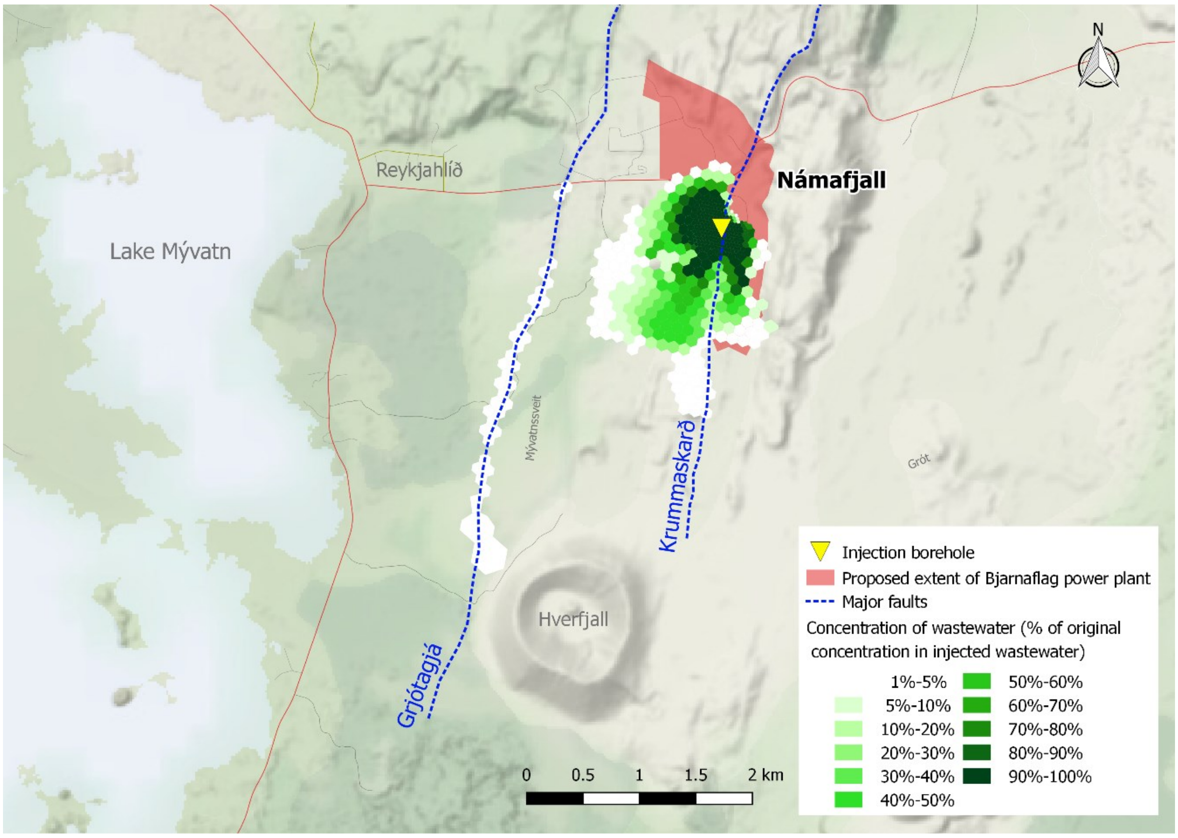

Figure 3: Calculated concentration of injected geothermal wastewater in the deep aquifer 20 years after start of injection (scenario 1: 260 kg/s injection of 136 °C fluid at 360 m depth).

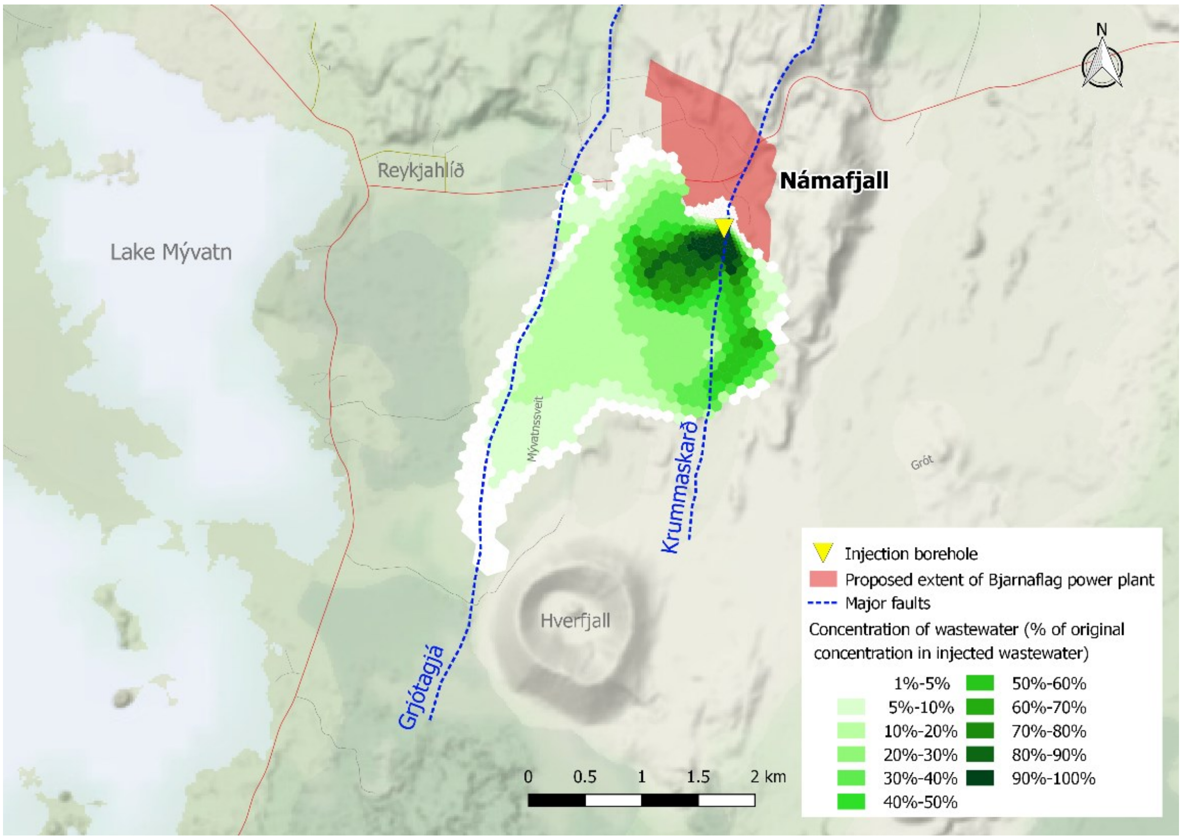

Figure 4: Calculated concentration of injected geothermal wastewater in the shallow aquifer 20 years after start of injection (scenario 1: 260 kg/s injection of 136 °C fluid at 360 m depth).

Figure 3 shows the calculated wastewater plume at the same depth the wastewater is released into the aquifer (360 m). Horizontal spreading of the plume is limited due to low hydraulic conductivity at this depth, and the plume is relatively confined to the immediate vicinity of the injection well. Significant horizontal spreading of the plume occurs within the shallow aquifer due to relatively high horizontal hydraulic conductivity (Figure 4). The wastewater plume is carried southwest towards the Grjótagjá fault, where most of the wastewater is forced downward through the fault. Analysis of all nine disposal scenarios indicate that changes to the chemical composition in the shallow groundwater aquifer are likely to occur within an approximately 10 km^2 area between Námafjall and the Grjótagjá fault due to mixing with the injected wastewater. For all scenarios examined, none of the injected geothermal wastewater reached Lake Mývatn within 20 years after the start of injection.

In addition to changes in chemical composition, the proposed wastewater injection is also likely to induce changes to the groundwater temperature in the shallow aquifer within the same 10 km^2 area mentioned above. The temperature of the groundwater within the shallow aquifer in the vicinity of Námafjall is naturally elevated due to the influence of the underlying geothermal reservoir. Measured temperatures range from approximately 25 °C at the eastern edge of Lake Mývatn up to an excess of 80 °C in the vicinity of the proposed Bjarnarflag power plant (Axelsson, 2014; Ármannsson et al., 1999; Ólafsson et al., 2013). The degree to which the groundwater temperature in the shallow aquifer is affected by the proposed wastewater injection is dependent on the rate and temperature of the injected wastewater. Figure 5 shows the calculated change in groundwater temperature in the shallow aquifer for scenario 1. As the figure shows, a decrease in groundwater temperature of up to 30 °C occurs within an area corresponding to the maximum calculated wastewater concentration, just southwest of the injection well (refer to Figure 4). As the wastewater migrates from 360 m depth upward, it cools below the natural temperature in the shallow aquifer within this limited area. Outside of this area, however, the wastewater causes a rise in groundwater temperature of up to 30 °C. Results for disposal scenario 2 (177 kg/s injection of 178 °C fluid at 360 m depth) show very minimal cooling and almost exclusively a rise in groundwater temperature in the shallow aquifer due to the higher temperature of injected wastewater (Figure 6).

Model results revealed that enhanced permeability along vertical faults is a major control on groundwater flow paths connecting the shallow groundwater aquifer with deeper sections of the groundwater system. The sensitivity analysis revealed that vertical hydraulic conductivity in the major faults has a significant effect on the calculated wastewater concentration in the shallow aquifer. The injection rate and temperature of the injected fluids are also important factors affecting the migration of injected wastewater, as well as the injection depth. The proposed location of wastewater injection in close vicinity to the Krummaskarð fault allows for a significant amount of wastewater to migrate upward through the fault. Relocating the injection well further from the fault would limit vertical migration.

5. SUMMARY

An integrated three-dimensional numerical model was constructed in order to simulate the injection of geothermal wastewater from a proposed new power plant at Bjarnarflag. The iTOUGH2 modelling software was utilized in conjunction with an existing regional groundwater model, resulting in an integrated model extending to a depth of 900 meters. A total of nine disposal scenarios were simulated in order to analyze the effects of variations in the injection parameters as well as to account for uncertainties in key model parameters.

The results of the disposal scenarios indicate that changes to the chemical composition and groundwater temperature in the shallow aquifer are likely to occur within an approximately 10 km^2 area between Námafjall and the Grjótagjá fault due to mixing with the injected wastewater. Due to its effectiveness as a hydraulic sink, the Grjótagjá fault prevents substantial migration of the wastewater plume further west towards Lake Mývatn. Model results indicate that the proposed injection will have minimal effects on groundwater entering Lake Mývatn within 20 years after the start of injection.

The integrated modelling approach utilized in the project proved effective for simulating groundwater flow and transport processes within a complicated geological environment. The approach is transferable to other geothermal fields where characterization of environmental impacts from wastewater disposal is required. An integrated three-dimensional model is a valuable management tool for use by geothermal developers during all phases of field development, including determining optimal disposal methods in the planning phase and mitigating existing impacts during the production phase.

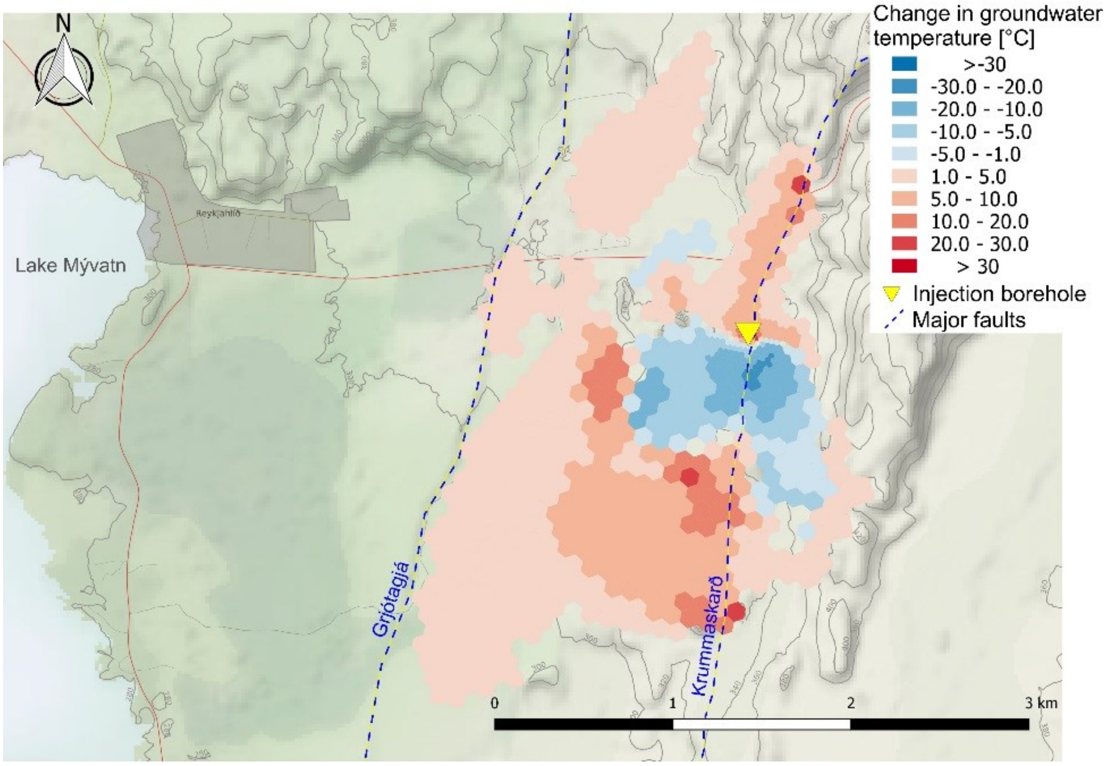

Figure 5: Calculated groundwater temperature change in the shallow aquifer 20 years after start of injection (scenario 1: 260 kg/s injection of 136 °C fluid at 360 m depth).

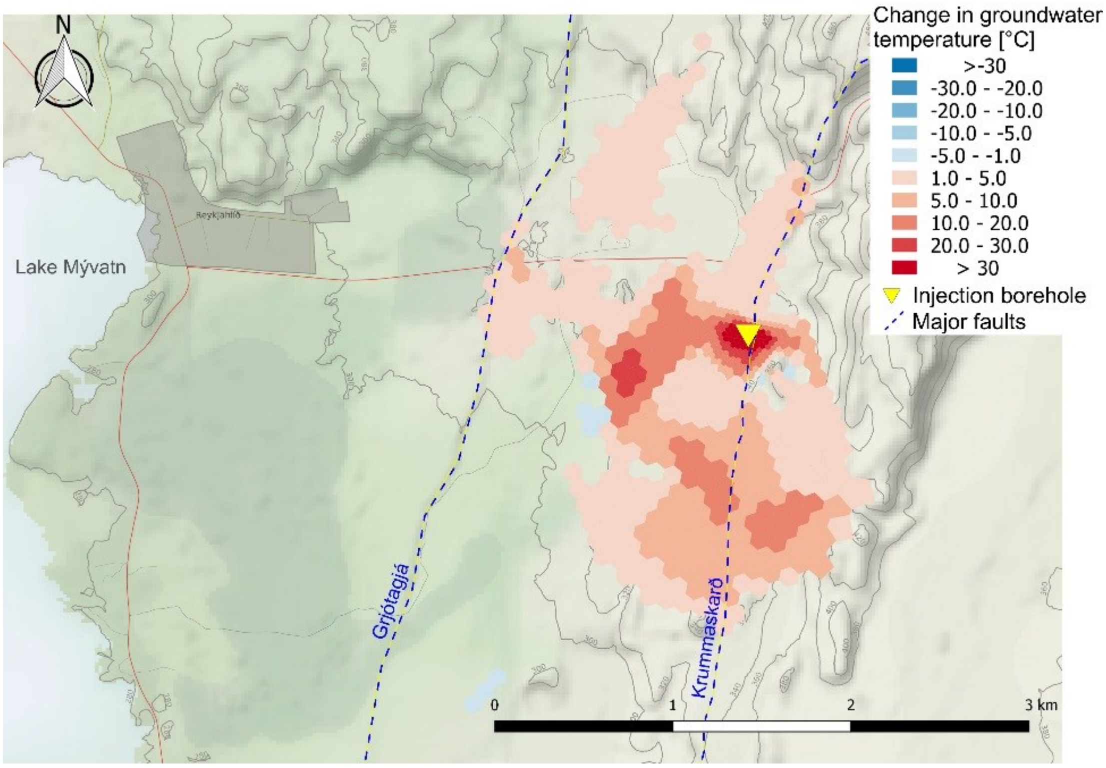

Figure 6: Calculated groundwater temperature change in the shallow aquifer 20 years after start of injection (scenario 2: 177 kg/s injection of 178 °C fluid at 360 m depth).

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