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A Review on Waste Water Disposal at the Nesjavellir Geothermal Power Plant

Sepideh Sahar M.Mirzaei Zarandi[1], Gretar Ivarsson[2]

1. Iran Department Of Environment,Hemmat Expressway,Pardisan Eco-Park,P.O.14155-7383 ,Tehran,IRAN,

2. Reykjavík Energy.Reyjavik, Iceland

ssmmz78@gamil.com, gretar.ivarsson@or.is

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ABSTRACT

Three types of waste waters are produced at the Nesjavellir geothermal power plant. They consist of condensate water and separate water derived from high enthalpy wells, and heated fresh groundwater derived from shallow cold water wells. These three different types of fluids all represent a potential source of pollution, either chemical and/or thermal pollution. Release of these fluids into surface streams or into shallow sink wells is today considered to be unacceptable as it can cause irreversible environmental problems. At the Nesjavellir geothermal field, surface springs in the Nesjahraun lava and lake water from Lake Thingavallavatn are sampled two times a year at ten locations and analyzed for major chemical components, as well as temperature and pH. Temperature loggers are also in place at various locations, including at various depths in shallow research wells for temperature profiling. This paper describes monitoring work done on waste water from the Nesjavellir geothermal power plant. It reviews chemical and thermal monitoring efforts for the last 30 years and describes the various methods used to prevent chemical and thermal pollution. This includes the use of cooling towers and reinjection wells. Finally suggestions are presented to fulfil both environmental standards and to prevent operational disruptions.

1. INTRODUCTION

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.

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.

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 discharged mainly 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 (Gíslason, 2000; Ívarsson, pers.comm.).

2. RUNOFF WATER IN THE NESJAVELLIR GEOTHERMAL AREA

The largest water ecosystem in the Nesjavellir geothermal area is Thingvallavatn which is 83 km^2 in area and 114 m deep. The lake fills a depression in the neovolcanic zone of Iceland and the northen basin of the lake lies within the central graben of the rift zone. Thingvallavatn receives inflow of cold and warm ground water as well as surface drainage. Extensive development of geothermal resources at Nesjavellir at SW Thingvallavatn brings water and gas including potentially toxic or harmful elements to the surface environment. The lake is fed largely by subterranean groundwater flow and springs, but three small rivers drain into it. A single outflow, 100 m^3/s, at the southern end of the lake drains it into the river Sog. At the southwestern shore the lake receives warm groundwater which flows from Hengill hydrothermal region underground through the Nesjahraun lava which has an area of 38 km^2 and erupted in 1800 B.P. (Sinton,J., 2005) Figure 1.

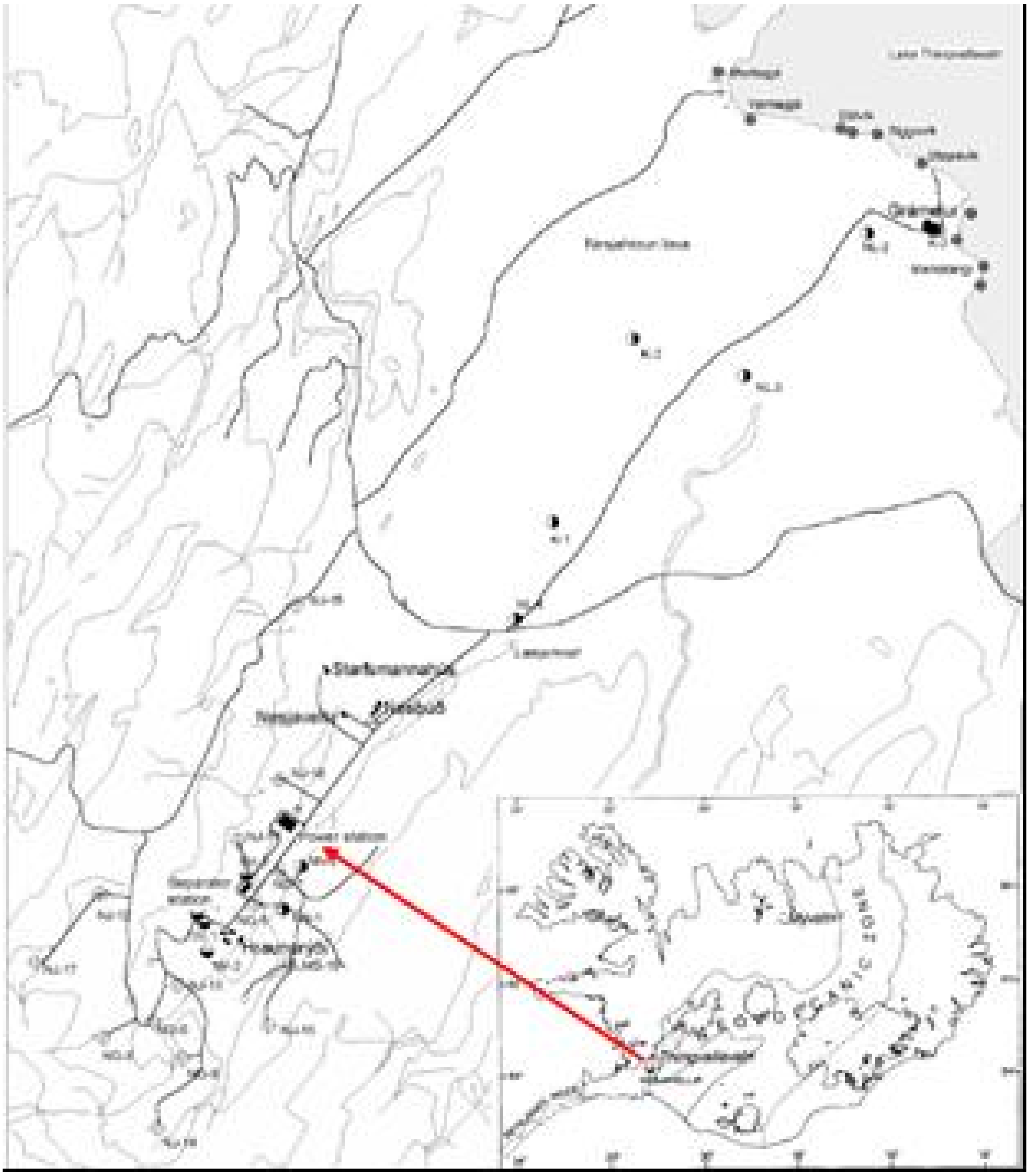

Figure 1. Location of Nesjavellir geothermal co-generation plant and Lake Thingvallavatn

The small streams of Nesjalaugalaekur and Köldulaugalaekur have through the ages carried runoff water from a section of the north 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 and separate waters are released into these streams, Figure 2. Today this practice is very uncommon.

In 1990 the Nesjavellir plant started with four 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 3).

In 2001, electrical production was increased to 90 MWe with a third turbine and a fourth turbine 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 (starting in 1999) and by the year 2005, 15 wells were in constant use.

Figure 2. Condensate water and the well SV-3 (left) separate water right

Figure 3. Condensate water (The well SV-3 is in background)

In 2004, reinjection started on a small scale, 40 l/s, and has since increased to accommodate almost all of the separated 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.

In January of 2004, a retention tank was added to the production line at Nesjavellir. Its purpose is to give time for the silica in the separated waters 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.

Today almost all of the separated water goes into the reinjection wells and, thus, vanishes from the upper groundwater levels. Excess separated water still goes into the stream. This is done at two locations, through 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 that 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.

2.1 Previous Study on Runoff Water in 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 four 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 freshwater 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 Planning Agency monitors the application of law and regulations on planning, building, and EIA.

In 2003, Annex I of "Environmental impacts of geothermal energy development" was issued. It says that for expanding 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 reinjection of geothermal fluids; and to examine methods of impact mitigation and produce an environmental manual (IEA, 2003).

The Icelandic government has also set critical limits on trace metals for surface water for the protection of biota (Table 1).

Table 1: Icelandic government's critical limits (in µg/l) for trace elements in surface water (Minister for the Environment,2007)

Element µg/l	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 Thorsteinsvík area are Markagjá, Varmagjá, Eldvík, Sigguvík and 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 two times a year, once in winter and once in summer. The following is a short description about each location. Sampling locations around southern shoreline of the lake Thingvallavatn is shown in Figure 4.

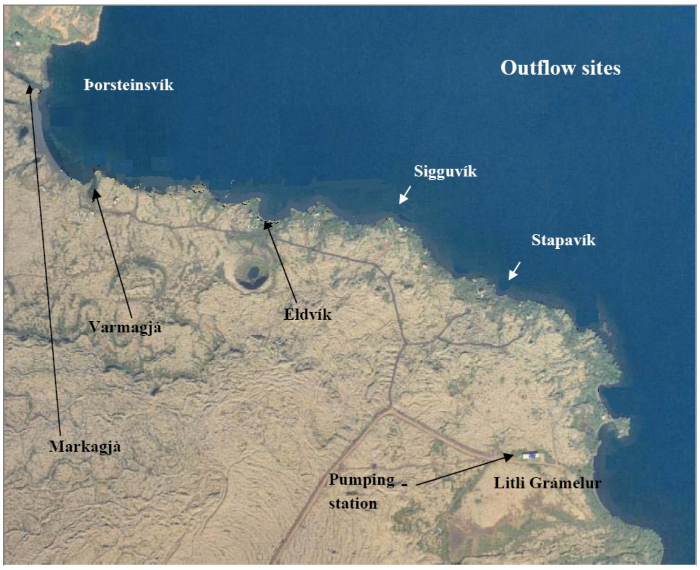

Figure 4. Sampling locations around southern shoreline of the lake Thingvallavatn

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. 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 2 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, 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 February 2009 show a decrease in water temperature at Markagjá, with temperatures fluctuating between 15 and 17°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.

Varmagjá. 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 3 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, conductivity, 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 in 2006, but has decreased to 27.4°C as measured in early 2009. Varmagjá follows the same trend as Eldvík and Stapavík, for all variables except pH and Cl.

Eldvík. 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 4). In February of 2009 the temperature measured 15.8°C.

Sigguvík. 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 5).

Stapavík is the sample location closest to the pumping station at Grámelur. 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 6).

Table 2: Average values of temperature and chemical constituents (in mg/l) in Markagjá

Period of time	Temp.°C	pH	S/25°C	CO2	SiO2	Na	K	Ca	Mg	SO4	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

Table 3: Average values of temperature and chemical constituents (in mg/l) in Varmagjá

Period of time	Temp.°C	pH	S/25°C	CO2	SiO2	Na	K	Ca	Mg	SO4	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

Table 4: Average values of temperature and chemical constituents (in mg/l) in Eldvík

Period of time	Temp.°C	pH	S/25°C	CO2	SiO2	Na	K	Ca	Mg	SO4	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

Markartangi represents the uncontaminated waters on the southern part of lake Thingvallavatn. 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 7).

Grámelur is the pumping station close to the shore of the Lake Thingvallavatn. Its six shallow wells 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 8).

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. 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 9.

Nesjalaugalaekur is a small stream which collects the natural surface runoff including precipitation, melting snow, spring water and natural runoff from the geothermal field. 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 10). The Nesjalaugalaekur stream combines with Köldulaugalaekur stream a short distance above the Nesjavellir power plant.

Table 5: Average of temperature and chemical constituents in Sigguvík

Period of time	Temp. °C	pH	S/25°C	CO2	SiO2	Na	K	Ca	Mg	SO4	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

Table 6: Average values of temperature and chemical constituents (in mg/l) in Stapavík

Period of time	Temp.°C	pH	S/25°C	CO2	SiO2	Na	K	Ca	Mg	SO4	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

Table 7: Average of temperature and chemical constituents in Markartangi

Period of time	Temp. °C	pH	S/25°C	CO2	SiO2	Na	K	Ca	Mg	SO4	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

Table 8: Average of temperature and chemical constituents in Grámelur

Period of time	Temp. °C	pH	S/25°C	CO2	SiO2	Na	K	Ca	Mg	SO4	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

Table 9: Average of temperature and chemical constituents (in mg/l) in Laekjarhvarf

Period of time	Temp. °C	pH	S/25°C	CO2	SiO2	Na	K	Ca	Mg	SO4	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

Table 10: Average of temperature and chemical constituents (in mg/l) in Nesjalaugalaekur from before 1991 to 2006

Period of time	Temp.° C	pH	S/25°C	CO2	SiO2	Na	K	Ca	Mg	SO4	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 11: Average of temperature and chemical constituents (in mg/l) in Köldulaugalaekur from before 1991 to 2006

Period of time	Temp .°C	pH	S/25° C	CO 2	SiO2	Na	K	Ca	Mg	SO4	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

Köldulaugalaekur is a small stream collecting natural surface runoff including precipitation, melting snow, spring water and natural runoff from the geothermal field. 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 11). The stream combines with Nesjalaugalaekur stream a short distance above the Nesjavellir power plant.

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 5 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.

Figure 5. Shallow well in Nesjahraun lava field

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.

Table 12 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. Table 12 is used 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).

Figure 6 shows a diagram of the fresh water, Condensate Water, Separate Water and Heated Ground water flows in and out of the power plant station.

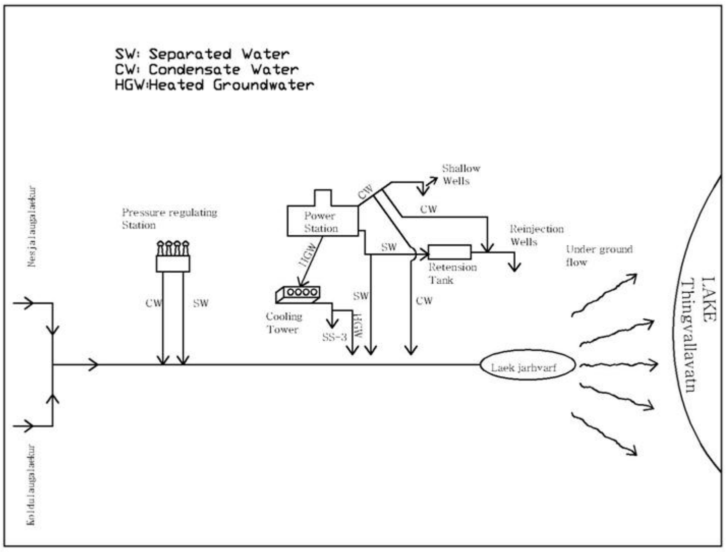

Figure 6. Diagram of water flows in and out of the power plant station.

Table 12: 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°C		27°C	32°C	32°C	33.5°C	34°C	32°C	33°C
NK-02	22°C		22°C	30°C	32°C	33°C	--	35°C	35.5°C
NL-02	9°C			15.12°C	19°C	--	--		26.5°C
NL-03	3.5°C			2.5°C	--	--	--		3°C
NL-04	15°C		34.5°C	41.5°C	19.5°C	28°C	25.5°C	17°C	26°C
NL-07		7.5°C	7.5°C	11°C	11°C	15.5°C	15.5°C	16°C	21°C
NL-08		11°C	16.5°C	18°C	21.5°C	23.5°C	25°C	25.5°C	27.5°C
NL-09		7.5°C	6°C	10°C	9°C	14.5°C	18°C	11°C	21.5°C
NL-10		4.5°C	5.5°C	6°C	6°C	30°C	34.5°C	32°C	32°C
NL-11		11°C	18.5°C	21.5°C	25°C	28°C	29.5°C	31°C	31.5°C
NL-02		4.5°C	5°C	4°C	--	--	--	7°C	9.5°C

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.

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 13 (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 13: Technical Specifications of DST milli (ebro.de, 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

Table 14: Technical Specifications of DST milli (star-oddi website, 2007)

Sensor	Temperature*
Size (diameter and length)	12.5 mm and 38.4 mm
Weight (in air/in water)	9.2g / 5g
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 (30°F to 104°F) Outside ranges available upon request
Resolution temperature	0.032°C (0.058°F)
Accuracy temperature	+/-0.1°C (0.18°F)
Depth survival	Up to 900m (user defined)
Response time temp.	20 sec.
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***
Corrosive 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 double increased.
*** For sampling interval of 5 minutes or greater.

5. DISCUSSION

Hot wastewater, both heated freshwater and geothermal water rich in dissolved solids, is released close to the Nesjavellir power plant, either into manmade wells or into the natural runoff (Laekjarhvarf). It flows by gravity towards the north into lake Thingvallavatn. The temperature of this water is generally above 40 degrees and therefore it floats on top of the colder groundwater. By the time it reaches the main road, a cold groundwater channel appears to intersect it from the west (from Háhryggur) and perhaps narrows it's flow path. North trending faults also help the progress of the wastewater towards the lake. The hot wastewater channel has therefore been preferably channelled to the eastern part of the valley. Farther north of the hot water channel spreads out over a wider area, thins towards the perimeter and cools. The lavas themselves have various porosities, some parts are highly porous and other parts are non-porous. The combinations of various porosity of the lavas and faults cutting through the lava pile probably control the distribution of the wastewater. The vast amount of cold water pumping occurring at Grámelur causes the wastewater 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 degrees have been measured and temperatures above 28 degrees have been measured west of Eldvík. Generally the whole area has risen in temperature since measurements started in 2000, and the wastewater channel has increased in thickness.

5.1 Temperature Variations

All sample locations at Lake Thingvallavatn, except Markartangi, have shown substantial temperature increase since 1998. Figure 7 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 leveling 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 4°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.

5.2 Chemical Comparison of Spring Water

Tables 2 to 11 show a very good correlation exists between the neighboring 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.

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.

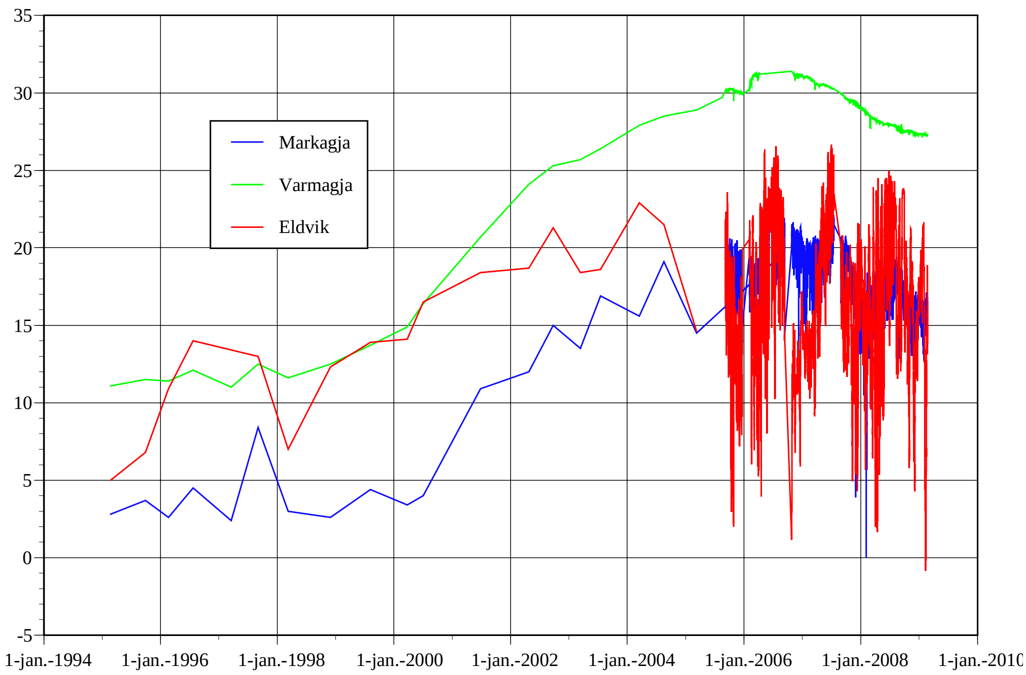

Figure 7. Temperature measurements at Markagjá, Varmagjá and Eldvík

6. 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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