Ecological risk assessment of Nesjavellir co-generation plant wastewater disposal on Lake Thingvallavatn, SW-Iceland

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Abstract

Production of electricity and hot water for district heating by Nesjavellir geothermal power plant in SW-Iceland utilizes high temperature steam, which contains various trace elements. The waste fluid from the plant is either pumped into shallow drill holes that connect to underground water or disposed of in the Nesjavellir stream, which disappears into the lava and finds its way into Lake Thingvallavatn, a rift lake of high conservational value. Here we evaluate data on temperature and quantities of trace elements in the geothermal wastewater discharged from the power plant and at lakeshore springs, and in biological samples of an aquatic plant, a gastropod snail, in the salmonid fish arctic charr and in sediments at Varmagja and at a control site, Vatnskot. Before the wastewater reaches the lake, trace elements are modified through chemical reactions or diluted to such an extent that there is little reason for concern except for arsenic. All trace elements in lake shoreline springs were within the international water quality criteria for protection of aquatic life except for arsenic. Aluminium was also found in concentrations that cause some concern. In most situations wave action ensures efficient mixing of the spring water at geothermally influenced sites with cold lake water precluding detrimental effects of elevated temperature and trace elements. However, following the development of electricity production at Nesjavellir since 1998 the disposal large amounts of 42°C cooling water has caused a rise in temperature at shoreline springs from around 12°C to around 20°C. This is of some concern at sheltered sites. There was no detectable rise or accumulation of trace elements in biological samples taken at Varmagjá, one of the geothermally influenced sites. However, taking into account the conservational value of Lake Thingvallavatn, sound wastewater management by deep re-injection and regular monitoring of trace elements and spring water temperature should be adopted.

Key words: *ecological risk, Nesjavellir co-generation plant, wastewater disposal, lake ecology, assessment.*

1 Introduction

Ecosystems are composed of the biological community (producers, consumers and decomposers) and various abiotic components (physical and chemical). Within ecosystems, a complex interaction of physical and biochemical cycles exist. In this sense ecosystems continually undergo change at various time scales. However, many ecosystems have developed over a long period of time and organisms have become adapted to their environment. In addition, ecosystems have an inherent capacity to withstand and assimilate stress based on their unique physical, chemical, and biological properties. Nonetheless, systems may become unbalanced by natural factors, including drastic changes in climatic variations, or due to human activities. Any changes especially rapid ones, can have detrimental effects.

Adverse effects due to human activities, such as release of toxic chemicals or heat in industrial effluents, may affect many components of aquatic ecosystem, the magnitude of which will depend on both biotic and abiotic, site-specific characteristics. In evaluation and planning, aquatic ecosystems should be viewed as whole units, not just in terms of isolated organisms affected by one or a few pollutants.

As chemicals or substances are released into the environment through natural processes or human activities, they may enter aquatic ecosystems as solutes which can enter the biological community. Some chemicals can partition into particulate phase, in which case the particles may remain in the water or may be deposited into the bed sediments where the contaminants can accumulate over time. Sediments may thus act as long-term reservoirs for contaminants (CCME, 2001).

Thingvallavatn is a rift lake located in SW Iceland and of high conservational value (Jónasson, 1992, 2003). The lake is 90% fed by underground springs with main springs entering in the north at a temperature of 2.8-3.5°C. Warmer groundwater enters the lake in the southwest from the Hengill geothermal area (Ólafsson, 1992). Since 1990 The Reykjavík Hot Water Company (now Reykjavík Energy) has utilized the Hengill geothermal resource in the Nesjavellir Power Plant, first by producing hot water for district heating and later by adding facilities for generation of electricity for the national grid.

The power plant at Nesjavellir utilizes high temperature steam, which contains various trace elements. The waste fluid from the plant is either pumped into shallow drill holes that connect to underground waterways or disposed of in the Nesjavellir stream, where it disappears into the lava and finds its way into Thingvallavatn. A study of the chemical composition of effluents from 4 geothermal drillholes sampled in the Nesjavellir field in the years 1983-1984 showed high concentrations of arsenic (5.6-310 µg/l) (Ólafsson, 1992). In the following years (1984-1991), while the geothermal field was being developed, arsenic concentrations rose markedly in two geothermally affected lakeshore springs, at Varmagja (from 0.6-2.2 µg/l) and Eldvik (from 0.7-4.7 µg/l). From these studies Olafsson (1991) concluded that arsenic was the only constituent of the geothermal effluent likely to be of concern in Thingvallavatn. Although trace elements were low in the affected springs and the arsenic concentration was within limits considered safe for the fresh water biota, precautionary monitoring measures were recommended (Snorrason and Jónsson, 1995).

Direct release of hot wastewater from a standard steam cycle power plant into an existing natural waterway leads to an increase in temperature, which can have a very significant impact on communities of aquatic plants and animals. In serious cases this results in a complete change of the community whereby high temperature tolerant species take over. In milder cases water temperature variation among sites may create differences in the physiological and behavioural advantages among aquatic organisms hence influencing their competitive ability and distribution as indicated by Taniguchi et al. (1998). At the present the electricity production phase at the Nesjavellir plant is a steam cycle design, which uses cold fresh water for cooling of condensed steam. Based on the geothermal wastewater disposal data, used and unused brine discharged from the power plant and separator station at an average flow rate of 32.89-11.4 kg/s at 79.9-100°C are discharged in the shallow boreholes or the nearby Nesjavellir stream that disappears into Nesjahraun lava at Lækjarhvarf (Figure 1). This mixes with groundwater, which flows some 3.8 km to the lake Thingvallavatn. About 109.07-169.86 kg/s of condensed steam (57.03-65.62°C), and 736.8-756.13 kg/s of cooling water at 57.6-64.6°C are also discharged into shallow drillholes (data from Reykjavik Energy). Variation in wastewater discharged exists between typical winter and summer months with level of cooling water disposed off being high in summer.

When geothermal wastewater reaches a lake via streams or springs, it mixes with lake water causing dilution of solutes and lowering of temperature. The effectiveness of this mixing process depends on wind driven currents and on local conditions at the point of entry, e.g. to what extent the site is sheltered from mixing currents. In Thingvallavatn wind action is frequent and spring water is quickly and effectively mixed with lake water (Snorrason, 1982). Therefore, any effects of high temperature or potentially harmful solutes in springs affected by geothermal effluents or wastewater, are predicted to be local and restricted to the spring sites (Snorrason and Jónsson 1995).

This paper is a collective review from an ecological risk assessment perspective of various chemical and biological studies on Lake Thingvallavatn and its environs. This is based on temperature and trace elements data for geothermal wastewater at the Nesjavellir power plant and lake shoreline springs i.e. Varmagjá, Eldvík and Markagjá (VGK, 2000), and trace element data from biological samples taken at one of the affected springs at Varmagjá and a control site, Vatnskot, at the northern shore. The samples represent the trophic levels of the local communities; i.e. an aquatic vascular plant (*Myrophyllum alterniflorum*), a gastropod snail (*Lymnea peregra*), a fish (arctic charr *Salvelinus alpinus*), and lake sediment, and cover the years 1989, 1994-6, and 2000 (Snorrason and Jónsson, 1995, 1996, 2000).

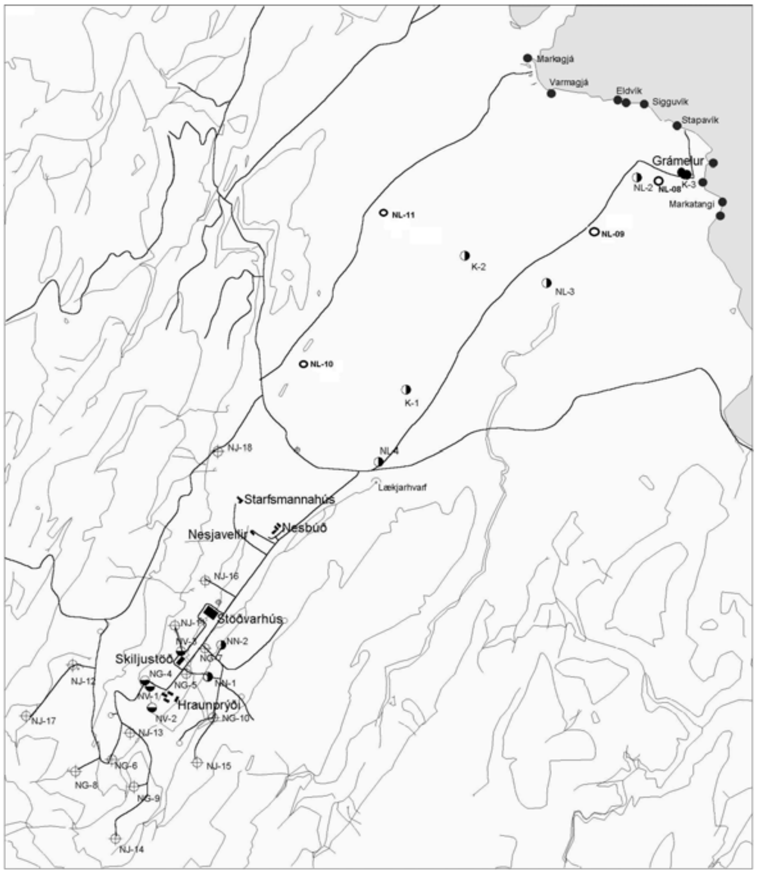

Figure 1: Nesjahraun geothermal wastewater runoff area. Positions of monitoring drill-holes (◑) and lake shoreline springs (●), Varmagjá and Eldvík, inside the affected area, and Markagjá, just outside the affected area, are indicated.

2 Assessment and discussion

2.1 Influence of increased geothermal discharge on lake ecology

The underground flow of geothermal water through the Nesjahraun area has been subjected to a study model based on empirical data from tracer experiments and experimental drilling. Based on injecting a sodium fluorescin tracer the geothermal water has been traced from Lækjarhvarf down to lakeshore springs (Kjaran and Egilson, 1986, 1987). According to these studies the flow was confined to a rather narrow area between Markagjá in the north and Stapavík in the south, the core of the flow being situated upwards of the Varmagjá area (Kjaran and Egilson, 1986, 1987; Ólafsson, 1992). Temperature profiles from experimental drillholes in Nesjaharaun show that the flow of the geothermal water is also confined vertically to a narrow zone a few meters above the cooler ground water table (Hafstað, 2001).

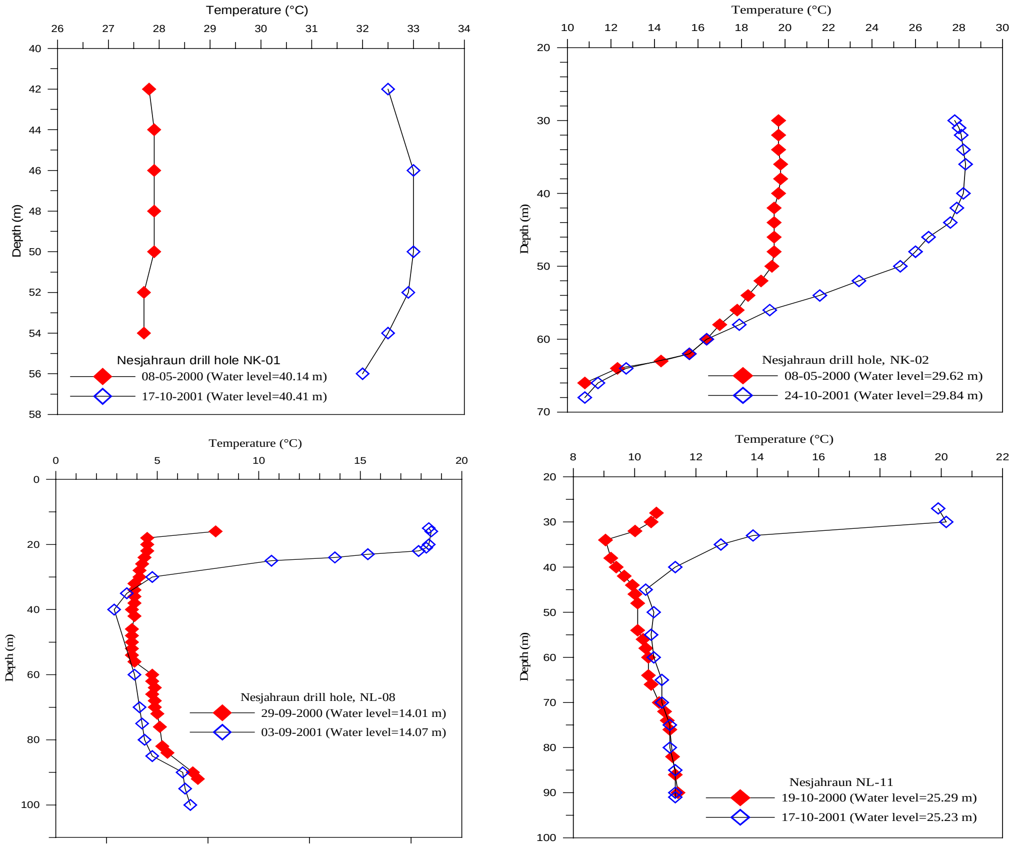

Figure 2: Changes in temperature profiles in four monitoring drillholes in the Nesjavellir lava following a 50% increase in waste water discharge from the geothermal power plant at Nesjavellir in 2001 (Hafstað, 2001).

This means that the main, central stream of geothermal wastewater does not mix much with colder ground water. The most significant change in the system stems from the added disposal of "unusable" cooling water coming from the turbines generating electricity first deployed in October 1998. This addition now amounts to an average of 736.8-756.13 kg/s at 57.6-64.6°C but sometimes can be as high as 1447.6 kg/s of water. The effect of this is clearly seen in changes of temperature profiles in several monitoring drill holes in the Nesjavalla lava from the spring of 2000 to the autumn of 2001 (Hafstað, 2001), when the electricity generation facilities had been in full operation for less than a year. These data show a marked rise in temperature of the central stream of geothermal water (Figure 2, NK-01 and NK-02) and an extension of the warm water tongue at the eastern and western edges (Fig. 2, NL-08 and NL-11).

The volume increase in warm water disposal from the powerplant is also seen in elevated temperatures the thermally affected springs at Varmagjá (a rise from 13-21°C) and Eldvík (a rise from 13-18°C) (unpublished data from Reykjavík Energy) and judging by elevated temperatures in drill holes at the edges of the warm water tongue we expect to see elevated temperatures in springs further to the south of Eldvík.

The effects of elevated spring temperatures in Nesjavallahraun on Thingvallavatn will only be on a local scale. In calm weather tongues of warm water floating on the surface may form temporarily. Such layering is likely to break down quickly due to wave action when the wind picks up. The elevated temperatures are likely to affect the winter ice along the shore between Markagjá and Grámelur with more extensive, permanent openings. Any large scale effects of elevated spring temperature on the Thingvallavatn ecosystem are not expected. Efficient water mixing (Snorrason, 1982) causes temperature drop to the normal lake temperature a few meters away from points of inflow. Hence, the normal cold water adapted benthic algal communities will not be affected (Jónsson, 1992). However, changes can be expected to the benthic communities of plants and animals in the nearest neighbourhood of the springs, particularly in Varmagjá, which, due to its isolation from the lake, is somewhat sheltered from wave action.

2.2 Transport of trace elements by geothermal discharge

To assess potential ecological risk of pollution by nutrients, minerals and trace elements from surface disposal of wastewater from the power plant, concentrations of trace elements in the wastewater have been measured and their fate during flow have been evaluated by measuring concentrations in two of the affected springs, Varmagjá and Eldvík, in the main fresh water source of the plant at Grámelur, and in Markagjá, which is not affected by geothermal activity (Ólafsson, 1992; VGK, 2000). Some of these chemicals, such as SiO_2, K, Al and As, are in high concentrations in the separator water from the plant and can potentially be used as markers for the level of influence of the waste water on the ground water and natural springs in the Nesjavellir area. On its way to the lakeside springs the separator water mixes with the “unusable” cooling water and to some extent with cold ground water. This dilutes the concentration of the above chemicals. The permeable bedrock may also retain some of the chemicals (e.g. the SiO_2). Despite this a clear chemical signal is seen from the cold water well at Grámelur in the east to Varmagjá in the west, the signal being consistently highest in Eldvík (Figure 2.2) (VGK, 2000). In 2001 the production of electricity was increased by 50%. This lead to a 100% average increase in discharge of cooling water while discharged separator water increased by approximately 25%. This could mean a further dilution of geothermal signal chemicals in the ground water.

In the summer of 2000 arsenic concentration was slightly above the recommended 5.0 µg/l Canadian water quality guidelines for protection of aquatic life (CCME, 2001) in the Eldvík spring (5,97 µg/l). Arsenic exists as arsenate (As^{V}) and arsenite (As^{III}). In geothermal water, arsenic exists as arsenate, which is a thermodynamically stable form of arsenic and less toxic (Webster and Timperly, 1995). This however could be reduced to As^{III} by blue-green algae (cyano-bacteria) in the lake springs (Webster and Timperly, 1995). Its high level makes it significant due to its toxicity to aquatic organisms that are influenced by temperature, pH, organic matter content

(Jonnalagadda and Prasada Rao, 1993) and phosphates (Ólafsson, 1992). Other trace elements in separator water and lake springs were below the recommended water quality guidelines for protection of aquatic life. Aluminium was first measured in the year 2000 (VGK, 2000). The concentration in the separator water is 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 protection of aquatic life (CCME, 2001). Such levels are toxic though toxicity depends much on the form of Al in solution, with Al^{+3} being most toxic. In natural waters Al are generally quite low, usually less than 100 µg/l. however at lower water pH (less than 4) and higher pH (more than 9), Al concentration be much higher making the water toxic to aquatic life. The concentration was also above the lowest biological risk level (LBRL) Swedish criteria of 80 µg/l of Al for protection of fish such as brown trout, *Salmo trutta* (Löfgren and Lydersen, 2002).

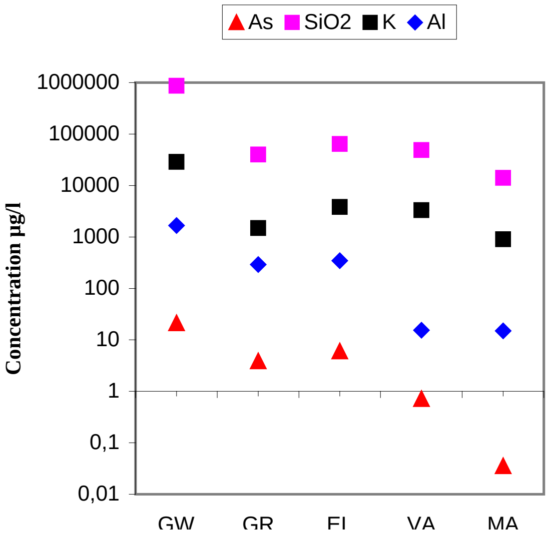

Figure 3: Concentrations of "signal elements" SiO_2, K, Al and As in separator water from the power plant (GW), cooling water well at Grámelur (GR), in two affected springs, Eldvík (EL) and Varmagjá (VA), and an unaffected spring, Markagjá (MA). Based on samples taken in May 2000 (VGK, 2000).

2.3 Trace metals in biological samples

In general the levels of the measured trace elements were low in the biological samples and there was no difference between the geothermally affected site, Varmagja in Thorsteinsvik, and the control site, Vatnskot. Apart from measurement errors the variation seen must be attributed to natural background variation (Snorrason and Jónsson, 2000).

The only trace element showing significant variations in time was Pb (Figure 4. In 2000 Pb in lake sediment at Vatnskot was 42 µg/g (dry weight basis), which is about 20 times the background level. This is above the interim sediment quality guidelines (ISQGs) (ISQG) but within the probable effect level (PEL) according to the Canadian sediment quality guidelines for protection of aquatic life (CCME, 2001). Pb vas also found in at elevated concentratoions in samples of *Myrophyllum alterniflora* in Vatnskot in 1995 and 2000 (about 170 and 10 times the background level, respectively). Such deviations from a background level are likely due to point sources of lead in the form of lead weights and strings of fishing gear that has been lost or left lying.

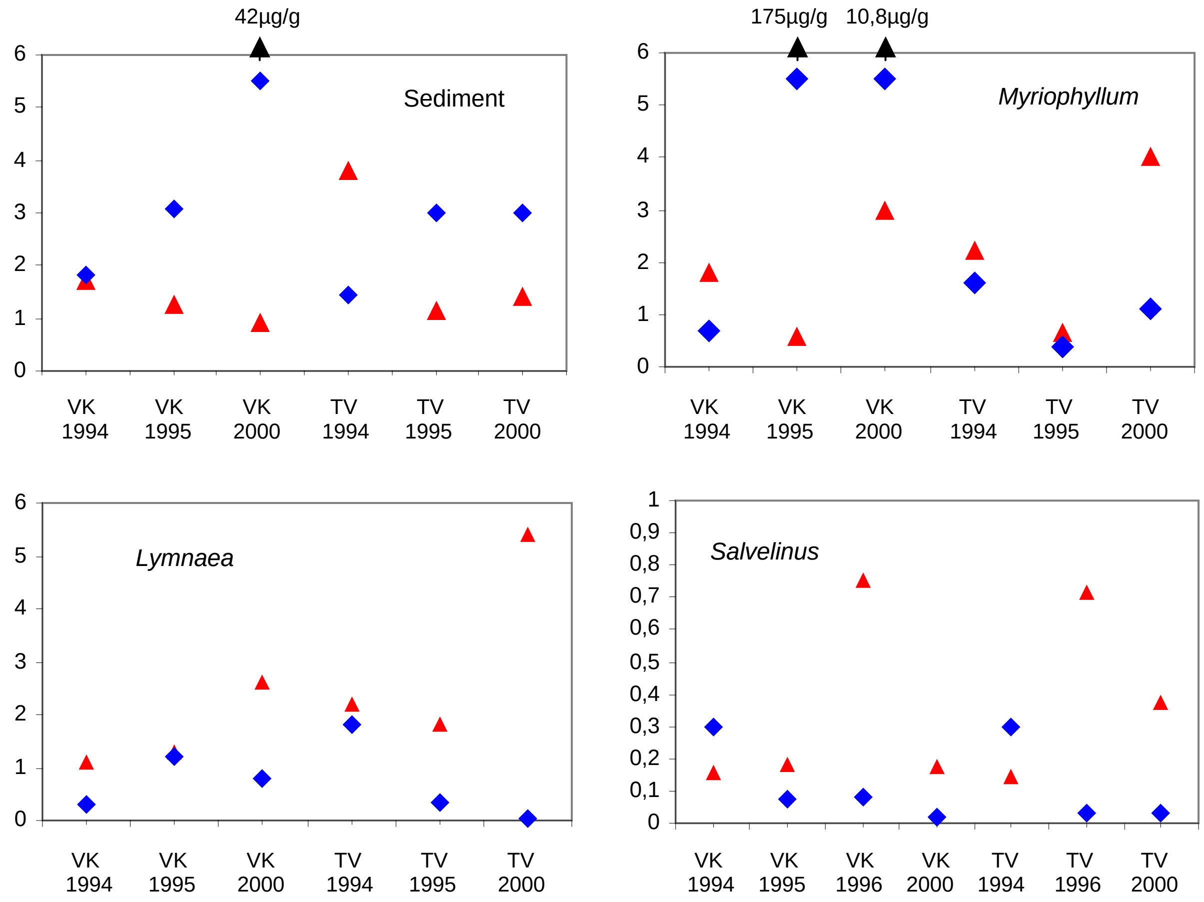

Figure 4: Average concentrations (µg/g) of As (triangle) and Pb (diamond) in biological samples at Varmagjá in Thorsteinsvik (TV) and Vatnskot (VK, control station at the north shore of Thingvallavatn). The samples represent different throphic levels; lake sediment; an aquatic plant, *Myriophyllum*; a gastropod snail, *Lymnaea* peregre; a fish, *Salvelinus alpinus*. Concentrations in the fish samples are on wet weight basis. Concentrations in the other samples are on dry weight basis. (↑) High Pb-concentrations, data points in parentheses are set at the detection limit for the method used this year but are most likely to be lower (data from Snorrasson and Jónsson, 2000).

3 Conclusions

After the start of electricity generation at the Nesjavellir Power Plant increased discharge of hot water has lead to a marked temperature rise, - from 13–20°C, of geothermally affected lakeside springs. Concentration levels of measured solutes in Nesjavellir geothermal power plant wastewater and Thingvallavatn shoreline springs are mostly within the acceptable international environmental quality guidelines on protection of watercourses and lakes. From an ecotoxicological point of view, arsenic and aluminium seem to be the only constituents of the geothermal effluents from the Nesjavellir Power Plant that could potentially affect the ecosystem of Thingvallavatn. In the year 2000 arsenic concentration in the Eldvík spring water was slightly above the recommended 5.0 µg/l Canadian guideline limit for protection of aquatic life. The level of aluminium was several times higher than the recommended 5-100 µg/l Canadian water quality guidelines for protection of aquatic life (CCME, 2001). Efficient, wind driven mixing of spring water with lake water (Snorrason, 1982) precludes any large-scale effects of elevated temperature and chemical concentrations in affected springs. Hence, any biological effects, are expected to be strictly localized. Despite of this, the high conservational value of Thingvallavatn and its surroundings calls for stringent wastewater management. The amount, temperature and chemical composition of wastewater and potentially affected lakeside springs should be closely monitored. The local biota at spring sites should be assessed for effects of increased temperature and chemical effects. To minimize local effects deep reinjection of geothermal wastewater and further cooling of the turbine coolant is recommended.

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