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WASTE WATER DISPOSAL AT THE NESJAVELLIR GEOTHERMAL POWER PLANT, APPARENT PROBLEMS AND POSSIBLE SOLUTIONS

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ABSTRACT

Geothermal fluids, brought to the surface by geothermal power plants, usually contain higher chemical concentrations and higher temperatures than those found in surface environments. The chemistry of the fluid discharged is largely dependent on the geochemistry of the reservoir and the operating conditions used for power generation, which varies from one geothermal field to another. The toxic compositions available in most high-temperature geothermal waters include: chloride (Cl), aluminium (Al), boron (B), arsenic (As), cadmium (Cd), lead (Pb), mercury (Hg), and sometimes fluoride (F). Samples, for major and trace element analyses, are collected twice a year at discharge areas between the Nesjavellir power plant and Lake Thingvallavatn. This paper reviews the monitoring on both chemical and thermal variations over the last 30 years, including periods both before and during the power plant's operation. It discusses present waste water disposal methods and their effectiveness. Finally, suggestions are presented to fulfil both environmental standards and to prevent operational disruptions. The results show that a correlation exists between the neighbouring sites around the shoreline of the lake, and that maximum temperature at the Varmagjá site has decreased by 1.5°C from 2006 (after reinjection started in 2004 and a cooling tower was installed in 2005).

1. INTRODUCTION

1.1 Geothermal energy in Iceland

Iceland is widely considered the success story of the geothermal community. The country of just over 300,000 people is now fully powered by renewable forms of energy, with 17% of electricity and 87% of heating needs provided by geothermal energy (fossil fuels are still imported for the fishing fleet and transportation needs). Iceland has been expanding its geothermal power production largely to meet growing industrial and commercial energy demands. In 2004, Iceland was reported to have generated 1465 GWh from geothermal resources; by 2009 geothermal production is expected to reach 3000 GWh. The Reykjanes power plant went on line at the end of 2006 with two turbines producing 100

MWe. The Hellisheidi power plant also went on line at the end of 2006, adding another 90 MWe. Also, the Krafla power plant has expansion plans underway. Recent talks with major aluminium companies about relocating in Iceland are based upon the abundance of electricity from the nation's geothermal and hydropower resources, and could entail the construction of new geothermal power facilities to meet their needs (Gawell and Greenberg, 2007).

1.2 Geothermal power plants in Iceland

Presently there are six steam generating geothermal power plants in use in Iceland and more are planned. They are all situated in high-temperature areas.

Bjarnarflag geothermal power plant was the first geothermal power plant in Iceland. It has a small steam turbine with 3.2 MWe power, but also delivers steam to industrial applications. Plans are to expand this activity by building a new modern 40 MWe geothermal power plant in combination with a visiting tourist centre, outdoor bathing facilities and sauna, using the runoff water from the power plant. The drilling of new exploration wells has already begun (ENEX, 2007).

Svartsengi combined heat & power plant now reaches a capacity of 46 MWe and 150 MWth. The total installed power consists of two individual steam turbine systems of 30 MWe and 8 MWe, respectively, and a total of 7 ORC bottoming units. The Svartsengi power plant is connected to the Blue Lagoon geothermal spa, of world renown for its skin healing powers, which makes use of the geothermal brine with its active ingredients. An additional 30 MWe are being added in the Svartsengi plant (ENEX, 2007).

Reykjanes geothermal power plant is located at the tip of the Reykjanes peninsula in Iceland. The plant uses steam from a reservoir with 320°C temperature. This is the first time that geothermal steam of such high temperature has been used for electrical generation. It can, therefore, be said to be a pioneer project in the world geothermal industry. The Reykjanes Power Plant generates 100 MWe using two 50 MWe steam turbines (ENEX, 2007).

Krafla geothermal power plant is now producing 60 MWe with two steam turbines. Recent research on the steam field suggests there is ample steam to expand the Krafla station beyond the 60 MWe capacity originally envisaged. At full capacity, the station utilizes 110 kg/s of 7.7 bar saturated high-pressure steam and 36 kg/s of 2.2 bar saturated low-pressure steam (ENEX, 2007).

Hellisheidi combined heat & power plant is a new geothermal plant in the Hengill area, SW-Iceland which currently provides Reykjavík with electricity; later (in 2009) space heating will be added as the demand for hot water is increasing, especially industrial demand. The plant went online in October 2006, producing 90 MW of electricity, and the plans are to add additional 30 MWe in late 2007 and 90 MWe in 2008. Already 21 wells have been drilled in the Hellisheidi area for exploration and the harnessing of the available geothermal energy. The production of hot water for Reykjavík´s district heating system is scheduled to start in 2009. The planned produced amount of hot water is said to suffice the water system until 2020 (ENEX, 2007).

Nesjavellir combined heat & power plant is also situated in the Hengill high-temperature area in SW-Iceland. The plant itself generates 120 MW of electricity and delivers 300 MWth as heat to Iceland's capital Reykjavík, 27 km away. The construction of the Nesjavellir power plant began in 1987 and the plant went online in 1990. Today it is a part of the largest and most modern geothermal district heating system in the world and Iceland's largest geothermal combined heat and power plant (CHP). A total of 25 boreholes (wells) have been drilled in the Nesjavellir area to depths ranging from 1000 to 2200 m; temperatures as high as 380°C have been measured (ENEX, 2007).

1.3 Hengill high-temperature area

One of the largest high-temperature areas in Iceland is around the volcano Hengill in SW-Iceland. There are three volcanic systems in the area, shown in Figure 1.

1. The geothermal fields in Reykjadalur and Grensdalur, as well as the geothermal field in Hveragerdi, make up the oldest of the three volcanic systems. There are abundant fumaroles and springs in the area.
2. North of Grensdalur is the volcanic area Hrómundartindur which last erupted about 10,000 years ago. In this area, there are many soda-springs.
3. The Hengill system lies to the west of these two systems and is the youngest and most active system of the three. It extends from Nesjavellir in the north, and then south to Hveradalur and Hverahlíd, while the volcanic rift zone extends even farther both to the south and north. The Hellisheidi highland lies in the southwest part of the area. This system has erupted several times during Holocene. At Nesjavellir and elsewhere in the area a lot of earthquakes are observed. The geothermal energy of the Hengill area is harnessed in three areas in the geothermal power plants at Nesjavellir and Hellisheidi and also at Hveragerdi (Ólafsdóttir, 2007).

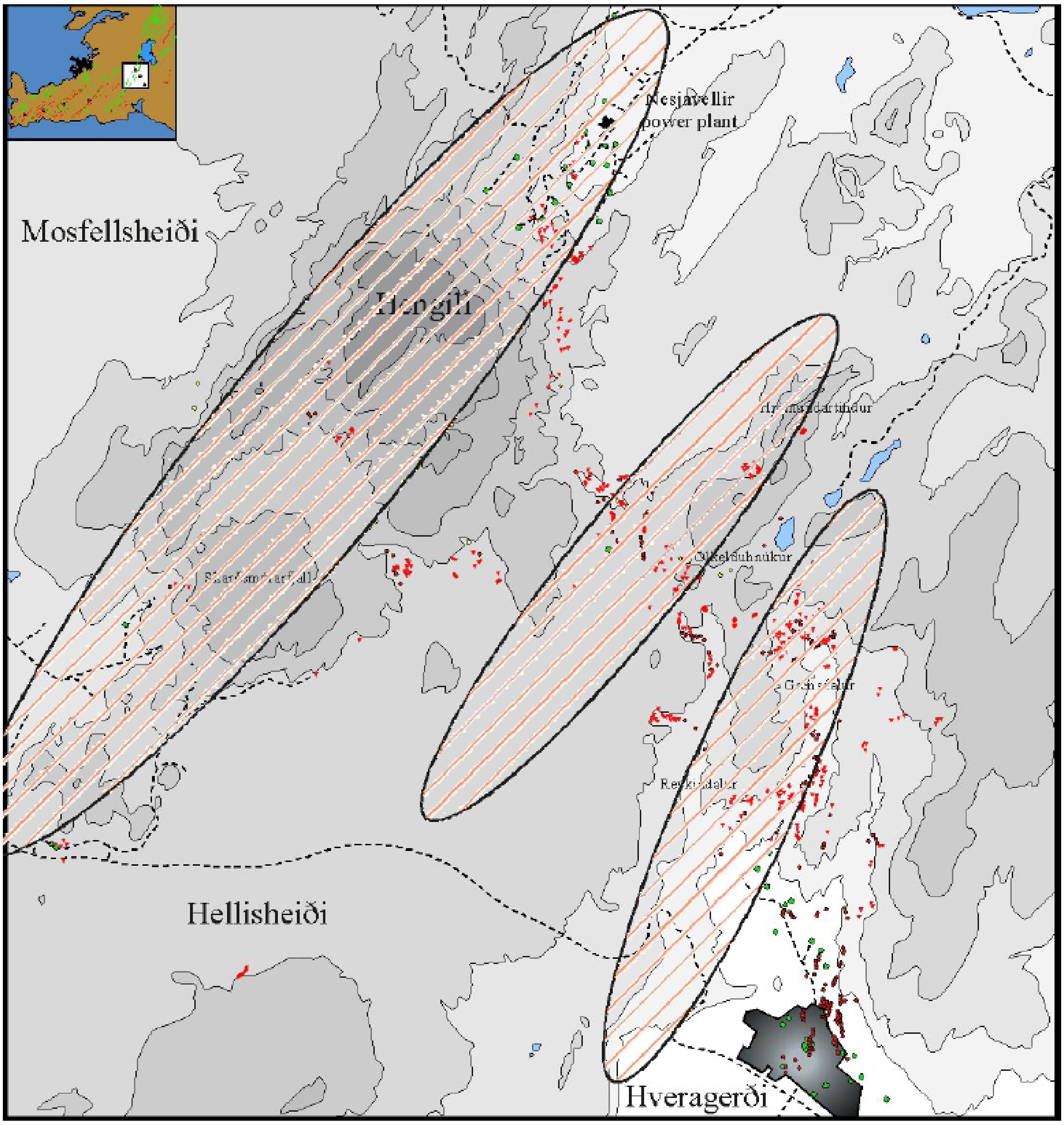

FIGURE 1: The three volcanic systems in the Hengill area (Ívarsson et al., 2005)

2. NESJAVELLIR GEOTHERMAL FIELD

The geothermal area at Nesjavellir is situated in a valley about 20 km east of Reykjavík, south of Lake Thingvallavatn, in the northern part of the Hengill area. Drilling at Nesjavellir began in 1946, and the water obtained was utilized for heating houses and a greenhouse at the site. Reykjavík District Heating bought the land at Nesjavellir in 1964. Now, heated cold groundwater is piped 27 km into the Reykjavík central heating system (Ólafsson, 1992). About 92% of the steam in Nesjavellir is used for electricity production and for warming cold water. Slightly less than 70% of the hot water is used for warming cold water.

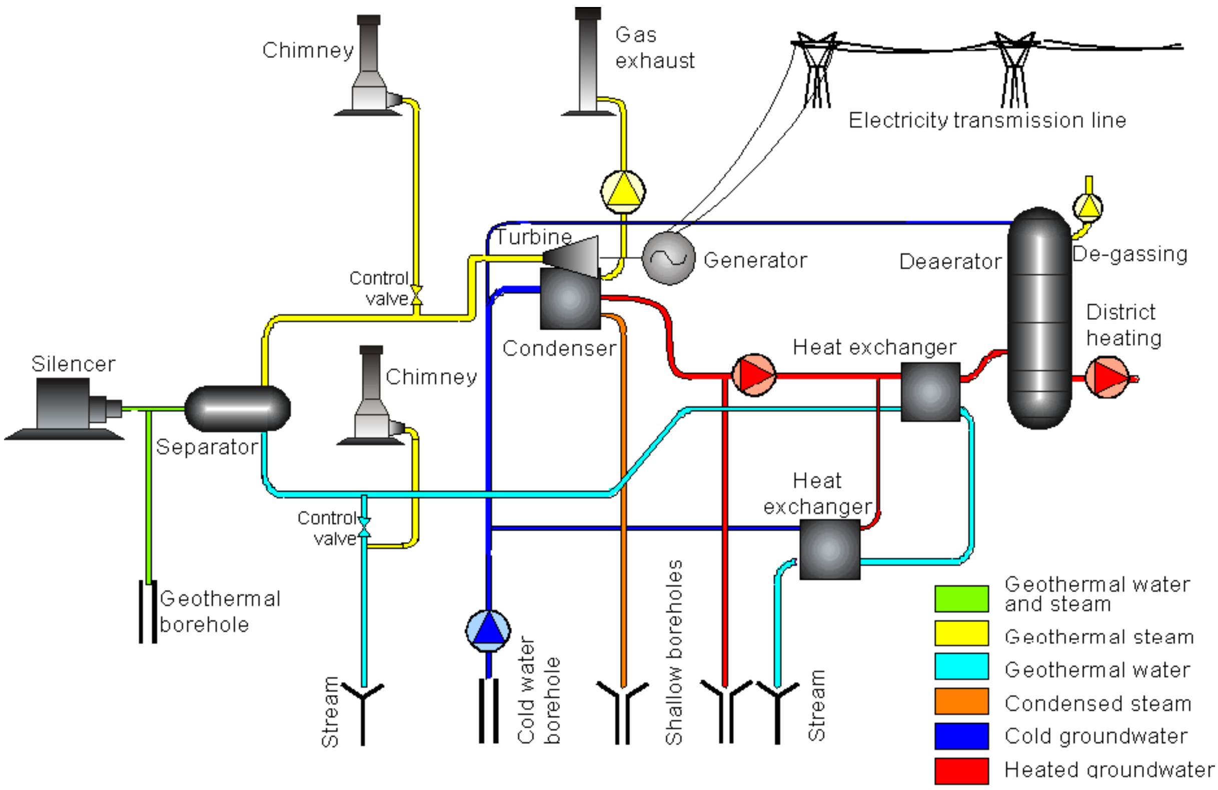

FIGURE 2: Design of the Nesjavellir plant

The co-generation power plant has two functions. The first is to produce electricity and 92% of the available geothermal steam is used for that. The second is to heat cold groundwater for district heating. Figure 2 shows the general design of the plant, but a detailed description is given by Ballzus et al. (2000). The first step is to separate geothermal water and steam. Initially, the separation pressure was 14 bar-g (198°C), but when electricity production began in 1998 the separation pressure was lowered to 12 bar-g (192°C). The water and steam are piped separately to the power house, but excess steam is released into the atmosphere through a high chimney; a control valve maintains a constant pressure in the steam supply system. A similar system controls the hot water supply to the power house. The excess water boils to atmospheric pressure, and the steam formed is released into the atmosphere by a control valve.

Electricity is generated by four steam turbines, requiring 240 kg/s of steam in total. The steam is condensed in a tubular condenser and cooled to approximately 55°C with cold groundwater. The condensate water is partly disposed of in a shallow well in the nearby lava field (210 l/s) and partly into reinjection wells (30 l/s). The cooling water is pumped from a shallow fresh-water aquifer in the lava field 6 km away from the power plant. The temperature of the cooling water is 5-7°C. About 2000 l/s of cold water are required for the condensers. The cooling water is heated to about 55°C in the condensers, and then piped through heat exchangers for final heating to 87°C, using the 192°C hot geothermal water from the separators. In the heat exchangers the geothermal water is cooled to 55°C, and is mainly discharged into a reinjection well but to some extent into a stream. By degassing under vacuum in the deaerators, the dissolved oxygen is removed from the heated water. The final treatment before the water is pumped to Reykjavík for district heating is to inject some geothermal steam, both to remove the last traces of dissolved oxygen by its reaction with the hydrogen sulphide (H_2S) in the steam, and to adjust the pH of the water to pH 8.5.

Before electricity generation started in 1998, the steam was only used for the district heating plant. At that time the heat extraction from the steam phase was more efficient; the temperature of the condensate effluent was about 9°C, compared to the present 55°C (Gíslason, 2000; Ívarsson, pers. comm.).

2.1 Runoff water in the Nesjavellir geothermal area

The largest water ecosystem in the Nesjavellir geothermal area is Lake Thingvallavatn, 83 km^2 in area and 114 m deep. The lake fills a depression in the neovolcanic zone of Iceland and the northern basin of the lake lies within the central graben of the rift zone. Thingvallavatn receives inflow of cold and warm groundwater as well as surface drainage. Extensive development of geothermal resources at Nesjavellir at SW Thingvallavatn brings to the surface environmental water and gas including potentially toxic or harmful elements. The lake is largely fed by a subterranean groundwater flow and springs, but three small rivers drain into it. A single outflow, the River Sog with about 100 m^3, runs from the southern end of the lake. On the southwest shore, the lake receives warm groundwater which flows underground from the Hengill hydrothermal region through the Nesjahraun lava, erupted around 1800 BP and is 38 km^2 in area (Sinton, 2005 (Figure 3).

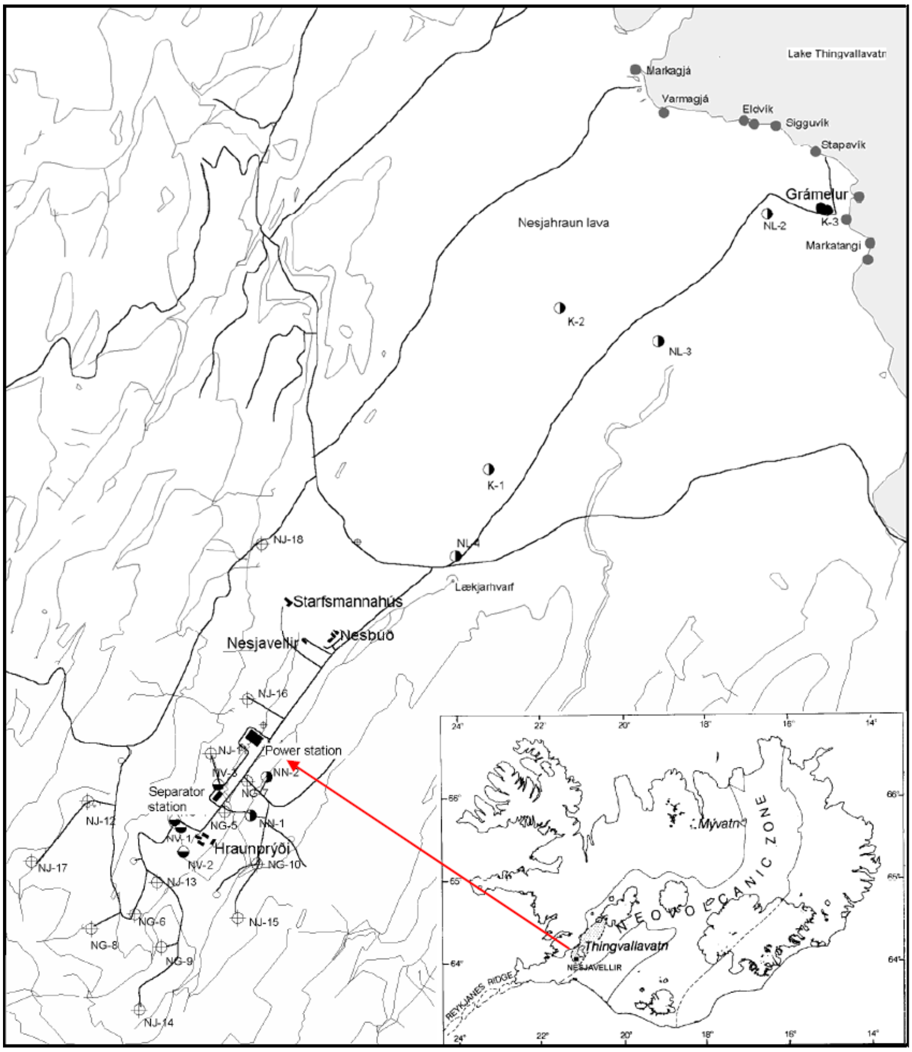

FIGURE 3: Location of Nesjavellir geothermal co-generation plant and Lake Thingvallavatn

The small streams of Nesjalaugalaekur and Köldulaugalaekur have through the ages carried runoff water from a section in the northern part of the Hengill central volcano. This runoff water consists of natural fresh coldwater springs, local precipitation, melting snow and runoff from the natural geothermal springs and fumaroles. Occasionally, high-temperature wells discharge into silencers

FIGURE 4: On the left is the stream with condensate water from the power plant and water from well SV-3, while separated water is seen on the right

FIGURE 5: Condensate water from the Nesjavellir power plant and well SV-3 (in the distance)

and separate waters are released into these streams (Figure 4). Today this practice is very uncommon.

In 1990 the Nesjavellir plant started with 4 connected wells, producing 100 MW thermal energy. Most of the condensate water was released into a shallow well close to the power station and the separated water was discharged into a surface stream slightly further upstream. As production has increased, this practice has continued to the present.

In 1998 electrical production began with 60 MWe. Heat production was increased, and more wells were put into use. To compensate for the increased hot water production, a shallow well (SV-3), 25 m deep, was drilled in 1997 close to the present cooling tower. Excess heated water has since then been injected into this shallow well. When SV-3 overflows (> 400/500 l/s), the excess water goes into the surface stream (Figure 5).

In 2001, electrical production was increased to 90 MWe with a third turbine and turbine 4 came online in 2005. Heat production increased as well and in 2005, Nesjavellir produced 120 MWe and around 280 MWth. Subsequently, more wells had to be drilled (started in 1999) and by the year 2005, 15 wells were in constant use.

In 2004, reinjection started on a small scale, 40 l/s, and has since increased to accommodate almost all of the separate water, and 30 l/s of condensate water. Two reinjection wells are in use and a third is planned. At the moment some 130 l/s of separate water and 30 l/s of condensate water go into the reinjection wells. The excess condensate water (some 200 l/s) goes into the shallow well close to the power station.

FIGURE 6: Inside the retention tank

In January of 2004, a retention tank was added to the production line at Nesjavellir. Its purpose is to provide silica in the separated waters time to polymerize before being disposed of into reinjection wells. The polymerization effectively decreases the monomeric silica concentration in the separate waters from 800 to 500 ppm. Further mixing with condensate water decreases this concentration below 400 ppm, thereby preventing scaling problems in the reinjection wells (Figure 6).

Today almost all of the separated water goes into the reinjection wells and, thus, vanishes from the upper groundwater levels. Excess separate water still goes into the stream. This is done at two locations, by a 6 m long pipe east of the power station and further upstream below the separation station. About 15% or 30 l/s of the condensate water goes into the reinjection wells; the rest goes into the shallow well just north of the power station. Variable flow of the excess heated water scheduled to go into well SV-3, overflows and enters the stream. The flow which goes into SV-3 or overflows into the stream varies through the year. It is relatively minor in winter, but can easily reach 500-800 l/s in summer when there is little market for heating of houses.

2.2 Previous studies on runoff water in the Nesjavellir geothermal field

In 1992 some of the chemical constituents in Nesjavellir well fluids were determined by Ólafsson, as well as that of the separator water and lake Thingvallavatn shoreline spring water. The chemical constituents of effluents from 4 geothermal wells sampled in the Nesjavellir field in 1983-1984 showed concentrations of arsenic ranging from 5.6 to 310 µg/l. In the following years (1984-1991) during geothermal field development, arsenic concentrations rose slightly in two geothermally affected lakeshore springs, at Varmagjá (from 0.6 to 2.2 µg/l) and Eldvík (from 0.7 to 4.7 µg/l). The lead concentration in Varmagjá and Eldvík was between 0.03 and 0.1 µg/l. The reported cadmium concentration was 0.04 µg/l in Varmagjá in 1991. Ólafsson (1992) found a copper concentration of 1.2µg/l in Varmagjá and 0.7-1.5 µg/l in Eldvík. Zinc in Varmagjá was 0.2 µg/l in 1984 and 1.1 µg/l in 1991.

From these results, Ólafsson (1992) concluded that arsenic was the only constituent of the geothermal effluent likely to be of concern in Lake Thingvallavatn. Although the concentrations of chemical constituents in the affected springs were low and the arsenic concentration was within limits considered safe for the fresh water biota, precautionary monitoring measures were recommended by Snorrason and Jónsson in 1995 (Wetang'ula and Snorrason, 2003). In the summer of 1996, Björnsdóttir also determined the concentrations of copper, zinc, lead and cadmium in separator water, condensate, effluent at Laekjarhvarf water and the water of Lake Thingvallavatn shoreline springs of Markagjá, Varmagjá and Eldvík (Wetang'ula, 2004).

VGK Engineering company (2002) conducted an environmental assessment with regard to the expansion of the Nesjavellir power plant to 90 MWe. As a part of that, the concentrations of chemical constituents in separator water, lake shoreline spring water (Varmagjá and Eldvík), in the main fresh water source of the plant at Grámelur, and in water from Markagjá, which is not affected by geothermal activity, were determined. The study revealed that chemicals such as SiO_2, Al and As were in high concentrations in the separator water from the plant. Wetang'ula and Snorrason (2003) noted that such chemical constituents could be used potentially as markers for the level of influence of the geothermal waste water on the groundwater and natural springs in the Nesjavellir area. The concentration of aluminium in the separator water was rather high, 1670 µg/l, and in the Eldvík springs, the level was 349 µg/l, much above the recommended 5-100 µg/l Canadian water quality guidelines for the protection of aquatic life. The VGK study was the first one where aluminium concentrations in separator water from the power plant were measured.

In 2004, Wetang'ula's studies showed that trace element concentration levels in waste water from most wells were within the international water quality criteria for the protection of plants and animals (mammals) against any potential ecotoxicological risk except for As, B and Mo in waste water from a few wells (Wetang'ula, 2004).

3. ENVIRONMENTAL LEGISLATION IN ICELAND

Legislation on environmental impact assessment was first passed in Iceland in 1993. The main aim of the act was to ensure that environmental impacts of projects likely to have significant effects on the environment, natural resources or community were assessed before any permission was given for implementation. High priority is now given to public review, unlike in the earlier acts, and to cooperation among different groups and the developer. The main changes in the new act are that responsibility for the screening process has been transferred from the Ministry of the Environment to the Planning Agency, and a new formal scoping process has been introduced whereby the developer prepares and submits an EIA programme for the proposed project to the Planning Agency as early in the procedure as possible. Thus, the Planning Agency monitors the application of law and regulations on planning, building, and EIA.

In Iceland, there are a number of laws addressing geothermal development. One is the “Nature conservation act no. 44/1999”. This act intended to ensure, to the extent possible, that Icelandic nature develops according to its own laws and to ensure conservation of its exceptional or historical aspects. The act is intended to facilitate the nation's access to and knowledge of Icelandic nature and cultural heritage and encourage the conservation and utilisation of resources based on sustainable development (Ministry of the Environment, 2007).

In 2003, Annex I of “Environmental impacts of geothermal energy development” was issued. It says that for expanding the use of geothermal energy, possible environmental effects need to be clearly identified and methods devised and adopted to avoid or minimize their impacts. The main purposes are in three subtasks: to investigate the impacts of development on natural features; to study problems associated with discharge and re-injection of geothermal fluids; and to examine methods of impact mitigation and produce an environmental manual (IEA, 2003).

Table 1 shows some maximum recommended values for drinking water set by the Ministry of Health in Iceland. The Icelandic government has also set critical limits on trace metals for surface water for the protection of biota (Table 2).

TABLE 1: Some maximum recommended values on chemical elements in cold water published by the Ministry of Health and Social Security (2007)

Chemical element	Unit	Maximum value
Cl	mg/l	250
SO_4	mg/l	250
F	mg/l	1.5
Ca	mg/l	100
K	mg/l	12
Mg	mg/l	50
Na	mg/l	200
Al	mg/l	200
As	mg/l	10
B	mg/l	1000

TABLE 2: Icelandic government’s critical limits (in µg/l) for trace elements in surface water for the protection of biota (Wetang’ula, 2004)

Element	Level I	Level II	Level III	Level IV	Level V
Cu	≤ 0.5	0.5-3.0	3-9	9-45	>45
Zn	≤ 5.0	5.0-20	20-60	60-300	>300
Cd	≤ 0.01	0.01-0.1	0.1-0.3	0.3-1.5	>1.5
Pb	≤ 0.2	0.2-1.0	1-0.3	3-15	>15
Cr	≤ 0.3	0.3-5.0	5-15	15-75	>75
Ni	≤ 0.7	0.7-1.5	1.5-4.5	4.5-22.5	>22.5
As	≤ 0.4	0.4-5.0	5-15	15-75	>75

Level I -Very low probability of effects;
Level II - Low probability of effects;
Level III - Some effects expected in case of sensitive ecosystems;
Level IV - Effects expected;
Level V - Permanently unacceptable levels for biota.

4. MONITORING IN NESJAVELLIR GEOTHERMAL AREA

The Nesjavellir geothermal area is monitored by Reykjavík Energy. Measurements began in 1975 in natural hot springs and streams, and more measuring locations were added when power plant operation started. Samples are collected twice a year. Sampling locations in Nesjahraun are selected based on accessibility and nearness to roads, and also around the lake shoreline where springs are observed to enter the lake.

4.1 Sampling locations and results in Nesjavellir geothermal field

Sampling locations at the lake shore in the Thorsteinsvík area include: Markagjá, Varmagjá, Eldvík, Sigguvík, Stapavík and Markartangi. Apart from those locations, samples have been taken at the fresh water pumping station at Grámelur and where the surface runoff water vanishes into a fault in the lava at Laekjarhvarf. Further sampling is done at Nesjalaugalaekur and Köldulaugalaekur, which represent the natural runoff water from the area prior to the plant's influence. Finally, samples are taken at the geothermal plant, representing the heated water from Grámelur which is being pumped to the Reykjavík area. These samples are usually taken twice a year, once in winter and once in summer. The following is a short description of each location. Sampling locations around the southern shoreline of Lake Thingvallavatn are shown in Figure 7.

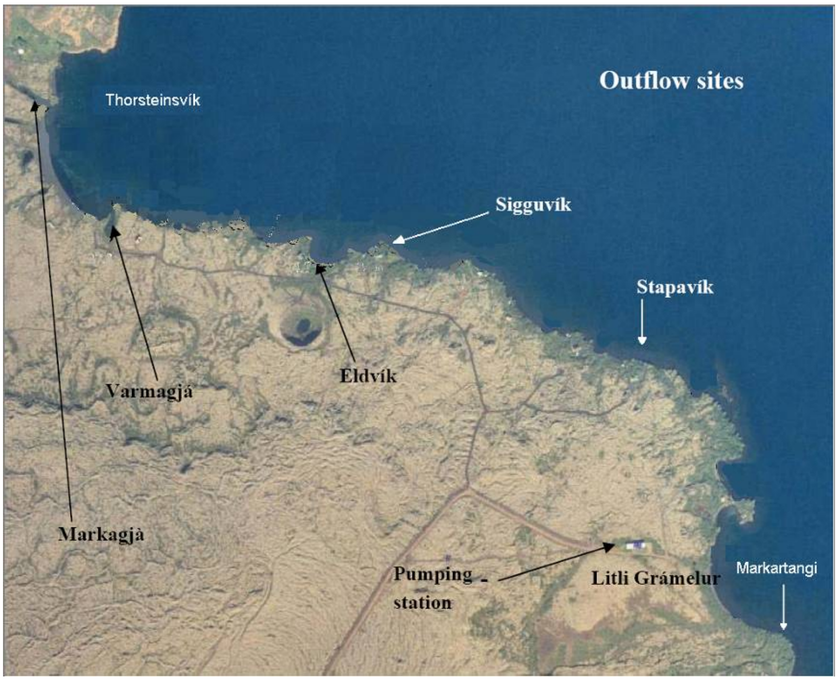

FIGURE 7: Sampling locations around the southern shoreline of Lake Thingvallavatn

Markagjá is the westernmost location on the lake's shore, just east of hyaloclastite ridges and on the western edge of the most recent lava fields in the area (Figure 8). Samples are taken from the lake in a fault where numerous springs occur. Initially no change was observed at Markagjá and concentrations did not change to any extent. Following the start of electrical production in 1998 and subsequent increases in electrical and thermal production, a marked increase in water temperature and chemical components occurred. From Table 3 it is obvious that both thermal and chemical pollution began in 1998 when electrical production commenced at Nesjavellir. Prior to that time only three or four wells were being utilized, but after 1998 ten wells were used. Today,

FIGURE 8: Markagjá sampling location at the west shore of Thorsteinsvík

Nesjavellir power plant is using 15 wells. All measured chemical components have increased in Markagjá since 1998 and the average temperature has increased from 4 to 18°C. Temperature logging at this site began in 2005 and recent measurements from July show no decrease in water temperature at Markagjá, with temperatures fluctuating between 20.5 and 21.5°C. In spite of increased sulphates, presumably because of oxidation of H_2S in condensate waters, pH has increased slightly from 7.6 to 8.3. Markagjá closely follows the neighbouring sampling locations of Varmagjá, Eldvík and Stapavík, but at considerably lower temperatures and concentrations, apparently due to its location.

TABLE 3: Average values of temperature and chemical constituents (in mg/l) in Markagjá

Period of time	Temp. (°C)	pH	Cond. (µS/25°C)	CO_2	SiO_2	Na	K	Ca	Mg	SO_4	Cl	F
<1991	3.8	7.55	82	19.8	11.7	7.3	0.7	3.08	2.67	3.8	8.2	0.09
91-98	3.5	7.57	89	18.5	14.2	7.8	0.8	4.88	3.08	3.5	8.8	0.08
99-02	8.3	7.83	122	32.4	23.8	11.1	1.5	6.84	4.07	9.4	9.1	0.08
03-06	17.5	8.03	150	31.0	40.4	15.2	2.5	8.75	4.18	16.0	9.6	0.16

Varmagjá. A few hundred metres southeast of Markagjá in a fault open to the lake is Varmagjá (Figure 9). The springs in Varmagjá have always had a geothermal signature, apparently inherited from the natural runoff, which includes runoff from the natural geothermal springs and fumaroles at the Nesjavellir geothermal field. Apparently, Varmagjá is well connected with subsurface faults and tends to react quickly to changes at the Nesjavellir plant. It, therefore, represents the most important monitoring site in the western part of Thorsteinsvík.

It is obvious from Table 4 that the springs at Varmagjá immediately started to change following the start of the Nesjavellir power plant in 1990. This process has continued since then, albeit with some exceptions. Some measured variables and chemical compounds appear to have peaked and some have even dropped in the last few years (pH, conduct., CO_2, Na, Ca, Mg, SO_4 and Cl). Others have increased continuously (T, SiO_2, K and F). Recent temperature logging at Varmagjá has shown that the temperature appears to have peaked at 31.3°C last year, but decreased to 30.3°C in the last 6 months. Varmagjá follows the same trend as Eldvík and Stapavík, for all variables except pH and Cl.

TABLE 4: Average values of temperature and chemical constituents (in mg/l) in Varmagjá

Period of time	Temp. (°C)	pH	Cond. (µS/25°C)	CO_2	SiO_2	Na	K	Ca	Mg	SO_4	Cl	F
<1991	10.2	7.54	176	56.7	32.4	15.6	2.0	10.00	5.21	12.0	9.8	0.13
91-98	11.5	7.70	211	59.9	40.8	19.0	2.5	14.81	6.80	19.2	11.7	0.12
99-02	19.2	7.66	227	59.6	52.9	21.4	3.3	13.86	6.28	27.1	11.6	0.17
03-06	28.6	7.70	201	49.1	64.9	20.9	3.9	12.58	5.05	25.0	11.6	0.21

Eldvík. About 500 metres further east is Eldvík (Figure 10). The sampling location is in a small pool separated from the lake proper by a sandbar. The pool is shallow with low input flow rates and is characterized by a lot of biological growth making sampling difficult. Eldvík closely resembles Varmagjá and Sigguvík in most respects, which is not unexpected as the sampling locations are fairly closely spaced (Table 5).

TABLE 5: Average values of temperature and chemical constituents (in mg/l) in Eldvík

Period of time	Temp. (°C)	pH	Cond. (µS/25°C)	CO_2	SiO_2	Na	K	Ca	Mg	SO_4	Cl	F
<1991	9.8	7.74	173	55.8	30.4	17.1	2.1	8.36	5.72	13.8	11.6	0.14
91-98	9.6	8.05	230	56.8	54.9	22.1	2.7	13.87	6.99	20.8	16.4	0.14
99-02	17.2	7.96	250	60.8	64.2	25.5	3.6	13.73	6.83	25.1	18.0	0.18
03-06	19.7	8.28	246	48.4	78.0	27.6	4.2	13.30	5.93	26.3	22.6	0.23

FIGURE 9: Varmagjá sampling location

FIGURE 10: Eldvík sampling location

Sigguvík. Only a couple of hundred metres further to the east is Sigguvík (Figure 11). As in Eldvík the samples taken here are from an inland pond isolated from the lake itself. The chemistry of the Sigguvík samples is very similar to those of Eldvík and Varmagjá (Table 6).

TABLE 6: Average values of temperature and chemical constituents (in mg/l) in Sigguvík

Period of time	Temp. (°C)	pH	Cond. (µS/25°C)	CO_2	SiO_2	Na	K	Ca	Mg	SO_4	Cl	F
<1991	9.3	7.88	149	49.9	26.4	15.3	1.9	7.54	4.32	12.5	10.4	0.13
91-98	9.5	8.13	224	51.3	55.1	21.4	2.6	12.76	6.57	20.4	17.4	0.14
99-02	14.9	7.94	252	55.9	64.4	27.4	3.8	12.70	6.29	24.7	21.0	0.20
03-06	19.7	8.28	246	48.4	78.0	27.6	4.2	13.30	5.93	26.3	22.6	0.23

Stapavík is the sample location closest to the pumping station at Grámelur (Figure 12). Samples are taken at the shoreline of the open lake and wave action tends to ensure relatively good mixing with lake water. During the last decade some geothermal contamination has become apparent, but this is relatively minor. In many respects this location resembles that of Markartangi (farther east), which represents the base uncontaminated waters from the lake. It is possible the Stapavík location was somewhat protected by the pumping at Grámelur in the years 1990 – 1998, when relatively little waste water was released into the lava field. After 1998 when production increased, the distribution of contaminated groundwater increased and Stapavík was affected as were other locations to the west (Table 7).

FIGURE 11: Sigguvík sampling location

FIGURE 12: Stapavík sampling location

TABLE 7: Average values of temperature and chemical constituents (in mg/l) in Stapavík

Period of time	Temp. (°C)	pH	Cond. (µS/25°C)	CO_2	SiO_2	Na	K	Ca	Mg	SO_4	Cl	F
<1991	8.7	7.32	93	22.5	14.0	10.6	1.2	11.01	3.20	6.1	7.3	0.09
91-98	5.7	7.58	73	16.6	11.8	8.4	0.6	4.26	1.53	3.2	6.5	0.07
99-02	9.4	7.86	99	21.4	18.1	11.2	1.1	4.87	1.90	5.5	9.9	0.10
03-06	8.6	7.84	107	22.7	25.0	12.6	1.5	6.00	2.23	7.3	9.9	0.09

Markartangi represents the uncontaminated waters on the southern part of lake Thingvallavatn (Figure 13). The sampling location is a few hundred metres east of Grámelur and sampling takes place in the open lake with no apparent spring activity. The chemical composition of Markartangi samples are, therefore, the baseline for other samples in this study. No samples were taken prior to 1990 at this location, but sampling since has shown very little change with time (Table 8).

TABLE 8: Average values of temperature and chemical constituents (in mg/l) in Markartangi

Period of time	Temp. (°C)	pH	Cond. (µS/25°C)	CO_2	SiO_2	Na	K	Ca	Mg	SO_4	Cl	F
91-98	6.1	7.80	73	16.0	12.1	8.2	0.7	4.53	1.84	3.5	6.7	0.07
99-02	9.8	8.01	76	17.5	10.3	8.4	0.7	4.05	1.48	2.4	6.5	0.09
03-06	8.6	7.94	80	17.2	13.3	9.2	0.8	4.94	1.78	3.5	7.3	0.07

Grámelur is the pumping station close to the shore of Lake Thingvallavatn (Figure 14). It provides all of the fresh water needed at the Nesjavellir power plant. At the moment, 6 shallow wells have been drilled and pumps installed. They are able to produce over 2000 l/s. Since the pumping station at Grámelur started operating in 1990, the chemistry of the water has changed considerably and an increased geothermal component in the water is obvious. The origin of this contaminant is the waste water from Nesjavellir. Even if the wells are spaced only a few metres apart, the well farthest south (closest to the power plant) displays a strong geothermal contaminant, while the well farthest to the north (closest to the lake) displays no contamination at all. The wells in between display intermediate contamination, depending on their relative position from north to south.

The waters sampled at Grámelur are apparently biased from the southern most positioned wells and, therefore, show greater geothermal contamination than the average from all the wells used by the power plant for heating (Table 9).

FIGURE 13: Markartangi sampling location

FIGURE 14: Grámelur sampling location

TABLE 9: Average values of temperature and chemical constituents (in mg/l) in Grámelur

Period of time	Temp. (°C)	pH	Cond. (µS/25°C)	CO_2	SiO_2	Na	K	Ca	Mg	SO_4	Cl	F
91-98	7.5	7.66	136	32.0	25.2	11.6	1.7	8.84	5.29	9.1	10.6	0.10
99-02	9.2	7.79	202	43.1	55.9	21.3	2.2	9.42	5.42	16.4	19.4	0.16
03-06	17.4	7.83	199	41.6	64.2	22.8	3.4	10.32	5.23	18.8	19.1	0.17

Laekjarhvarf. A small lagoon represents the collective streams of Köldulaugalaekur and Nesjalaugalaekur plus all of the waste water released from the Nesjavellir power plant into the stream (Figure 15). Located some 1.8 km north of the power plant, this lagoon banks against an open normal fault and the waters percolate into the fault and vanish. The water then flows underground, preferably along faults, some 4.5 km where it is released into Lake Thingvallavatn, either in springs by the shoreline or under the surface of the water. The Laekjarhvarf waters represent the collective components that are released on the surface, either naturally or by man. The rest of the Nesjavellir waste waters go either into shallow wells (ending up in lake Thingvallavatn) or into deep reinjection wells (thus, effectively being removed from circulation). The average values of the chemical constituents are given in Table 10.

TABLE 10: Average of temperature and chemical constituents (in mg/l) in Laekjarhvarf

Period of time	Temp. (°C)	pH	Cond. (µS/25°C)	CO_2	SiO_2	Na	K	Ca	Mg	SO_4	Cl	F
<1991	14.8	7.65	341	46.3	121.8	51.7	9.2	9.08	3.63	55.0	29.6	0.39
91-98	19.8	8.65	591	38.1	432.6	89.0	17.1	9.34	2.53	59.9	71.2	0.58
99-02	30.9	8.64	560	38.6	388.8	68.6	15.4	7.98	2.67	48.3	71.6	0.64
03-06	27.2	9.03	452	28.8	332.5	76.5	13.6	9.39	2.77	50.2	67.5	0.66

Nesjalaugalaekur is a small stream which collects the natural surface runoff including precipitation, melting snow, spring water and natural runoff from the geothermal field (Figure 16). Occasionally, when wells discharge into silencers, separate water is released into the stream. No systematic change has been observed in the chemistry of the stream (Table 11). The Nesjalaugalaekur stream combines with Köldulaugalaekur stream a short distance above the Nesjavellir power plant.

Köldulaugalaekur is a small stream collecting natural surface runoff including precipitation, melting snow, spring water and natural runoff from the geothermal field (Figure 17). Separate water is released into the stream, on occasion, when wells discharge into silencers. No systematic change has been observed in the stream's chemistry (Table 12). The stream combines with Nesjalaugalaekur stream a short distance above the Nesjavellir power plant.

FIGURE 15: Laekjarhvarf sampling location

FIGURE 16: Nesjalaugalaekur sampling location

TABLE 11: Average of temperature and chemical constituents (in mg/l) in Nesjalaugalaekur from before 1991 to 2006

Period of time	Temp. (°C)	pH	Cond. (µS/25°C)	CO_2	SiO_2	Na	K	Ca	Mg	SO_4	Cl	F
<1991	12.6	7.69	250	43.3	65.7	28.0	4.5	17.23	5.06	33.1	25.7	0.21
91-98	11.4	7.78	254	50.0	72.4	19.3	2.3	19.84	5.84	35.2	12.7	0.11
99-02	14.9	7.80	230	49.1	58.2	18.3	2.3	17.27	5.37	29.0	10.9	0.13
03-06	13.2	7.72	176	39.0	31.5	12.4	1.2	16.75	4.60	25.9	7.2	0.07

TABLE 12: Average of temperature and chemical constituents (in mg/l) in Köldulaugalaekur from before 1991 up to 2006

Period of time	Temp. (°C)	pH	Cond. (µS/25°C)	CO_2	SiO_2	Na	K	Ca	Mg	SO_4	Cl	F
<1991	18.5	7.18	298	32.4	66.7	22.5	2.9	24.79	7.65	91.5	7.7	0.20
91-98	15.4	7.91	399	44.8	116.3	32.3	4.1	30.21	8.86	105.2	16.6	0.17
99-02	21.4	8.14	440	52.2	210.2	52.9	8.6	22.65	6.96	80.8	62.4	0.35
03-06	20.3	7.93	266	39.9	64.1	17.5	1.8	24.26	7.46	69.9	6.7	0.09

Nesjahraun temperature profiles. There are 11 shallow wells located in the Nesjahraun lava field, mostly close to the road, for studying underground flow. The depths range from 25 to 268 m. Samples are collected at 1 m below the water level. Figure 18 shows one of these shallow wells.

Results of sampling show the effect of the hot waste water channel was at first only seen in the eastern part of the area; after 2003, the channel spread to the western part as well. An interesting development is that temperatures below 55 m depth have now begun to rise. This development might suggest that waste water discharged into shallow wells close to the power station is now starting to affect lower portions of the groundwater flow; this might increase in the future.

FIGURE 17: Köldulaugalaekur sampling location

FIGURE 18: A shallow well in the Nesjahraun lava field

Table 13 shows the temperature at the top in each well. Most often the temperature is measured 1 m below the surface water level, or where the temperature reaches maximum. One has to take into account that temperature anomalies can be at different depths in different wells, so a certain amount of approximation is required. The table is use to draw isotherms on maps. These represent the surface groundwater temperature changes with time. According to this study the water being released at Laekjarhvarf appears to have much a greater influence than water released in the shallow wells. One has also to take into account that Laekjarhvarf has been actively accepting geothermal water from natural runoff for centuries. It is possible that the Laekjarhvarf fault allows the water to pass more quickly to the lake with minimum mixing with groundwater, compared to the shallow well discharge. Today it appears that the Laekjarhvarf waste water has spread out and is actively mixing with fresh groundwater (Hafstad et al., 2007).

TABLE 13: Measured temperature with time (in °C) in wells in the runoff area in Nesjahraun recorded 1 m below water level (Hafstad et al., 2007)

Wells	May 2000	Sept. 2000	March 2001	Sept. 2001	April 2003	Nov. 2003	Sept. 2004	March 2006	Oct. 2006
NK-01	28		27	32	32	33.5	34	32	33
NK-02	22		22	30	32	33	--	35	35.5
NL-02	9			15.12	19	--	--		26.5
NL-03	3.5			2.5	--	--	--		3
NL-04	15		34.5	41.5	19.5	28	25.5	17	26
NL-07		7.5	7.5	11	11	15.5	15.5	16	21
NL-08		11	16.5	18	21.5	23.5	25	25.5	27.5
NL-09		7.5	6	10	9	14.5	18	11	21.5
NL-10		4.5	5.5	6	6	30	34.5	32	32
NL-11		11	18.5	21.5	25	28	29.5	31	31.5
NL-02		4.5	5	4	--	--	--	7	9.5

4.2 Sampling methods

The instrument used to measure temperature is DST milli-T, a small waterproof data logger. Data are stored in a non-volatile memory. All measurements are time related, utilizing a real time clock inside the DST; measuring is done hourly.

The DST milli-T is used for temperature measurements in oceans, freshwater, soil, beverages and various other applications. It is ideal as a stand-alone logger for research in oceans and lakes, or for temperature measurements in liquids. DST milli-T is supported by the SeaStar software for Windows, and a communication box which connects to a PC computer. All communications and data transfer are wireless via the communication box. Prior to usage and data retrieval, the DST is inserted into the box to establish communication through the SeaStar software. The user sets the start date/time and sampling interval. The data is retrieved to a PC computer, using the communication box and software. After retrieving the data, the DST can be reprogrammed and reused for as long as the battery lasts. Technical specifications are shown in Table 14 (Star-Oddi, 2007).

For pH, CO_2 and H_2S data, samples are collected in Teflon tubes, 0.5 l plastic bottles (for SiO_2 and F) and a 200 ml plastic bottle for ICP measurements. The last sample is treated with 1 ml nitric acid (HNO_3) to prevent reactions in the bottle and for allowing the solution to be stored for some time.

Temperature is measured in the field with a TLC1598 thermometer, which has a fold back probe made of stainless steel for measuring air, liquid and semi-solid goods such as meat, fruits etc. Technical specifications are shown in Table 15 (Ebro, 2007).

The value of pH was measured in the laboratory, CO_2 was measured by titration with HCl between pH 8.2 and 3.5, H_2S was measured with titration with Hg $(CH300)_2$. A spectrophotometer was used for SiO_2 determination. Cl was determined by titration using $AgNO_3$ solution. ICP measurements were done at the University of Iceland.

TABLE 14: Technical specifications of the DST milli-T temperature recorder (Star-Oddi, 2007)

Variable	Specification
Size (diameter and length)	12.5 mm and 38.4 mm
Weight (in air/in water)	9.2 g / 5 g
Memory capacity	43,000 temperature measurements**
Data resolution	12 bits
Memory type	Non-volatile EEPROM
Data retention	25 years
Temperature range (standard)	-1°C to +40°C, outside ranges available upon request
Temperature resolution	0.032°C
Temperature accuracy	+/- 0.1°C
Depth survival	Up to 900 m (user defined)
Response time temp.	20 s
Clock	Real time clock, accuracy +/- 1 min/month
Sampling interval	User programmable in second(s), minute(s), hour(s)
First recording	User defined
Computer interface	Com box, RS-232C serial, or USB (optional)
Battery life	4 years***
Corrosion resistance	Oil, water, salt, antifreeze, brake fluid, diesel and gasoline
Attachment hole	0.9 mm (in diameter)

* A depth or pressure sensor can optionally be added;
** Memory can optionally be doubled;
*** For sampling interval of 5 minutes or greater.

TABLE 15: Technical specifications of DST milli thermometer (Ebro, 2007)

Sensor type	Platin1000
Temperature range	-50 to +200°C
Resolution	0.1°C
Accuracy	± 0.2°C ± 1 Dig
Display	LCD, 9 mm
Battery life	Approximately 4 year
Weight	Approximately 70 g

5. DISCUSSION

Hot waste water, both heated freshwater and geothermal water (and condensate) rich in dissolved solids, is released close to the Nesjavellir power plant, either into man made wells or into natural runoff (Laekjarhvarf). Via gravity, it flows towards north into Lake Thingvallavatn. The temperature of this water is generally above 40°C and it floats on top of the colder groundwater. By the time it reaches the main road, a cold groundwater flow appears to intersect it from the west (from Háhryggur) which perhaps narrows its flow path. North trending faults also help the progress of the waste water towards the lake, channelling it to the eastern part of the valley. Farther north, hot water flow spreads out over a wider area, thins towards the perimeters and cools. The lavas themselves have various porosities; some parts are highly porous and other parts are non-porous. The combination of the variable porosity of the lavas and faults cutting through the lava pile probably controls the distribution of the waste water. The vast amount of cold water pumping occurring at Grámelur causes the waste water to flow more to the east towards Grámelur and causes considerable temperature increase in the wells. In a research well at Grámelur, temperatures of up to 24°C have been measured, and temperatures above 28°C have been measured west of Eldvík. Generally, the whole area has risen in temperature since measurements started in 2000, and the waste water flow has increased in thickness.

Maps with isothermal lines of groundwater, drawn for Nesjahraun for the years 2000 to 2006, show increasing temperature (Appendix I). The isothermal lines show that from 2000 to 2006, the temperature of the underground water reaching the lake shore is getting higher for every year.

5.1 Temperature variations

All sample locations at Lake Thingvallavatn, except Markartangi, have shown substantial temperature increase since 1998. Figure 19 shows temperature measurements at Markagjá, Varmagjá and Eldvík from 1994 to the present. A temperature logger has been located at these sites since 2005. Most locations demonstrate relatively broad short term variations, which are probably related to external factors such as precipitation, wind and air temperature. Interpreting the data is, therefore, difficult although one could argue that the temperature increase at Eldvík and Markagjá has peaked and is levelling off. Only at Varmagjá (where the temperature logger is located at the spring's source and, therefore, shows little fluctuations) can we see a clear indication of temperature decrease with time. Maximum temperatures at Varmagjá appear to have peaked in the fall of 2006 and have decreased by 1.5°C since then. This is an indication that preventative measures (reinjection and building of the cooling tower) at the Nesjavellir plant are starting to change the situation.

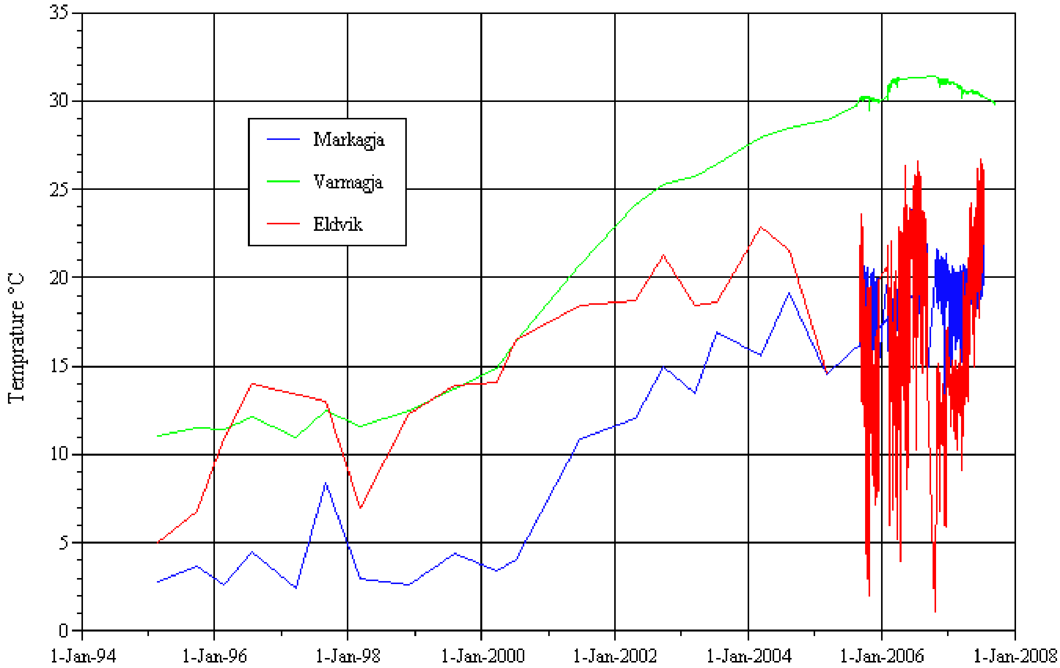

FIGURE 19: Temperature measurements at Markagjá, Varmagjá and Eldvík

5.2 Chemical comparison of spring waters

Figures 20, 21 and 22 show variation in average composition of major elements at different sample locations (M = Markagjá, V = Varmagjá, E = Eldvík, S = Sigguvík, s = Stapavík, m = Markartangi and G = Grámelur) by Lake Thingvallavatn and from the pumping station at Grámelur. A very good correlation exists between the neighbouring sites Varmagjá, Eldvík and Sigguvík. Varmagjá tends to deviate from the others by being both warmer and with lower pH, SiO_2, Na, K and F. Markagjá and Grámelur tend to follow similar trends, but generally at much lower concentrations. Markartangi and Stapavík appear to be least affected by geothermal pollution, being perhaps shielded by the pumping at Grámelur and helped by mixing in Lake Thingvallavatn.

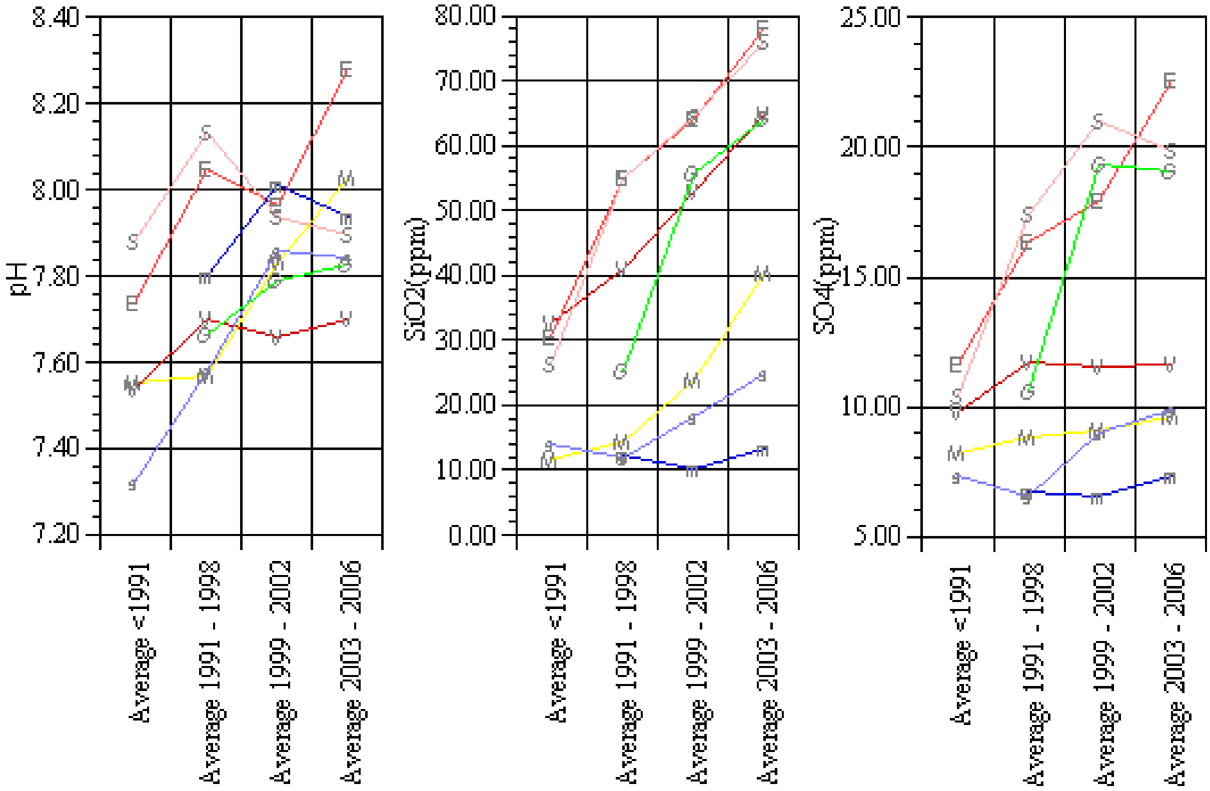

FIGURE 20: Variations in average of pH, SiO_2 and SO_4 at sampling locations at the shore of Lake Thingavallavatn

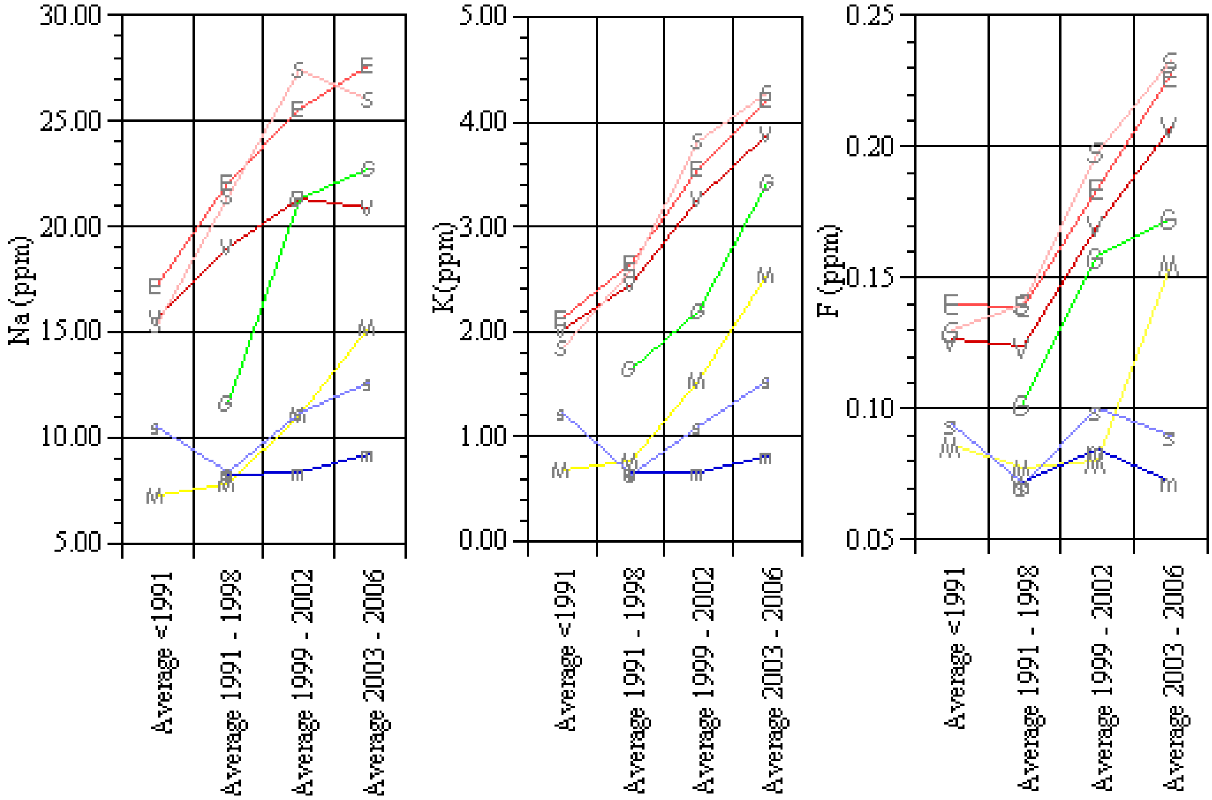

FIGURE 21: Variations in average of Na, K and F at sampling locations at the shore of Lake Thingavallavatn

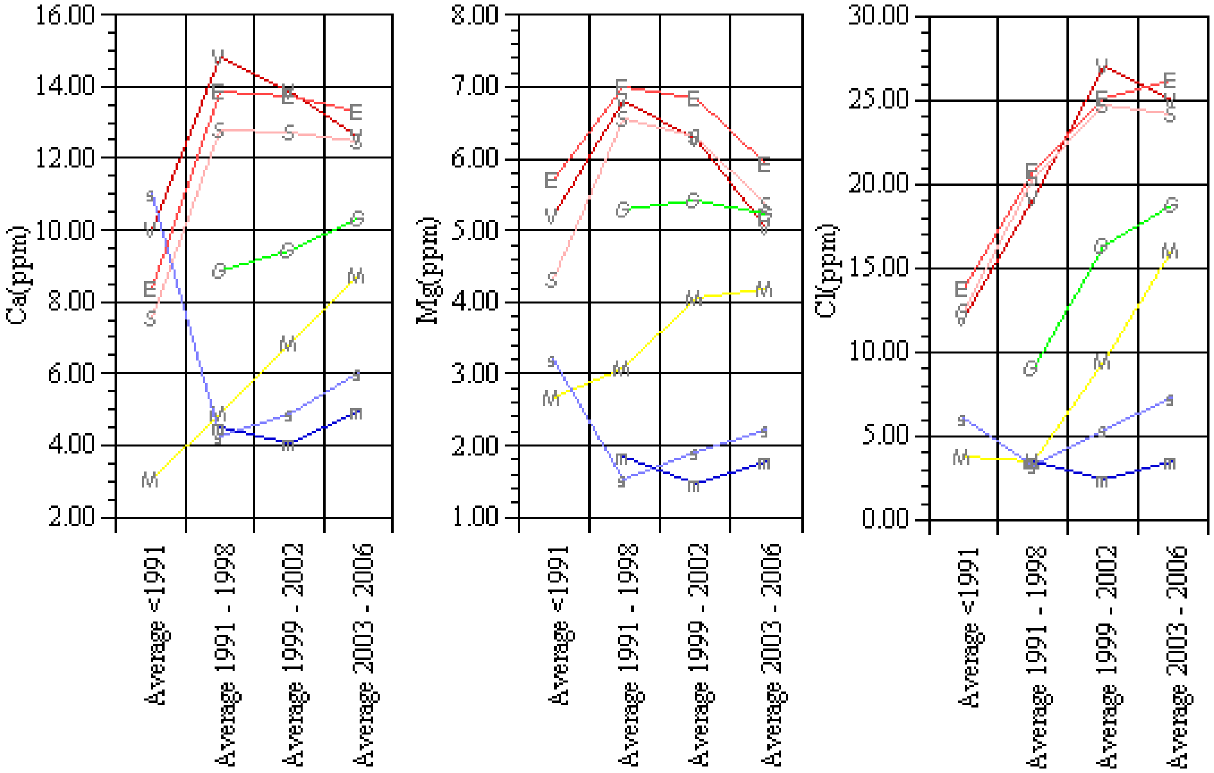

FIGURE 22: Variations in average of Ca, Ng and Cl at sampling locations at the shore of Lake Thingavallavatn

For comparison, the fluids from the Salton Sea field (USA), which is hosted by evaporate deposits, are highly saline ([Cl] = 155 000 ppm) while those of the Nesjavellir field in Iceland are of low salinity ([Cl] = < 25 ppm). Chloride (Cl) is the major anion in most geothermal waters, at least if the salinity is relatively high. This element only forms soluble salts with cations that can be abundant in natural waters.

Thermal- and chemical pollution found in the surrounding surface runoff, springs and Lake Thingvallavatn can drastically alter the biological ecosystem in a relatively short period. A further increase in the Grámelur pumping station water temperatures can and will have a direct influence on electrical power production at Nesjavellir. It is estimated that 2°C increase in water temperatures at Grámelur, compared to present day values, will cause the turbines at Nesjavellir to run outside production parameters, resulting in less electrical production.

5. CONCLUSIONS AND RECOMMENDATIONS

Apart from the ecological impact resulting from increased temperatures and increased chemical components in springs and Lake Thingvallavatn, the most pertinent problem concerning operations at Nesjavellir is the continued rise in temperature at the Grámelur pumping station. Many chemical components have apparently peaked and show some signs of decreasing, while the temperature continues to rise (except for Varmagjá location). Therefore, it is necessary to expand the present waste water disposal area or implement new methods.

Today, the main problem areas are constricted to the area of the shallow wells. Well SV-3 usually receives between 100 and 1000 l/s of heated freshwater. Its capacity is about 500 l/s; values above that lead to overflow into the surface stream. This discharge is seasonal, being greatest in summer, least in winter. Another shallow well receives about 200 l/s of condensate water. This discharge is constant throughout the year. Neither of the waste water types contain substantial amounts of dissolved solids, one being heated groundwater and the other condensed steam, but both present thermal problems, being in the range of 35 to 65°C. The condensate waters also contain some incondensable gases which can result in the water becoming acidic.

The following methods appear to be most applicable:

1. Increase the size of the cooling tower by at least one unit (500 l/s). This is usually a relative quick and cheap method with known results. The greatest drawback with cooling towers is that the final product is still 20°C, i.e. much higher than unaffected groundwater which is close to 5°C.
2. Drill deep reinjection wells for these waters. This would remove the waters from circulation and would be the best solution. The main drawbacks are the relatively high cost of drilling and uncertain results with reference to the long-term permeability of these wells.
3. A temporary solution might be to change the discharge area to another location, i.e. to the western part of the valley which would require a pipe and possibly some drilling. This is expected to cause the discharge waters to bypass Grámelur, at least temporarily, while more permanent solutions are found and implemented.

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APPENDIX I: Isothermal maps in the Nesjahraun lava for the years 2000-2006

The following figures are based on a report from Hafstad et al. (2007).

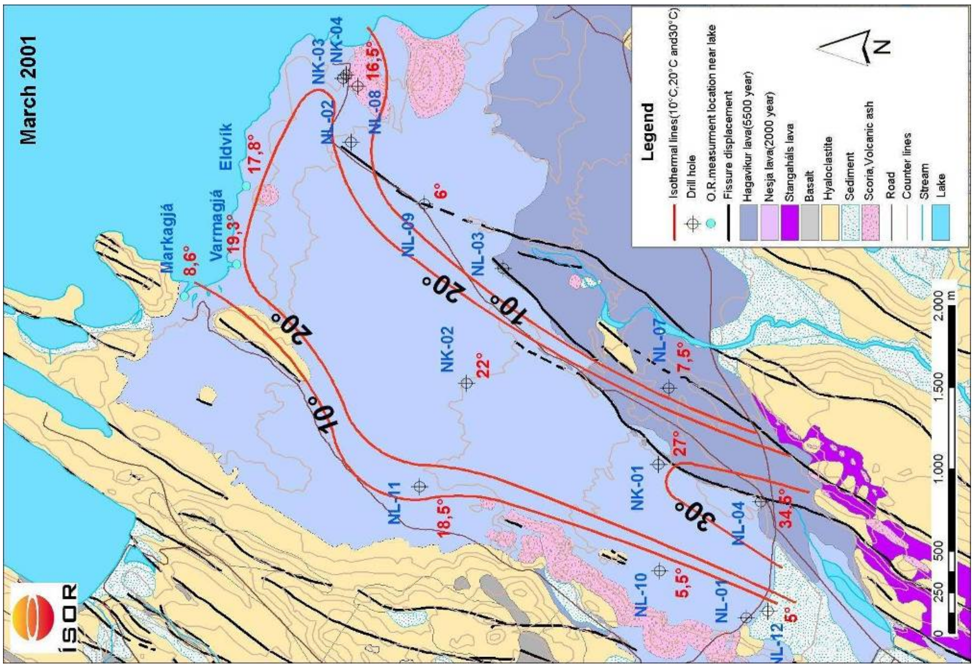

FIGURE 2: Isothermal map (°C) in the Nesjahraun lava in March 2001

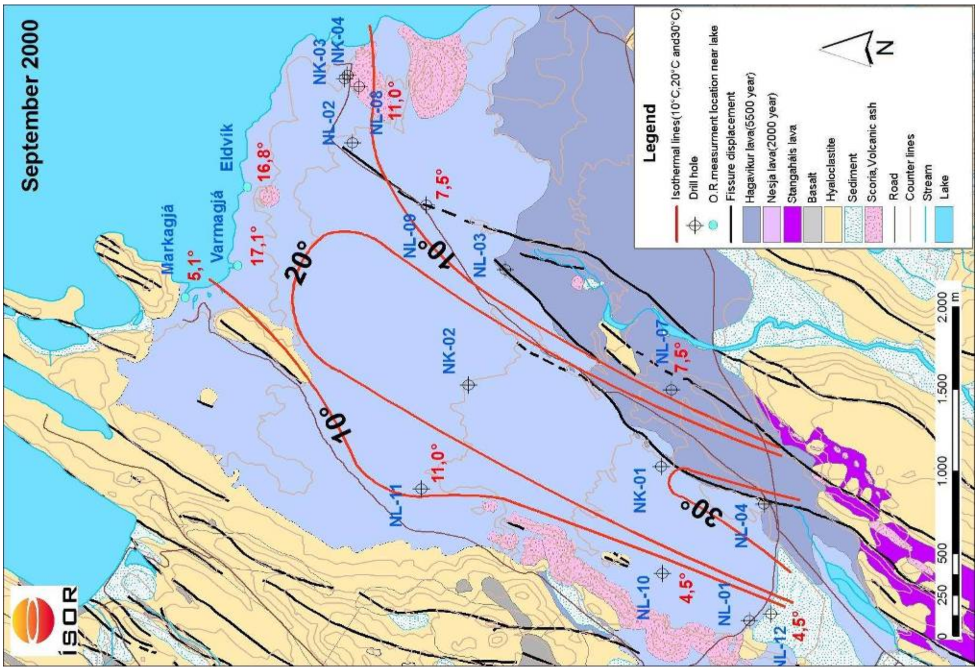

FIGURE 1: Isothermal map (°C) in the Nesjahraun lava in September 2000

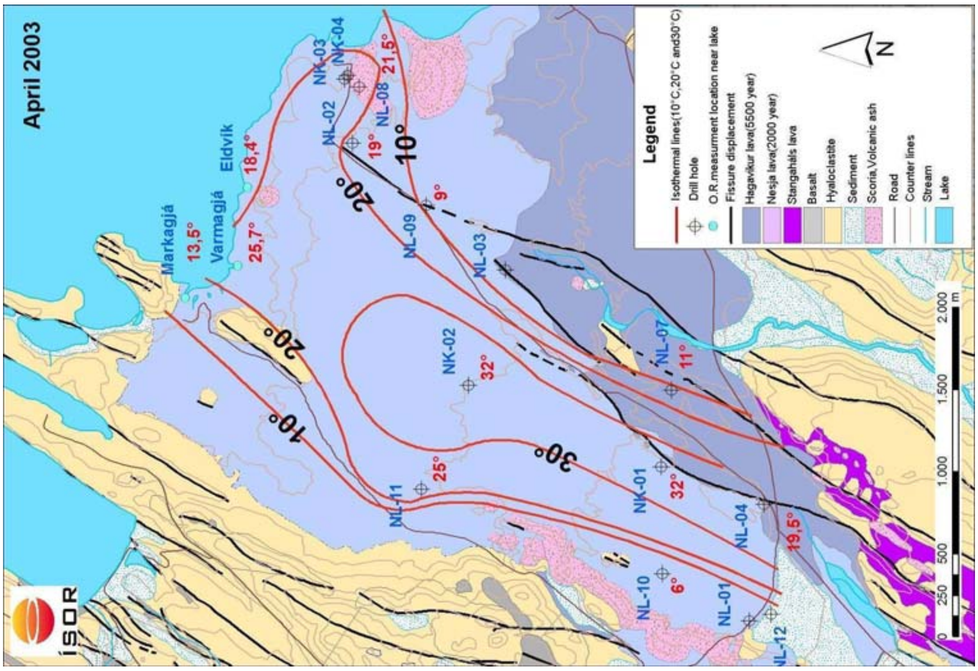

FIGURE 4: Isothermal map (°C) in the Nesjahraun lava in April 2003

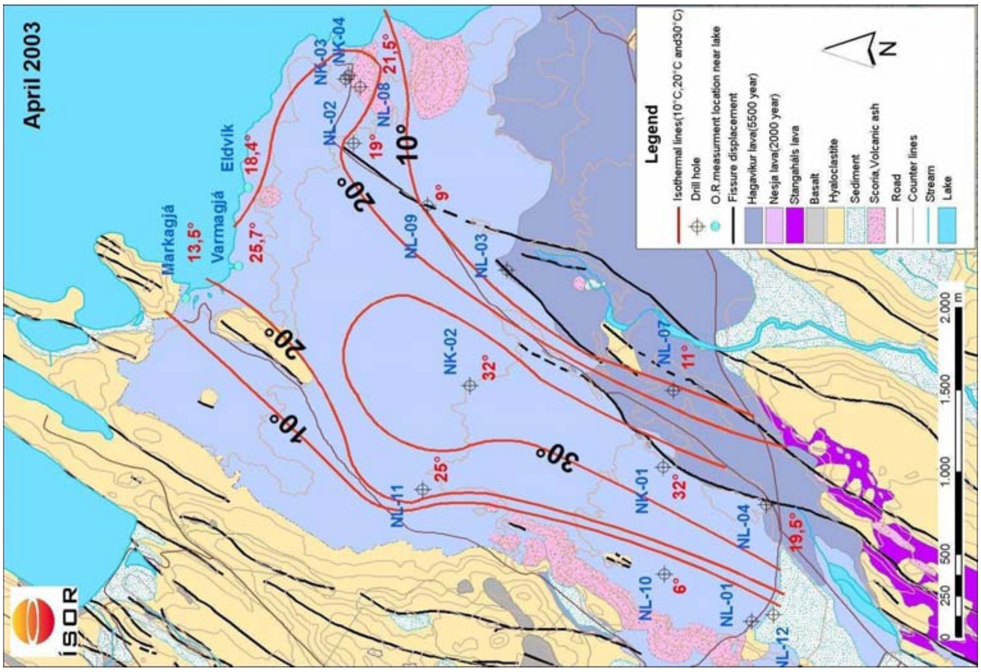

FIGURE 3: Isothermal map (°C) in the Nesjahraun lava in September 2001

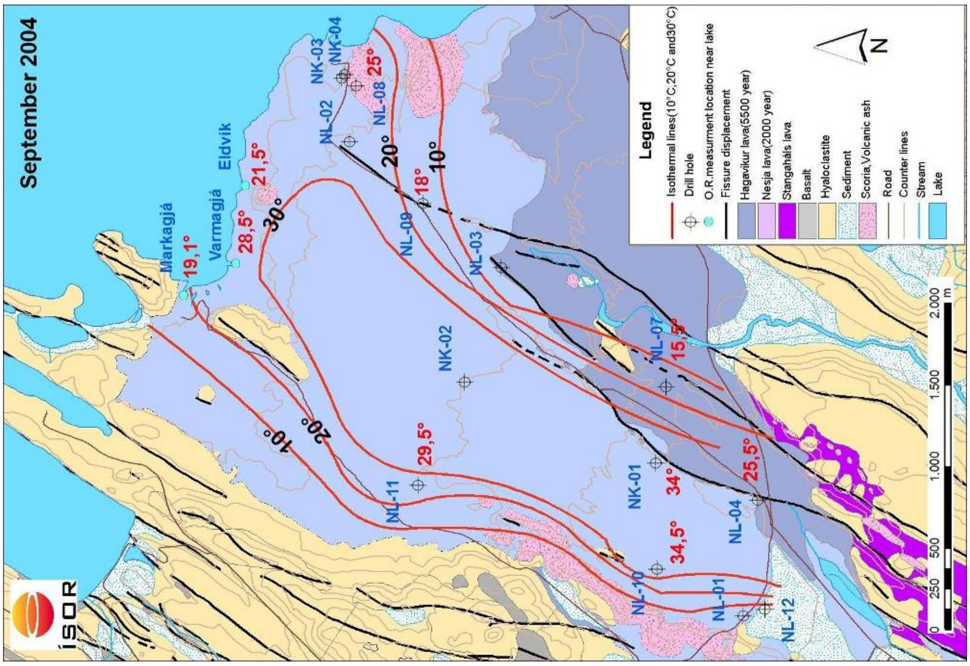

FIGURE 6: Isothermal map (°C) in the Nesjahraun lava in September 2004

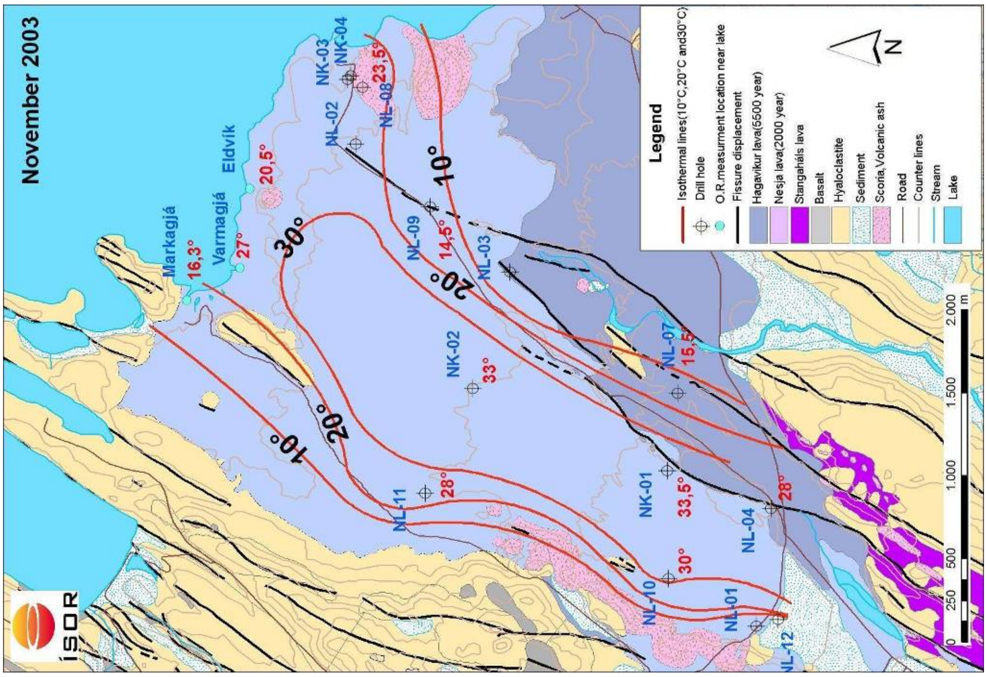

FIGURE 5: Isothermal map (°C) in the Nesjahraun lava in November 2003

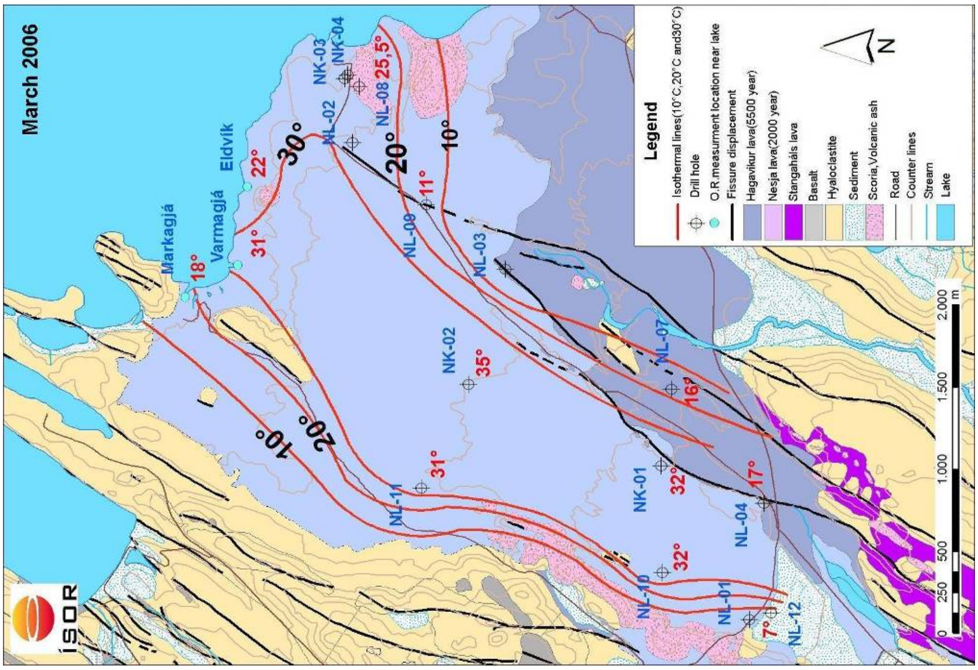

FIGURE 7: Isothermal map (°C) in the Nesjahraun lava in March 2006

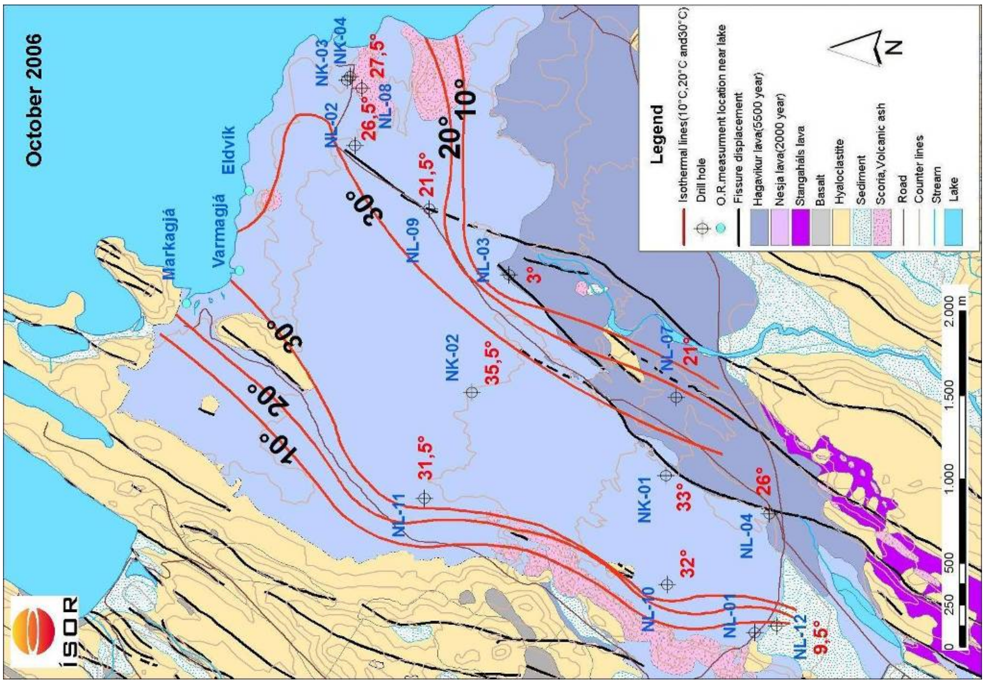

FIGURE 8: Isothermal map (°C) in the Nesjahraun lava in October 2006