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Reinjection into Two-Phase High-Enthalpy Liquid Dominated Geothermal Fields in NE-Iceland

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ABSTRACT

This paper presents an overview of the experience gained from reinjection strategies at two high-enthalpy liquid dominated geothermal fields operated by Landsvirkjun in NE-Iceland.

Krafla geothermal power station has been in operation for more than 40 years, but currently the installed capacity is 60 MW_e. Until 2002 all brine was discharged on the surface, but since 2002 gradually increasing proportions of brine has been reinjected into infield wells deep in the reservoir. Mainly two wells have been used as reinjection wells.

Well K-26 is located in the south-western part of the well field and is 300-500 m from the nearest production wells. Reinjection in well K-26 commenced in 2002. Initially the objective with reinjection of 120°C hot brine was to attempt to diminish the corrosive properties of fluids in the lower part of the reservoir, but the main aquifer in well K-26 is at 2050 m depth and is within the superheated part of the reservoir, where temperatures exceed 340°C. In the past 10 years reinjection rates in K-26 have been 70-76 l/s. Signs of thermal or chemical breakthrough have thus far been negligible and have been limited to one well at the edge of the current production field.

Well K-39 is located in the southern part of the production field and is 150-300 m from nearby production wells in Suðurhlíðar. Reinjection in well K-39 commenced in 2013 with the objective to provide pressure support to the reservoir in Suðurhlíðar, which had experienced decline in production. The main aquifers in K-39 are rather shallow between 1200-1600 m depth. Despite of this, reinjection rates have been rather high or up to 60 l/s, partially prompted by the objective to reduce surface discharge of brine. Initially a stabilisation in steam output had been observed, however, chemical breakthrough has subsequently been observed as well as enthalpy decrease in nearby production wells. In response to this reinjection in K-39 has been reduced. Work is ongoing to achieve appropriate ratios of reinjection in K-39, which will provide pressure support while at the same time avoiding severe thermal breakthrough.

At Theistareykir geothermal field production commenced in December 2017 and the installed capacity is 90 MW_e. The initial reinjection strategy at Theistareykir is to reinject all brine into shallow wells above the cap rock of the geothermal reservoir. The reinjection wells are 450 m deep and are located more than 1 km northwest of the main production field, where they have been drilled into the outflow from the geothermal reservoir. Production history is short, but despite of this pressure increase has been observed in monitoring wells west of the production field.

1. INTRODUCTION

Reinjection is common in management of geothermal fields worldwide (Diaz *et al.*, 2015), but management of reinjection in geothermal fields can serve different objectives such as to dispose of effluent from power plants in order to reduce environmental impact; provide pressure support; supplement natural recharge or enhance thermal extraction within geothermal fields (Axelsson, 2012). Landsvirkjun have used reinjection in geothermal field management for 17 years with site specific objectives including to dilute fluid composition of deep, superheated reservoir; supplement natural recharge through deep infield reinjection; provide pressure support through shallow infield reinjection and through shallow reinjection in outflow zone from geothermal reservoir. Furthermore, increasing use of reinjection is also motivated by an ambition to reduce environmental impact through reduction of surface disposal of brine or effluent. This paper presents an overview of experiences and lessons learned from three different reinjection strategies at two high-enthalpy liquid dominated geothermal fields operated by Landsvirkjun in NE-Iceland.

2. REINJECTION AT KRAFLA GEOTHERMAL FIELD

Krafla geothermal power plant is located in the caldera of Krafla central volcano, but Krafla volcanic system is part of the neo-volcanic zone in NE-Iceland (Figure 1). Krafla geothermal power plant has been in operation for more than 40 years, but production commenced in 1978. Initially only 7 MW_e was produced due to the impact on the geothermal reservoir from the volcanic eruptions “Krafla Fires”, which began 1975 and lasted until 1984. Production reached 30 MW_e the same year the Krafla Fires ceased. The second turbine was installed in 1999 with installed capacity reaching 60 MW_e and production reaching 9000 ktonnes per year (Figure 2). The geothermal field in Krafla is a two-phase high-enthalpy liquid dominated reservoir. The main production field is divided into three subfields; Suðurhlíðar and Vesturhlíðar in the eastern part of the field with reservoir temperatures between 280-350°C and Leirbotnar in the western part of the field with an upper reservoir at 180-220°C and a lower reservoir with temperatures at 280-350°C (Stefánsson, 1981; Mortensen *et al.*, 2009; Weisenberger *et al.*, 2015).

A total of 46 exploration and production wells have been drilled in the field, but up to 20 wells are currently used for production. In the first 20 years of production all brine from the power plant was discharged on the surface in the nearby stream Dallækur and from there it flowed 9 km south into Búrfell lava field where it flowed into a fissure in the ground. Since 2002, gradually increasing proportions of brine has been reinjected into two infield wells deep in the reservoir. Reinjection has been up to 4650 ktonnes per year equivalent to 48% of mass production (Figure 2), but with these measures up to 80% of the brine is reinjected and the environmental impact from surface disposal has been reduced.

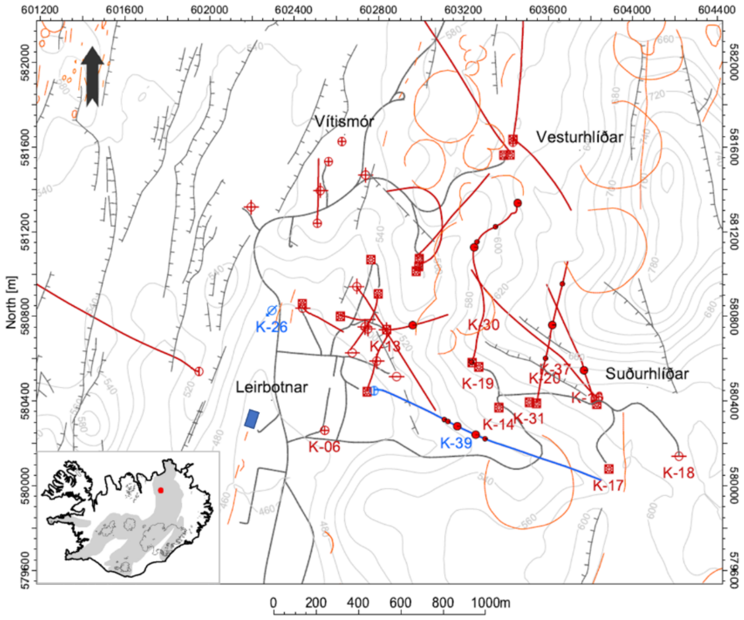

Figure 1: Krafla Well field. Production wells are red while reinjection wells K-26 and K-39 are blue. Red dots on well trajectories indicate location of significant aquifer zones in the wells.

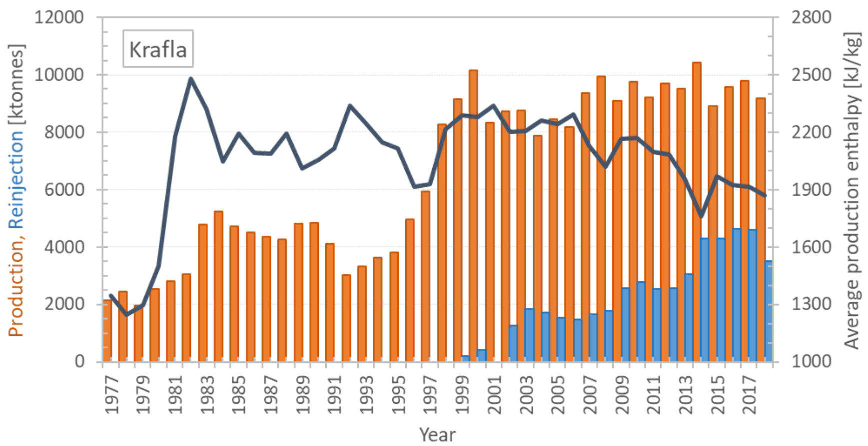

Figure 2: Mass production (orange) and reinjection (blue) at Krafla geothermal field and average production enthalpy (black line).

2.1 Deep Infield Reinjection into Superheated Reservoir in Krafla

The first reinjection well in Krafla was well K-26 located in western part of the production field within the Leirbotnar subfield (Figure 1). K-26 is a 2127 m deep vertical production well that was drilled in 1991. However, discharge tests proved fluids to be corrosive resulting from the impact of the Krafla Fires as well as superheated conditions in the lowermost part of the reservoir, thus the well had to be abandoned. Following the continued problems with corrosive fluids in production wells, it was decided to attempt to dilute the fluid in the deep reservoir below 1800 m depth through reinjection of geothermal brine at 120°C in well K-26. The main aquifer in well K-26 was at 2050 m depth, with minor aquifers at 1425 m and 1600-1700 m depth (Friðleifsson et al., 2006). Reinjection commenced in 2002 and during the first seven years brine was reinjected at a rate of 45-50 l/s, equivalent to 1400-1600 ktonnes pr. year (Figure 2). To further reduce the amount of brine discharged at surface, it was considered acceptable to increase reinjection in well K-26 and since 2008 reinjection in K-26 has been 70-75 l/s.

Deep infield reinjection in K-26 does not appear to affect the production wells as enthalpy and chemical composition has remained stable in nearby wells, and tracer tests were inconclusive as no tracer was detected in production wells (Friðleifsson *et al.*, 2016). It could be that the 120°C brine with its higher density dissipates deeper into the superheated part of the reservoir rather than spreading laterally, diminishing the thermal impact it can have on neighbouring wells, even though the mass reinjection in K-26 has been equivalent or more to the mass production from well located in Leirbotnar subfield. The exception is well K-6, which is located 675 m SSE of K-26. The well has been used as a monitoring well as it also had to be abandoned because of problems with scaling due to corrosive fluids. The maximum logging depth is 1200 m, but at this depth cooling of 1,85°C/yr has been observed since the onset of reinjection in K-26 (Figure 3). The correspondence between onset of cooling in K-6 and reinjection K-26 indicate that some of the brine may be causing cooling in K-6, possibly through flow from shallow aquifers between 1400-1700 m depth in well K-26.

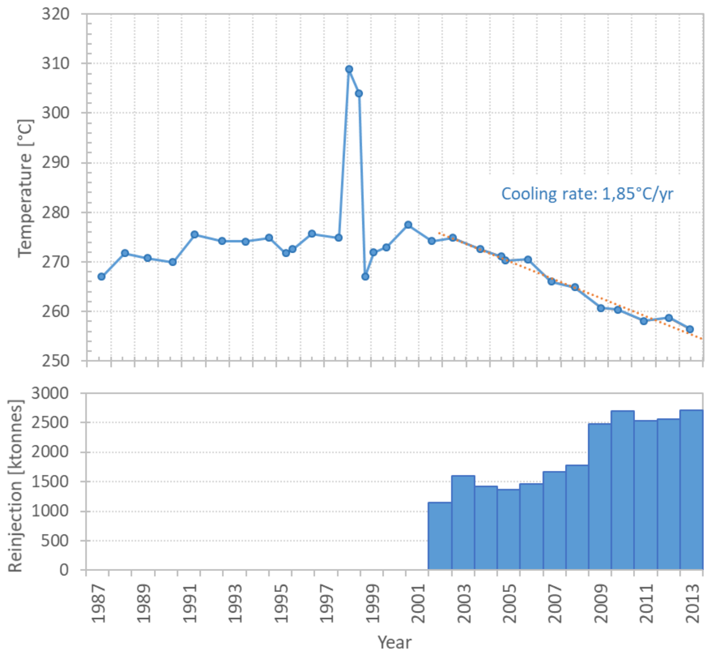

Figure 3: Temperature at 1200 m depth in well K-6 and reinjection in well K-26 for comparison.

2.2 Infield Reinjection into Two-Phase High Enthalpy Liquid-Dominated Suðurhlíðar Field

The reservoir in the Suðurhlíðar subfield has been under exploitation from 1984, but since production at Krafla power plant reached 60 MW_e, decline in Suðurhlíðar subfield has been approx. 2.5% pr. year (Figure 4), while monitoring data indicate pressure drawdown of up to 30 bar in the center of Suðurhlíðar subfield (Mortensen et al., 2009). As flowrate from several wells was <2 kg/s, it was decided to attempt to increase production by providing pressure support through infield reinjection. For this purpose well K-39 was selected to be the second reinjection well in Krafla, but K-39 is a 2865 m long, deviated well located south of the production wells in Suðurhlíðar subfield (Figure 1). Well K-39 drilled into magma and was plugged and later abandoned due to superheated fluid from the lowermost aquifers causing corrosion and scaling in the well (Mortensen et al., 2010). The main aquifers in K-39 are located between 1200-1600 m depth in the well, but the aquifers are within a lateral distance of 150-300 m from nearby production wells.

Reinjection started in august 2013 and initially reinjection in K-39 was approx. 25 l/s, but it was increased rather quickly to 50-55 l/s within the first year of reinjection and reached maximum capacity of 60 l/s at 6 bar-g, equivalent to reinjection of approx. 2200 ktonnes per year of brine over a three year period (Figure 4). The drastic increase in reinjection in K-39 came from demands to reduce surface discharge of brine, but reinjection was 100-125% of produced mass from Suðurhlíðar field, and in those three years reinjection was at a maximum (2015-2017). Infield reinjection at reservoir level in K-39 was quickly breaking through to neighbouring production wells and changes both in enthalpy and fluid composition were observed (Figure 4, 5). The first breakthrough occurred at well K-19 north of K-39, followed by K-13 northwest of well K-39. In K-14, which is located at the shortest distance north-northeast of K-39, breakthrough was observed after it had occurred in well K-19 and K-13. Well K-19 had a high enthalpy at 2600 kJ/kg, but during reinjection in K-39 enthalpy declined by 1300 kJ/kg and eventually the well choked and was temporarily inactive. Well K-13 had an enthalpy of 1500 kJ/kg, but reinjection in K-39 resulted in 200% increase in flow of brine with a resulting decrease in enthalpy by 350 kJ/kg. Changes in fluid composition included increase in SO_4 and by 2016 the SO_4 concentration in K-19 was similar to the SO_4 concentration in the brine, underlining the good connectivity between well K-39 and K-19 (Figure 5). Similarly, fluoride concentration in the neighbouring production wells approached the fluoride concentration in the reinjected brine with time. The concentration of fluoride is relatively high in well K-19 and K-14, which is originating from fluid reaction with rhyolitic rock formations in the subsurface in this part of the field, but in both wells a significant drop in fluoride concentration is observed. In well K-19 the decrease in fluoride concentration occurs within the first year after reinjection in K-39 commenced, while it did not occur until 2017 in well K-14. In well K-13 fluoride concentration was low as the well is located in a part of the field were basaltic rock formations are predominant, but in well K-13 fluoride concentration increased gradually from 2015 and within two years reached a similar level of concentration as is in the reinjected brine (Figure 5). From the timing of first breakthrough between the three wells and the magnitude of change it appears that main flow-path of the reinjected brine is towards north-northwest.

In the summer 2018 the impact of reinjection in K-39 resulted in several wells choking in the Suðurhlíðar subfield, while a significant decrease in average production enthalpy due to increasing flow of brine made it more and more difficult to continue to reinject 80% of the brine from Krafla power plant. Subsequently reinjection in K-39 was reduced to <10 l/s at the same time as several low-enthalpy wells, including well K-13, were shut-in temporarily. Despite the significant changes in enthalpy the steam decline has ceased after reinjection began in K-39 and more than 15% increase in steam flow has been observed in parts of the Suðurhlíðar field (Figure 6). The reduced reinjection rate in K-39 lead to that the mass of reinjection into Suðurhlíðar subfield will represent approx. 20% of the mass being produced from the field, but future work includes continued optimization of reinjection in K-39 to further improve steam recovery, while aiming to maintain production enthalpy steadier.

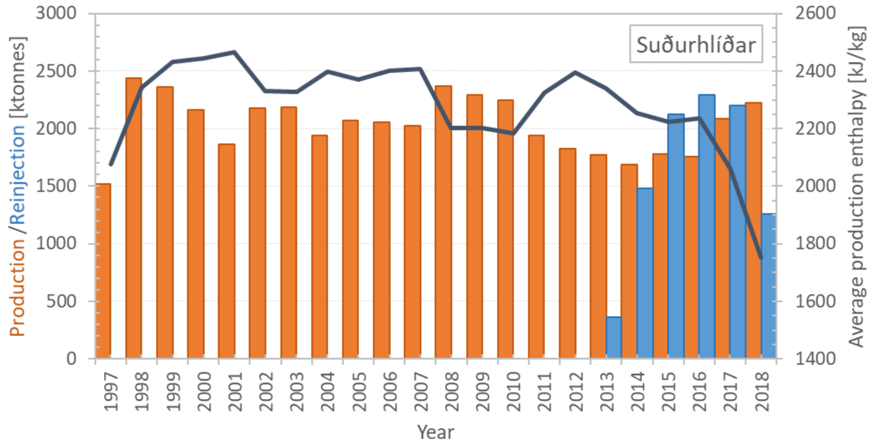

Figure 4: Mass production and reinjection in Suðurhlíðar subfield and average production enthalpy (black line).

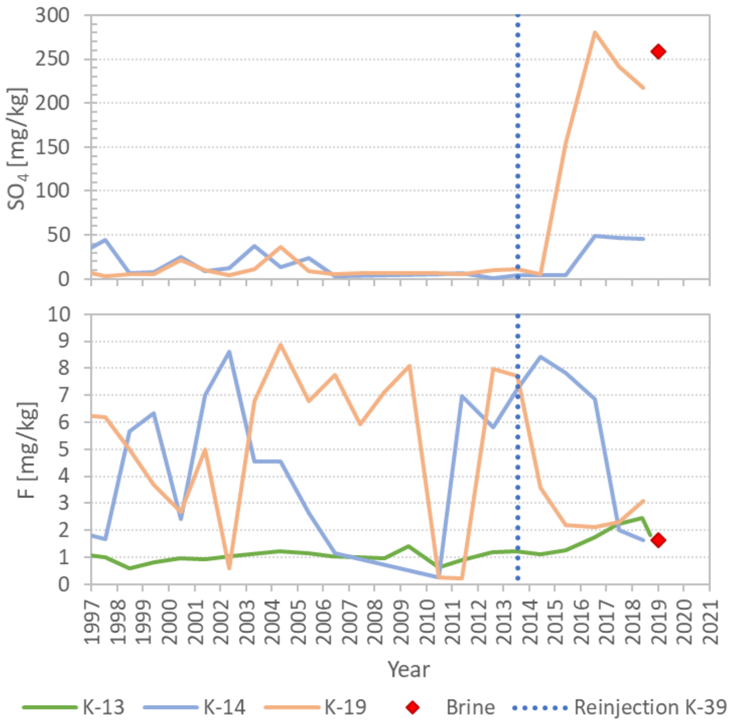

Figure 5: Changes in fluid concentration of SO_4 and F in well K-13, K-14 and K-19 in relation to onset of reinjection in well K-39.

3. REINJECTION AT THEISTAREYKIR GEOTHERMAL FIELD

Theistareykir power plant is located within the central volcano of Theistareykir volcanic system (Figure 7), which is west of Krafla volcanic system. Power production commenced at Theistareykir geothermal power plant in December 2017 and the installed capacity is 90 MW_e generated by two 45 MW_e turbines. The geothermal field at Theistareykir is divided into two fields; east and west field subdivided by the Tjarnarás fault. 18 exploration and development wells have been drilled at Theistareykir, but the center of production is from the wells centered beneath and north of Bæjarfjall mountain within in the eastern field (Figure 7), where reservoir temperatures are 280-340°C. In the western field temperatures were lower than expected, thus this field is undeveloped.

In recent years environmental requirements for operation of geothermal power plants have been strengthened in Iceland including obligations to reinject all effluent. To fulfil these requirements the strategy at Theistareykir geothermal power plant has been to reinject all brine into shallow wells above the cap rock of the geothermal reservoir. Three 450 m deep reinjection wells have been drilled, but they are located more than 1 km northwest of the main production field. The wells have been drilled into the shallow outflow from the geothermal reservoir, where temperatures are >200°C.

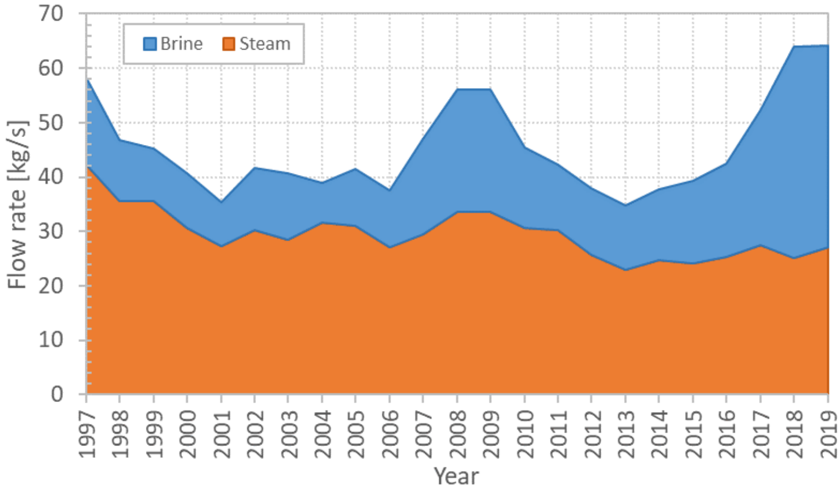

Figure 6: Changes in steam and brine flowrates with time from wells in Suðurhlíðar field (including K-13).

Reinjection started in the fall 2017 and by February 2018 reinjection was increased to 200-220 l/s and has been maintained at this level, except during maintenance stops. Production history is short and changes in enthalpy of the wells or fluid composition that can be related to reinjection have not appeared. However, pressure increase correlating with increased reinjection has been observed in three monitoring wells west of the production field, well ÞG-02, ÞG-08 and ÞR-07. Well ÞG-02 is located 1.2 km south of the reinjection wells and is a 1723 m deep well with the deepest casing at 617 m depth. Well ÞG-08 is located 1.6 km west-southwest of the reinjection wells and is a 2503 m deep well with the deepest casing at 1486 m depth, while ÞR-07 is located 2.1 km northwest of the reinjection wells and is a 459 m deep well with the deepest casing at 150 m depth. Despite the difference the monitoring wells have in vertical connection to the reservoir and their variable distance and direction from the reinjection wells, changes in water level are at similar magnitude and occur almost simultaneously and even short-term changes in reinjection can be correlated with changes in water table in the monitoring wells (Figure 8). These first observations indicate that there is a good vertical and horizontal connectivity between the reinjection wells and the monitoring wells within the western field.

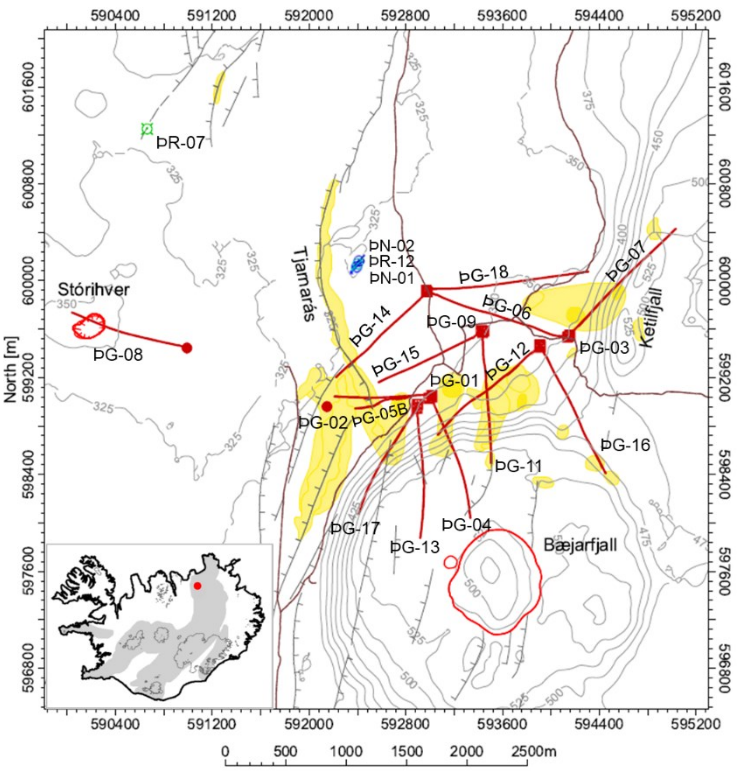

Figure 7: Theistareykir well field. Production wells are red, while reinjection wells are blue. Monitoring wells are ÞG-02, ÞG-08 and ÞR-07. Yellow patches outline altered ground.

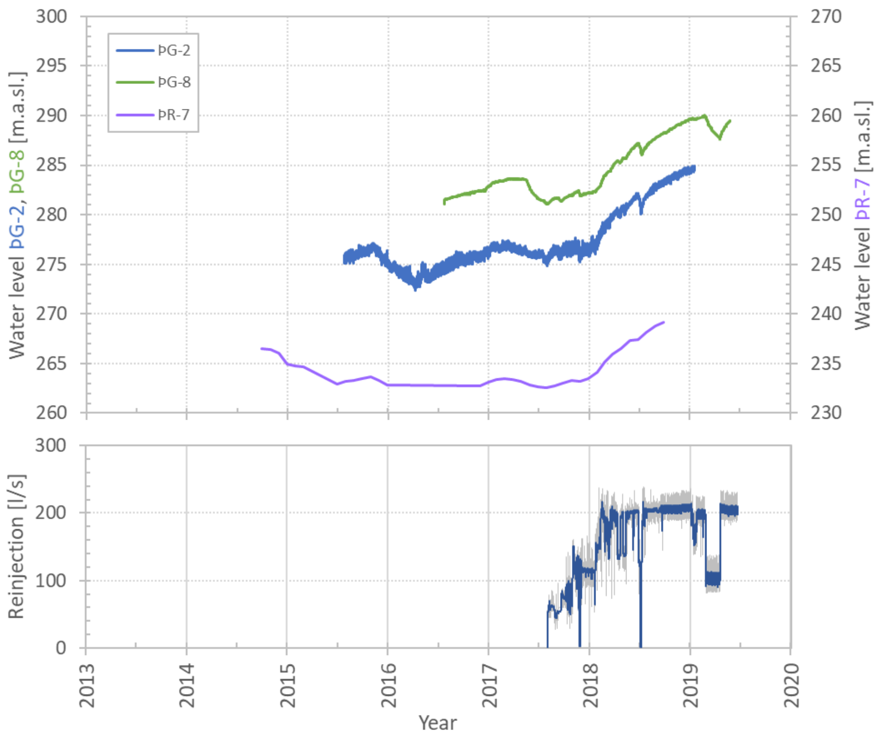

Figure 8: Water table in monitoring wells ÞG-2, ÞG-8 and ÞR-7 (upper) and reinjection in wells ÞN-1, ÞN-2 and ÞR-12 (lower).

4. CONCLUSIONS

Shallow and deep reinjection strategies have been applied with some success at two high-enthalpy liquid dominated geothermal fields Krafla and Þeistareykir, NE-Iceland. Deep infield reinjection into superheated reservoir at well K-26 in Krafla have been sustained for 17 years without clear impact being observed in neighbouring production wells, but deep reinjection in K-26 supplement natural recharge into the geothermal reservoir in Krafla. Relative shallow infield reinjection in well K-39 is in close proximity to productions wells and large reinjections rates have resulted in too much pressure support and wells have choked and become temporarily inactive. Despite of this, shallow infield reinjection in Suðurhlíðar has been successful in increasing steam output, but future work will focus on continued optimization of infield reinjection in Suðurhlíðar subfield.

Shallow reinjection into outflow zone from Theistareykir geothermal field has been brief, however, pressure increases in monitoring wells indicate that the reinjection wells have good vertical and horizontal connectivity to the western field of Theistareykir geothermal reservoir.

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