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Monitoring the Effect of Geothermal Effluent from the Krafla and Bjarnarflag Power Plants on Groundwater in the Lake Mývatn Area, Iceland, with Particular Reference to Natural Tracers

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ABSTRACT

The chemical composition of the inflow into Lake Mývatn and the lake itself is stable due to the fact that almost all the inflow is supplied through groundwater by artesian springs. Geothermal and volcanic activity affects the groundwater system and thus the chemistry and biological activity of the lake which is unique especially at this high latitude. The area has been protected by a special law since 1974 and it is listed as an important habitat for birds in the RAMSAR convention on wetlands. This groundwater inflow is abundant and the residence time in the lake is short. The Krafla and Námafjall geothermal areas are close by and their effluent water drains to a large extent into the lavas containing the groundwater. There has been some concern that the effluent might affect the inflow to Lake Mývatn and therefore the groundwater near Lake Mývatn has been thoroughly studied concurrent with the construction of power plants in Krafla and Bjarnarflag (Námafjall), both operated by Landsvirkjun.

The results of artificial tracer tests suggest that dilution is great, e.g. that effluent discharged into a fissure at Bjarnarflag has been diluted about 100 million times by the time it reaches the fissure Grjótagjá about 2 km to the southwest. The Krafla effluent is discharged into a stream that flows into a fissure about 7 km to the east of Lake Mývatn in Búrfellshraun lava. Chemical studies of the area have led to the division of the groundwater into six groups on the basis of stable isotopes and accounting for B/Cl ratios, two of which constitute effluent waters from Krafla and Námafjall and as expected show strong high-temperature geothermal characteristics. The constituent that is most worrisome as regards possible contamination of the lake is arsenic which also happens to be one of the most characteristic constituents of the effluent.

Based on that evidence and of great dilution and little effect of previous effluent on Lake Mývatn it has been decided that the proposed enlarged Krafla and Bjarnarflag power plants can carry on discharging effluent into the lavas to the east of Lake Mývatn. The concentrations of certain chemicals characterizing geothermal effluent will be used as natural tracers for monitoring of fluid from five new wells drilled in the area, the old one and several fissures and springs and the effluent.

1. INTRODUCTION

Lake Mývatn (37 km^2) is situated in North Iceland at an altitude of nearly 300 m. It is divided into two main basins, the North Basin (8.5 km^2)and the South Basin (28.2 km^2) (Figure 1). The eastern part of the South Basin is frequently described as a separate basin (the East Basin) on geographical and ecological grounds. It is much influenced by inflowing cold spring water. Extensive areas in the South Basin are between 3 and 4 m deep, maximum depth is about 4 m. In the North Basin a large bottom area has been dredged, which has increased the depth from about 1 m to 2–5.5 m. Water enters the lake almost exclusively from springs along its east shore. Most of the springs are about 5°C but springs in the North Basin are warmer, generally warmest at Helgavogur where up to 23.6°C were found in 1971-1976 (Ólafsson 1991), but this increased to at least 32.5°C during the Krafla fires (de Zeeuw and Gíslason 1988) but had gradually cooled to 25.6°C in 1998 (Ármannsson and Ólafsson 2002). The average duration of ice cover is about 190 days (Rist, 1979a). Lake Mývatn was formed about 2300 years ago following a major volcanic eruption (Thorarinsson, 1951; Einarsson, 1982; Sæmundsson, 1991). The South Basin of the lake lies in a shallow depression in an extensive lava field produced by the eruption. Another lake existed at the same site before the eruption, but it appears to have been wiped out by the lava. The North Basin was formed by the same volcanic eruption as the South Basin, but by damming at the edge of the lava field. The geology of the area has been described by Thorarinsson (1979) and Sæmundsson (1991). Primary production has been estimated to be 3800 kcal m^{-2} $year^{-1}$ (Jónasson, 1979), of which 600 kcal m^{-2} $year^{-1}$ come from phytoplankton. Most of the primary production therefore takes place on the bottom of the lake, mainly by diatoms. Average sediment thickness in the South Basin is about 4.3 m. Diatom frustules comprise about 55% and minerogenic material (mostly tephra) about 30% of the dry weight of the sediment in the North Basin (Líndal, 1959). The ecology of the lake is described by Einarsson et al. (2004).

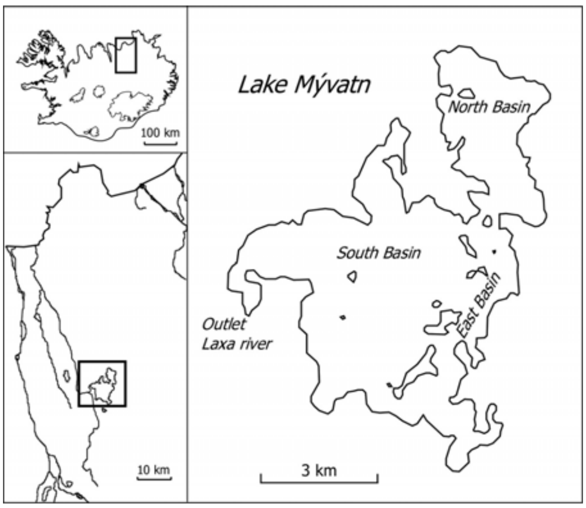

Figure : Lake Mývatn. Location and basins.

The River Laxá leaves Lake Mývatn in three main branches that merge a short distance downstream to form a single swift river which flows on a bed of lava rock and sand. The Lake Mývatn area is sparsely populated, with 10 to 15 farms, traditionally based on sheep farming and fishing. In the last three decades the human population has grown as a result of industrialization (diatomite production, power production from the Krafla geothermal plant) and increased tourism, and a village has been built up at the north end of the lake. The total number of inhabitants now is about 480. Human impact on the ecosystem is mostly felt through the diatomite mining operation as it interferes with the nutrient and sedimentation dynamics of the lake. Grazing by sheep maintains an open landscape and may have contributed to excessive soil erosion in a large area south and east of the lake (Ólafsdóttir and Gudmundsson, 2002). The decision to discontinue the diatomite plant from the beginning of 2005 has now been made so that dredging the bottom of the lake will cease. There are plans afoot as to setting up different industries to occupy the population but its nature and extent is not as yet clear.

The catchment of Lake Mývatn is covered by highly permeable, sparsely vegetated lava terrain, partly covered with aeolian and waterborne sand (Käyhkö,et al., 2002). There is little surface runoff so the extent and subdivisions of the catchment can only be determined by indirect methods. Based on Árnason (1976), who used spatial variation in the deuterium ratio in precipitation to trace groundwater origin, the catchment area has been estimated at about 1400 km^2 (Rist 1979b, Gíslason, 1994). Only about 17% of the catchment area has organic topsoil with vegetation (Gíslason, 1994). The spring water discharge entering Lake Mývatn is about the same as the outflow from the lake (32–33 m^3s^{-1}) since surface runoff is negligible. Of the spring water, 8.3 m^3s^{-1} (24%) enter the North Basin and flow via the South Basin on the way to the outlet. The springs in the SE corner of the lake contribute about 14.6 m^3s^{-1} (44%). Grænilækur, a river flowing a short distance from the spring-fed Lake Grænavatn and entering the southeast part of Lake Mývatn, has a discharge of 6.4 m^3s^{-1}. The remaining 3.7 m^3s^{-1} emerge along other parts of the shore. The springs on the eastern shore of Lake Mývatn have a high pH, relatively high concentrations of phosphate, some nitrate, and high concentrations of silicate, especially the warm springs, resulting in inputs of P, N and Si amounting to 0.05 mole m^2 $year^{-1}$, 0.14 mole m^2 $year^{-1}$, and 12 mole m^2 $year^{-1}$, respectively (Ólafsson, 1979, 1991a). Nitrogen in the groundwater is mostly in the form of nitrate from precipitation in the catchment area of the lake. The mean phosphate concentration of 1.62 µM in groundwater entering Lake Mývatn (Ólafsson, 1979) is more than twice the world average lake concentration of 0.65 µM (Wetzel, 2001). The high pH and phosphate concentrations of groundwater feeding the lake are due to the highly reactive basaltic bedrock, and the sparse vegetation in the catchment area. Thus, the groundwater, with its constant flow and temperature, acts as a stable source of dissolved constituents (Thorbergsdóttir & Gíslason, 2004).

Lake Mývatn is unique in its productivity and biodiversity for a lake at its latitude and altitude. Therefore the area has been protected by a special law since 1974 and it is listed as an important habitat for birds in the RAMSAR convention on wetlands. There has been some concern that the effluent from the Krafla power station, the diatomite plant and the small power plant in Bjarnarflag, as well as the proposed 90 MW_e Bjarnarflag power plant might affect the inflow to Lake Mývatn and therefore the groundwater near Lake Mývatn has been thoroughly studied concurrent with the construction of the power plant in Krafla and more recently as part of the environmental impact assessment of the Bjarnarflag (Námafjall) power plant. The purpose of this paper is to describe the work that has been carried out on groundwater flow and groundwater chemistry in connection with these two power plants, describe the latest developments and the monitoring plan that now has been agreed for the two plants.

2. INDUSTRY AND POWER PRODUCTION IN THE LAKE MÝVATN AREA

Sulfur was mined in the Námafjall area with intervals for centuries using traditional methods, the last period of such mining being during World War II. During the 1950s here were plans to drill for sulfur and erect a modern factory. Several wells were drilled in the Hveraröнd part of the Námafjall field at the time but these were abandoned. The remains of some of them still exist as hot springs that are a much praised tourist attraction. Instead interest grew in a diatomite plant using diatomites from the bottom of Lake Mývatn and geothermal steam for drying. The diatomite plant was erected during the 1960s with 10 geothermal wells drilled from 1963 to 1965. These were to a large extent damaged by magmatic activity in 1977 and two make-up wells were drilled outside the most active area in 1979 and 1980. There are few records of hydrological studies or the possible fate of effluent water from this early activity except that Sæmundsson (1969) stated that the water level in Bjarnarflag wells remained very constant but that earlier records showed the water level in a well east of Námafjall to oscillate between 321 and 345 m a.s.l.

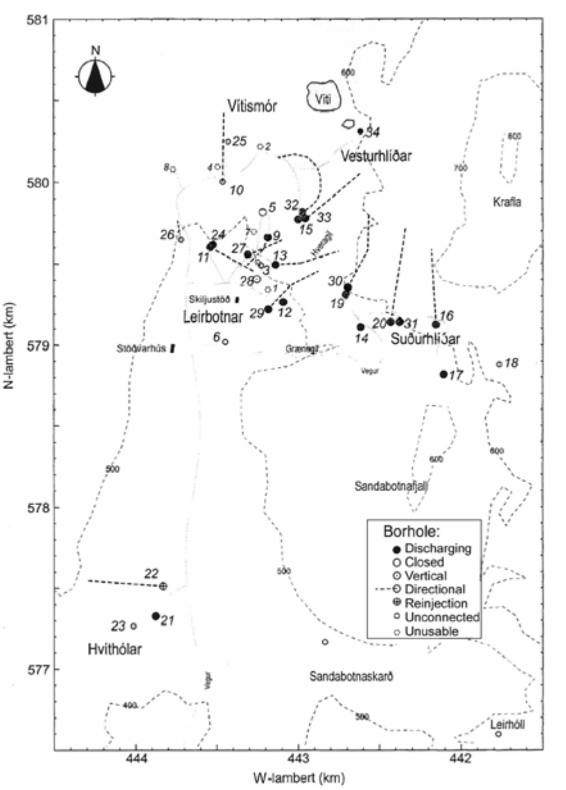

Figure 2: Krafla. Wellfields and wells.

The Krafla 60 MW_e power plant, comprising two turbines, was commissioned in 1975 on the basis of surface exploration and the drilling of two exploratory wells. Progress was hampered by the Krafla fires 1975-1984 so to start with only one of the 30 MW turbines was installed at the time. The first 7 MW went on line in early 1978 when

11 wells had been drilled. One **more** well was drilled in 1978 but after further surface exploration it was decided to drill two more wells in the old drilling area of Leirbotnar but at the same time try drilling in a new area, Sudurhlídar that seemed less affected by volcanic activity. Later it was decided to test yet another drilling area, Hvíthólar, seemingly unaffected by the volcanic activity. From 1980 to 1983 two wells were drilled in the Leirbotnar area, 6 wells in the Sudurhlídar area and 3 wells in the Hvíthólar area and sufficient steam had been obtained to fully utilize the installed 30 MW turbine. A make-up well was drilled in 1988 and two exploratory wells in 1990-1991, all in Leirbotnar. In 1996 Landsvirkjun (the National Power Company) decided to complete the installation of unit 2 and to drill for additional steam to reach fully rated power on the plant. The project has been successfully completed and the plant has been running on full load since 1998. For the completion 5 wells were drilled in Leirbotnar and 2 wells in Sudurhlídar, and one in a new drillfield, Vesturhlídar. An overview of the wells and wellfields in Krafla is presented in Figure 2. There are plans to extend the plant to 100 MWe by drilling 3 new boreholes in Vesturhlídar in the vicinity of well K-34. Exploratory drilling is planned in a new field to the west of Hvíthólar.

3. EFFLUENT DISCHARGE FROM THE KRAFLA AND BJARNARFLAG PLANTS

It has been estimated that from the beginning about 200 million tons of effluent have been discharged into the lavas from Krafla and Bjarnarflag. The early results for the exploration in Krafla suggested that the field was water-dominated and its utilization would involve vast quantities of effluent (Sæmundsson et al. 1975). This aspect of the utilization was therefore thoroughly studied during the early stages of the project. Ármannsson (2003) has given a detailed overview of these studies.

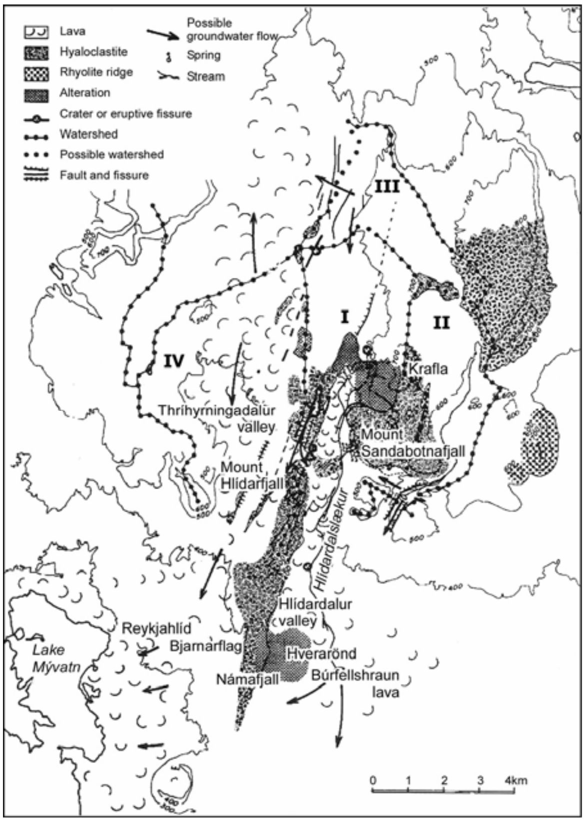

Figure 3: Krafla and Námafjall catchment areas.

Sigbjarnarson et al. (1974) estimated that the effluent flow from the then proposed plant would become about 0.6 m^3s^{-1} and the major environmental effects a steam cloud and silica deposits. They proposed to discharge the effluent into Búrfellshraun lava, this being the cheapest way, the dilution would be great and the water would take a long time to reach Lake Mývatn if ever. Shallow wells should be drilled in the lava to monitor the effluent's progress. If a potential danger were identified the water could be cooled and dangerous substances precipitated, it could be directed to the catchment area of river Jökulsá or it could be reinjected. Sæmundsson et al. (1975) suggested that the effluent be cooled and directed into a lagoon, preferentially located in the valley Thríhyrningadalur. VST and Virkir (1975) showed that locating the lagoon in the valley Hlídardalur was financially and technically a better option. Arnórsson and Gunnlaugsson (1976) divided the Krafla area into three catchment areas I, II and III (Figure 3). One more catchment area can be defined to the west of these, catchment area IV. The stream Hlídardalslækur which would receive any effluent outflow thus has a catchment area of 21-41 km^2. In September 1975 the flow from the springs that feed the stream was 87 ls^{-1}. Water from á Thríhyrningadalur lagoon was expected to flow into the valley Hlídardalur or to the west of mount Dalfjall about 15 km from Lake Mývatn and most likely flow beneath the bottom of the lake. Model calculations by Ingimarsson et al. (1976) suggested that the greatest changes in groundwater level and also the greatest likelihood of the water flowing back into the geothermal system would be obtained if a lagoon were to be formed in Thríhyrningadalur. If the water flowed along the shortest possible path it would take 30 years to reach Lake Mývatn.

Jóhannesson (1977, 1980) suggested that the major groundwater flow to the area was from the Dyngjufjöll area, 60-80 km to the south, but a part of the current is heated up rises to the surface and flows back south in the Námafjall area, and that this current joins a local current flowing from Krafla south to Lake Mývatn. This is the macro-structure that has been used for later models of flow in the area into which local detail has been added (Thóroddsson and Sigbjarnarson 1983, Verkfrædistofan Vatnaskil 1999, Ármannsson and Ólafsson 2002). Darling and Ármannsson (1989) using stable isotope ratios confirmed that this could be the pattern and using their results in conjunction with those of Árnason (1976) and Jóhannesson (1977, 1980). Hjartarson et al. (2004) have constructed an overall view of the origin of the flow to the area (Figure 4). Any effluent from the Námafjall area would thus be likely to be discharged into the 8.3 m^3s^{-1} entering the North Basin and if effluent water from Krafla were to reach Lake Mývatn it would be as part of that same flow.

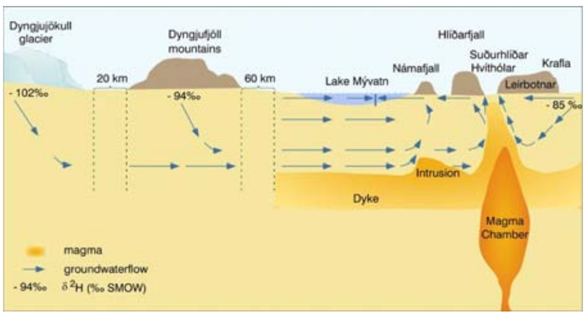

Figure 4: Possible origin and flow of groundwater in the Lake Mývatn area.

The drilling results at Krafla revealed a higher enthalpy geothermal system than had been predicted and presently the amount of effluent from there is a little over 100 ls^{-1} about half of which is being reinjected. The enthalpy of the two wells drilled in Bjarnarflag in 1979 and 1980 was higher than of the previous ten. The effluent from the early wells had not affected Lake Mývatn and therefore it was decided that it was not likely to affect the lake to discharge these relatively small quantities directly into the lavas.

Several tracer tests have been carried out to establish the flow pattern and dilution of the effluent when it has mixed with the groundwater. In 1980 fluoroscein was added to a downflow about 190 m to the NE of well AB-02 in Búrfellshraun lava (Figure 5) most of which was recovered from the well within 40 days (J. Ólafsson, personal communication). During the next two years fluoroscein was added to effluent from the Diatomite Plant pumping station at Helgavogur, most of which was recovered in the springs at Helgavogur with traces recovered from Stóragjá and Kálfstjörn but it was argued that very little or anything could be transported via Grjótagjá to Langivogur (Figure 5) (Thóroddsson and Sigbjarnarson 1983). In 1998-1999 several tests were run both from the Hlídardalslækur downflow and the Bjarnarflag lagoon downflow using fluoroscein, potassium iodide and rhodamine WT the only result being a faint response to the iodide and a very faint one to fluoroscein in Grjótagjá, about four months after their addition to the Bjarnarflag lagoon downflow (Kristmannsdóttir et al. 1999). A more detailed test with potassium iodide in 2002 showed the first signs of tracer return in Grjótagjá 2 km to the south of the Bjarnarflag lagoon downflow, 2 months after its additition to it, reaching a peak after 5 months. A smaller trace was recovered from a spot in the same fissure about 1 km further south. The dilution from the downflow to Grjótagjá is 100 millionfold (Kristmannsdóttir et al. 2001). Reinjection of several types has been considered for effluent from the Krafla power plant. Shallow reinjection into a permeable fissure in eastern or western Hlídardalur valley has been estimated as likely to be effective but would probably involve unacceptable damage to vegetation (Elíasson et al. 1998). Reinjection was tested in the Hvíthólar area and the reinjected effluent was soon recovered from a nearby well so the reinjection would have to be designed differently injecting the fluid at a great depth so that it does not enter the production aquifer. A reinjection test involving injecting effluent from the separator plant at Krafla into well No. 26 (Figure 2) has been in progress since January 2002 and results seem promising. An earlier test with cold groundwater had blocked the well but the geothermal effluent has removed the blocking and increased the volume received by the well from 10-20 ls^{-1} to about 60 ls^{-1}. The injectate has not been detected in nearby wells yet but no specific tracer tests have been performed. Plans to use artificial tracers have been postponed due to logistical problems but preliminary work suggests that the concentrations of and ratios between noble gases in conjunction with stable isotopes may be used as natural tracers for the injectate (B. Christenson, pers. comm.)

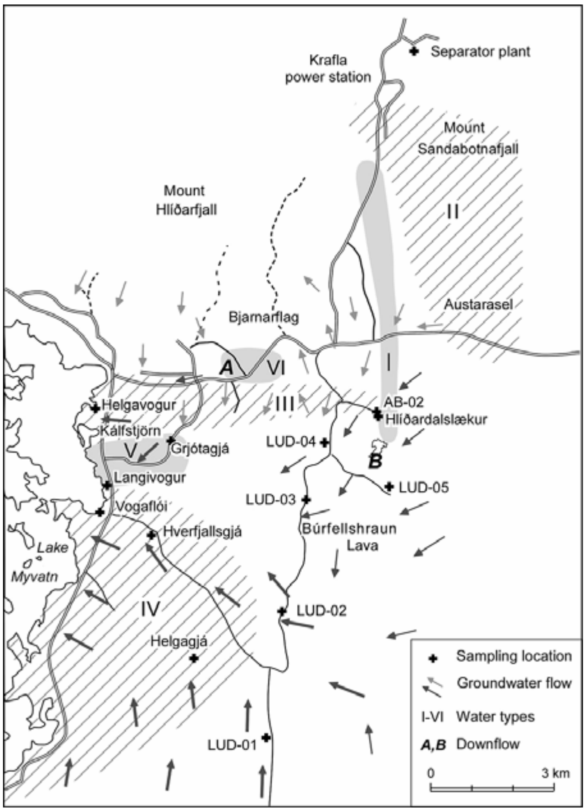

Figure 5: Groundwater flow patterns in the vicinity of Lake Mývatn. Areas distinguished by water groups I-VI, and wells, fissures and springs sampled are shown.

4. CHEMISTRY OF THE GROUNDWATER AND THE EFFLUENT FROM THE KRAFLA AND NÁMAFJALL PLANTS

The groundwater studies, including the chemistry are described in detail by Kristmannsdóttir and Ármannsson (2004). The water table in the Krafla and Námafjall geothermal systems is at a great depth and in natural circumstances only steam will reach the surface from them. Heated groundwater can be accessed in some fissures and springs in the Námafjall area close to Lake Mývatn. Early records compared to present day ones do not suggest an increase in undesirable components (Jardboranir ríkisins 1951, Stefánsson 1970, Ólafsson 1979). There were, however, some changes in composition, especially increases in chloride and silica in some of these fissures and springs coincident with an increase in temperature, recorded during the Krafla fires but these have gradually returned to the previous values (de Zeeuw and Gíslason 1988, Ármannsson et al. 1998). On the basis of δ^2H and δ^{18}O values waters in the Lake Mývatn area have been divided into 6 distinct groups (Ármannsson et al., 1998, 2000) which can also be distinguished geographically (Figure 5). Groups I (δ^{18}O = -80.4 - -80.7), II (δ^2H = -83.0 - -86.9) and III ((δ^2H = -87.7 - -88.9) are local waters, whereas the waters in groups IV (δ^2H = -91.5 – -94.8) and V (δ^2H = -90.9 - -93.5%) originate from the inland far to the south. Water in group I is discharge from the Krafla power plant and water in group VI is effluent water from Námafjall geothermal field. Oxygen shift due to water-rock interaction suggesting geothermal influence is observed in group V (δ^{18}O = -11.58 - -11.92) which thus differs from group IV (δ^{18}O = -12.72 - -13.03) and constitutes groundwater significantly influenced by geothermal effluent. Oxygen shift is observed in groups I, V and most prominently in group VI. The Icelandic meteoric line differs slightly from the world meteoric line (Árnason,

Table 1: Geothermal constituents in samples from selected locations 2002-2003 (Ármannsson and Ólafsson 2002, 2004).

Location	SiO_2 mg/l	Al mg/l	Mo μg/l	As μg/l
Hlídardals-lækur downflow	285	0.706	4.18	25.1
LUD-04	28.4	0.418	1.75	5.69
Langivogur	69.0	0.0017	0.36	0.15
Bjarnarflag lagoon	227	0.735	0.30	157
Helgavogur	77.4	0.0081	1.30	0.16
Grjótagjá	156	0.0098	0.19	0.17

1976, Sveinbjörnsdóttir et al., 1995). The grouping of the Mývatn groundwater based on δ^2H and δ^{18}O values is confirmed by the relationship of Cl and B (Ármannsson et al. 2000). In 1978-1979 well AB-02 in the Búrfellshraun lava was drilled to monitor underground flow from the Krafla effluent downflow from the Hlídarsdalslækur stream, and as indicated above a tracer was recovered there within 40 days, having been flushed down 190 m to the northeast of the well. Since then the location of the downflow has moved further south and it is thought that the location of this well is now probably not right for monitoring this flow as was suggested by the fact that fluoroscein flushed down into the present downflow in 1998 was never detected in the well (Kristmannsdóttir et al.

Table 2: ***Environmental limits for some chemicals in surface water for biological protection***

Limit μg/l	I	II	III	IV	V
Cu	**≤ 0.5**	**0.5- 3**	3-9	9-45	>45
Zn	≤ 5	5- 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	1-3	3-15	>15
Cr	≤ 0.3	0.3- 5	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	5-15	15-75	>75

I: Negligible or no risk. II: Very small risk. III: Effects on sensitive biota. IV: Effects expected. V: Always intolerable (The Ministry of the Environment , 1999)

1999). Samples from the above mentioned fissures and springs give valuable information but in many cases for rather distant locations. The hydrological model of Verkfræðistofan Vatnaskil (1999) suggests a major flow from the south but turning to the west towards Lake Mývatn but with a current from the north towards Lake Mývatn and there was some evidence that some of that current traveled south east of Lake Mývatn before joining the current from the south (Ármannsson et al. 1998). In an attempt to account for all these possibilities and obtain a more representative distribution of results five wells LUD-01-05 (Figure 5) were drilled and sampled. As tracer tests had proved expensive and difficult it was felt desirable to find out whether any natural tracers could be found, i.e. constituents that were present in a large concentration in the geothermal effluent but in a small concentration in the groundwater. Constituents that are characteristic of geothermal fluid such as SiO_2, Al, Mo and As seem possible candidates. One of the difficulties here is that the springs feeding Lake Mývatn are geothermal in their own right, i.e. the water is heated by a heat source close to the springs. Thus geothermal constituents such as SiO_2 may be diluted to start with but then replenished by this second geothermal heat source. Therefore the task is to find a constituent that is characteristic for high-temperature geothermal water but dissolves slowly at lower temperatures. In Table 1 there is a survey of possible natural tracers in water from selected sampling locations. The conclusion was that As was probably the most useful natural tracer for high-temperature geothermal effluent but results for Al and Mo would provide support. This is also convenient as As is the only constituent whose concentration in the groundwater may exceed permitted concentrations (Table 2). Table 2 published by the Ministry of the Environment in Iceland is a general guide to environmental limits but attention has to be paid to differing effects on large aquatic vascular plants and algae/plankton. The latter is more sensitive to enhanced metal concentrations and the primary producer in a lake ecosystem. In the long-term the tolerance of the biotic ecosystem may be surpassed.

The first results of these studies confirmed the main features of the hydrological model with the current to the west to Lake Mývatn in Búrfellshraun lava in that the effluent water was clearly detected in one well about 1 km to the west of the downflow from the stream from Krafla and less clearly in a well about 300 m NNW of the downflow but not elsewhere. The Bjarnarflag effluent was not similarly detected in the fissure and spring closest to its downflow. The chemical composition from fluids of the downflows, **springs,** fissures and wells is shown in the latest report on monitoring of fluids (Ármannsson and Ólafsson 2004). That of the downflows and the springs that feed Lake Mývatn and may receive water from the effluent are in Table 3.

4. CONCLUSIONS

In light of the 200 million tons of effluent that already has entered the groundwater under the lavas in the Lake Mývatn area during the last 40 years without causing harm and the relatively small amount of effluent water due to the high enthalpy of the borehole fluids in the Krafla and Námafjall geothermal areas it is considered relatively safe to permit continued release of effluent from the Krafla power plant, its enlargemement and the proposed Bjarnarflag power plant into the lavas in the vicinity of Lake Mývatn.

Table 3 Spring and effluent water chemical composition

Constituent	Hlídar-dalslækur. downflow	Bjarnar-flag down-flow	Voga-flói spring	Langi-vogur spring
pH/°C	9.20/22	7.68/24	8.62/23	8.54/23
CO_2 mg/l	87.3	35.9	66.9	84.7
H_2S mg/l	1.26	0.11	<0.03	<0.03
B mg/l	0.69	3.11	0.06	0.31
Cond. $\mu Scm^{-1}/25°C$	850	813	210	443
SiO_2 mg/l	285	227	21.4	122
TDS mg/l	894	1098	118	362
Na mg/l	151	144	21.5	69.0
K mg/l	16.0	21.3	1.74	5.63
Mg mg/l	6.30	0.364	6.26	3.50
Ca mg/l	18.6	1.92	10.9	13.4
Sr mg/l	0.0302	0.0112	0.0127	0.0160
F mg/l	0.80	0.84	0.22	0.38
Cl mg/l	35.9	59.0	4.89	15.6
SO_4 mg/l	233	191	19.6	78.6
Ba µg/l	2.60	0.84	0.33	1.69
Mo µg/l	4.180	0.499	0.739	0.356
Al µg/l	706	119	7.8	1.7
Cr µg/l	0.677	0.033	1.450	0.355
Mn µg/l	37.9	1.47	0.182	<0.03
Fe µg/l	73.1	6.0	2.8	0.9
Cu µg/l	1.15	0.687	1.48	0.30
Zn µg/l	8.06	2.65	1.77	0.56
As µg/l	25.1	157	<0.01	0.154
Cd µg/l	0.0394	0.004	0.0503	0.0065
Hg µg/l	0.008	0.0124	<0.002	<0.002
Pb µg/l	0.073	0.233	<0.01	0.023
Ni µg/l	0.627	0.239	0.308	0.108
Co µg/l	0.120	<0.005	0.034	0.018
P mg/l	0.0091	0.00558	0.0621	0.0499
δD‰	-73.9	-88.0	-91.6	-90.8
$\delta^{18}O$‰	-8.42	-6.24	-12.66	-11.64

Continued experiments with reinjection at Krafla are recommended as this is the most efficient means to dispose of effluent and also extends the lifetime of the geothermal system. It is also suggested that if the proposed Bjarnarflag power plant becomes as large as producing 90 MW_e reinjection is desirable so as not to avoid undue strain upon the system (Hjartarson et al. 2004). In view of the possible danger to the biotic ecosystem in Lake Mývatn that is being protected by RAMSAR in the long-term anearly shift to reinjection in Bjarnarflag is proper.

The size of the Bjarnarflag lagoon and the Hlídardalslækur downflow pond should be monitored annually using aerial photography. The water table of the wells in Búrfellshraun lava should similarly be monitored twice per year and samples for total chemical analysis collected once per year and samples for trace metal analysis twice per year from the following locations: Hlídardalslækur downflow, wells AB-02, LUD-02, LUD-03, LUD-04, Bjarnarflag downflow, Grjótagjá fissure and the springs at Langivogur and Vogaflói by Lake Mývatn (Figure 5). This monitoring scheme has already being implemented and one report has been issued on its progress (Ármannsson and Ólafsson 2004)

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