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CHEMICAL ASSESSMENT OF ICELANDIC GEOTHERMAL FLUIDS FOR DIRECT APPLICATIONS

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ABSTRACT

This research deals with the chemical assessment of geothermal fluids for direct applications from low-temperature geothermal fields in Iceland. In addition, geothermal brine, geothermally heated groundwater, cold spring water, seawater or a mixture of two of these different fluids were evaluated for direct use or for use via a heat exchanger for space heating, balneotherapy, agriculture, aquaculture, and industrial applications. In order to fulfil the objectives, all the water samples were analysed and compared with the standards and guidelines for physicochemical parameters as well as for trace elements. The results revealed that, in some cases, there is the possibility of scaling and corrosion from low-temperature geothermal waters, brine and heated groundwater. The risk of amorphous silica scaling was observed only for brine water and the risk of magnesium silicate scaling was observed both for low-temperature geothermal water and heated groundwater. No scaling is likely to occur due to the mixing of brine water from Svartsengi and cold groundwater from Lágar at 40°C and 15°C, which are the ideal temperatures for balneotherapy and agriculture. Geothermal brine is effective for balneotherapeutic applications. A mixture of 37% brine and 63% cold groundwater at a temperature of 40°C also appears to be effective for this purpose as is sea water if it is heated to a temperature of 40°C. Some geothermal waters are permissible for agricultural application with respect to EC, TDS, sodium percent, SAR, boron toxicity and trace elements. Brine and sea water should not be used for this purpose. Dissolved H_2S gas in geothermal fluids was identified as a major limiting factor for aquaculture applications, even after mixing with 90% cold groundwater. Geothermal fluids that contain H_2S are not suitable for food processing industries because of their taste and odour and sometimes because of high concentrations of trace elements such as fluoride and boron. Cold spring waters are suitable for this purpose.

1. INTRODUCTION

The rapid acceleration of geothermal development in recent years has coincided with growing public awareness about potential problems connected to direct exploitation of geothermal fluids as well as with health issues. Geothermal fluids contain different concentrations of a wide variety of dissolved constituents. The amount and nature of the dissolved chemical species in geothermal fluids are function of temperature and the local geology. In addition to providing beneficial minerals, geothermal fluids may give rise to undesirable or toxic properties through the deficiency or excess of various elements. Use of geothermal fluids must be subject to certain guidelines prescribed for different physicochemical parameters for different direct applications such as space heating, balneotherapy, agriculture, aquaculture, and industrial uses.

The principal direct use of geothermal fluids in Iceland is for space heating. However, during utilization, the space heating systems sometimes face problems such as corrosion and scaling in the supply pipes. Scaling and the possibility of corrosion can be predicted by using the mineral equilibria and chemistry. For geothermal water, it is important to evaluate the chemical characteristics, not only for different applications but also when making decisions on the selection of proper reinjection sites to avoid affecting the quality of the groundwater. Water that people drink to slake their thirst may also supply major and especially minor or trace elements which are nutritionally essential to good health (Keller, 1978). However, it is most important to realise that whatever the element, it is the dosage that is critical, as even essential elements can cause ill health if taken in excessive amounts.

On the other hand, high dissolved solid and gas concentrations in geothermal water, termed mineral water, are thought to give certain health benefits (Skapare, 2010). From a balneological point of view, trace elements could have pharmacological benefits (Manuel, 2010). In agriculture, a number of trace elements known as micronutrients are essential to plants, albeit in very small quantities. Often their deficiency can cause devastating effects (Gandouzi, 1999). However, in most irrigation situations, the primary water quality concern is the salinity. An excess or deficiency of dissolved salts and trace elements such as micronutrients in water can limit its use for agricultural applications. According to available guidelines, some elements are essential to fish growth while others are very toxic. Temperature, pH, dissolved oxygen, hydrogen sulphide, ammonia and carbon dioxides are the most frequently recorded physicochemical components that may cause harm in aquaculture (Svobodová, 1993). Trace elements can be concentrated in fish tissues to a level that may be unsafe for human consumption (Roberts, 1975). Even some chemical characteristics of water might be suitable for one species of fish but not for others. Therefore, the aim of this work is to study the chemical characteristics of geothermal fluids in order to evaluate their suitability for major direct applications.

2. DIRECT APPLICATIONS OF GEOTHERMAL FLUIDS

Geothermal energy is a renewable, clean and cost effective energy, an alternative to conventional fuels for heat and power generation. The source of the geothermal energy is the earth´s internal heat. Electric power generation and direct utilization are two applications of geothermal energy in Iceland. Direct application of geothermal fluids is one of the most common, versatile and oldest forms of utilization. It usually uses geothermal energy with temperatures below 150°C (Lund, 2007). In Iceland, the major area of direct utilization for space heating includes district heating systems; swimming, bathing and balneology; agricultural applications such as greenhouse and soil heating; aquaculture applications such as pond and raceway water heating; and industrial processes such as mineral extraction, food and grain drying. Other applications include ice melting in the winter season.

The use of geothermal energy for space heating in Iceland was initiated in 1907 when a farmer ran a concrete pipe from a hot spring that led steam to his house. It started on a small scale in Reykjavík in 1930. Now, space heating is the principal direct application of geothermal energy in Iceland. It distributes geothermal water through piping systems to homes and other buildings. It is estimated that 89% of all houses in the country have access to geothermal or geothermally heated water (Ragnarsson, 2010) and about 90% of the country´s inhabitants are connected to a district heating service (Gunnlaugsson, 2004). About 30 separate geothermal district heating systems are operated in towns and villages and an additional 200 smaller systems in rural areas.

Geothermal water has been used for bathing for thousands of years. In balneology, the practice of using natural mineral water for the cure of diseases and ailments has a long history. The important factors to be considered in balneology are the temperature of the water and the mineral content. In this modern age, geothermal swimming pools and hot baths have been constructed in several places around the world, including Iceland. Swimming pools and hot baths are typically supplied with warm water direct from a low-temperature geothermal system. Among the approximately 163 swimming centres in Iceland, 134 use geothermal water (Orkustofnun, 2010). These are mainly for recreational and social purposes. Swimming has been gaining in popularity in Iceland and the attendance for swimming increases year by year.

The main uses of geothermal energy in agriculture are greenhouse heating, soil disinfection, soil heating and drying crops. Geothermal heating of greenhouses started in Iceland in 1924. Before that, warm soil had been used for growing potatoes and vegetables. A greenhouse produces different types of vegetables (tomatoes, cucumbers, peppers, herbs, and berries), flowers, potted plants and even bananas for the domestic market. Soil heating has been used since the 1970s when the systems for soil heating became economical and applicable for modern cultivation with the appearance of plastic pipeline materials (Gunnlaugsson, et al., 2003). Soil disinfection uses only a minor part of the total energy used in agriculture.

The main use of geothermal fluid in aquaculture is to adjust the water to a suitable temperature for fish growth. Geothermal heat allows better control of pond temperature, thus optimising growth. Geothermally heated aquaculture ponds are common in Iceland. In Iceland, fish farming is mainly practised in shore-based plants, although some plants are on dry land. Geothermal water, commonly at 20-50°C, is used to heat fresh water directly or in heat exchangers. In 2008, there were about 50 registered fish farms in Iceland (Ragnarsson, 2010).

The uses of geothermal fluid for industrial processes in Iceland are very diverse. It has been used for drying fish, seaweed, hardwood, wool washing and cement blocks, retreading car tires, baking bread etc. However, the most important water consuming sectors are food processing industries such as for drying food, salt and grain and for the dairy, beverage, fat and margarine industries. Commercial liquid carbon dioxide is also produced from geothermal fluid. Next to the geothermal power plant in Svartsengi, a plant produces methanol from CO_2 gas exhausted by the power plant. Several other industrial processes have been operated in the past such as a diatomite plant and salt production from geothermal brine.

3. DESCRIPTION OF THE SAMPLE LOCATIONS AND FLUID CHEMISTRY

The chemical composition of 14 different water samples was taken from the ÍSOR database for evaluation of direct applications. Among them, 6 water samples are from low-temperature geothermal waters, 2 are from geothermal brine, 1 from geothermally heated groundwater, 3 from cold groundwater and 2 from sea water. The proximity of cities, communities, existing and potential direct applications and municipal water supply systems were considered for the sample selection. The reasons behind the selection of cold water sources are due to cold water being heated with geothermal water by means of a heat exchanger, and sometimes by mixing with geothermal water for different direct applications. Figure 1 shows the sample locations and Table 1 gives a summary of all the samples.

3.1 Reykir, Reykjabraut, Hrolleifsdalur, Ósbrekka, Laugar, and Urridavatn low-temperature geothermal areas

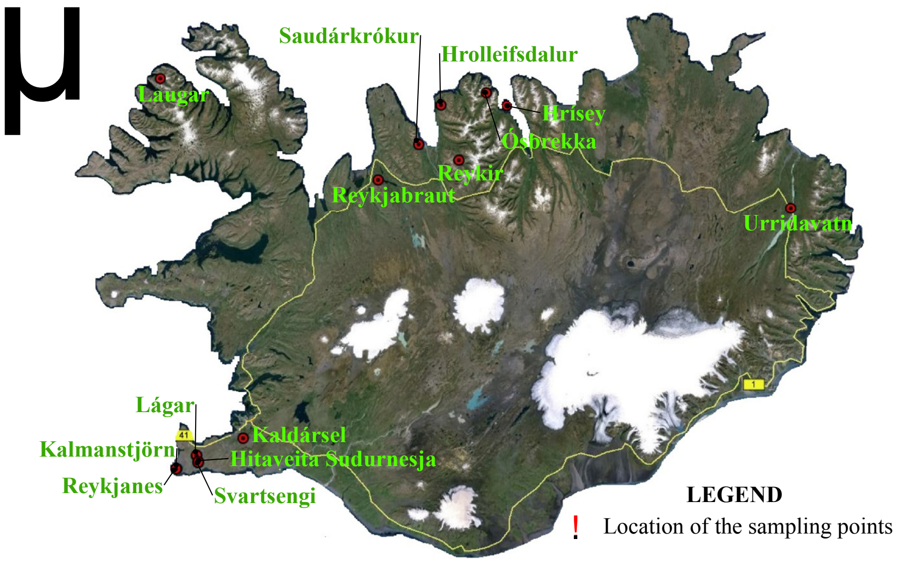

FIGURE 1: Map of Iceland showing the locations of all samples

TABLE 1: Description of all the water samples

No.	Location name	Location type	Sample type
1.	Laugar	Borehole	Low-temperature
2.	Urridavatn	Borehole	Low-temperature
3.	Reykjabraut	Borehole	Low-temperature
4.	Reykir	Borehole	Low-temperature
5.	Ósbrekka	Borehole	Low-temperature
6.	Hrolleifsdalur	Borehole	Low-temperature
7.	Reykjanes	Pipeline	Brine
8.	Svartsengi	Pipeline	Brine
9.	HS Orka	Pipeline	Heated
10.	Lágar	Spring	Cold
11.	Kaldársel	Spring	Cold
12.	Hrísey	Borehole	Cold
13.	Kalmanstjörn	Borehole	Seawater
14.	Saudárkrókur	Pipeline	Seawater

The Reykir (in Hjaltadalur), Reykjabraut and Hrolleifsdalur low-temperature geothermal areas are located in northwest Iceland, in an area which is entirely composed of Tertiary basalt, characterised by high mountains, deep fjords and valleys. Several geological studies have shown that most of the formations consist of a number of tholeiitic lava flows of varying thickness interbedded with soil layers, several sedimentary horizons and a number of extinct volcanic systems. The geothermal waters in these areas are used for space heating, greenhouse heating, bathing and swimming. Ósbrekka is situated within the Laugarengi low-temperature geothermal field at Ólafsfjördur in NE-Iceland. Several geological maps have shown that Tertiary basaltic layers extend deep into the formation. There are sedimentary layers and scoria beds between the lava layers with horizontal intrusions (Sbterev, 1994). The water is used for space heating and swimming. Laugar is situated southeast of the town of Sudureyri within the West fjords peninsula in northwest Iceland. The volcanic rocks there are also Tertiary, but relatively older than the rest of the country. The lack of flat lowlands in this area makes it unsuitable for agriculture activities, except for sheep farming, but fishing is vital for the local economy. Three exploration wells and two production wells have been drilled in the Laugar field for district heating, swimming and fish drying purposes. The Urridavatn geothermal field is a low-temperature geothermal field located in Tertiary formations in east Iceland, outside the neo-volcanic zone below Lake Urridavatn. It is situated on the flanks of active volcanic zones. Many faults pass through the area, actually part of a graben (Haddadin, 1995). The production of hot water from the field started in 1980; the water is utilized for district heating service in the towns of Egilsstadir and Fellabaer.

3.2 Reykjanes and Svartsengi high-temperature geothermal areas

The Reykjanes high-temperature geothermal field is located at the southwest tip of the Reykjanes peninsula. This peninsula is elongated, oriented in forming an oblique segment of the constructive plate margin. The formation history of this peninsula can be explained by the geodynamic processes which are responsible for an anomalously large extrusion rate of magma to its maximum just south of central Iceland (Jakobsson, et al., 1978). It is characterised by extensive postglacial lava fields and steep-sided mountains and ridges of pillow lavas, pillow breccias and hyaloclastites which protrude through the lava fields. The exploited geothermal system is hosted by basaltic rocks, sub-glacial hyaloclastites, breccias and pillow lavas as well as tuffaceous sediments. The aquifer is liquid dominated but has developed a steam cap since production started at the 100 MWe Reykjanes power plant in 2006. The geothermal brine has seawater salinity and is believed to have originated as seawater. The sample was collected from the effluent channel to the ocean and is a mixture of geothermal brine (~10%), condensate (~10%) and seawater coolant (~80%) (Hardardóttir and Óskarsson, 2012). The Svartsengi high-temperature geothermal field is associated with an active rift zone on the Reykjanes peninsula in southwest Iceland. The accumulated rocks are of basaltic composition and formed in two different environments: lava flow sequences erupted from volcanoes during interglacial periods, and the hyaloclastite formation erupted under ice during glacial periods (Franzson, 1983). The boundaries of this field are thought to follow the boundaries of the westernmost fissure swarm on the Reykjanes peninsula and extend to the southwest in connection with the Eldvörp geothermal area. The Svartsengi system is liquid dominated and also has a steam cap. The salinity of the geothermal brine is about 2/3 that of seawater salinity. The sample was collected from the brine pipeline to the reinjection well and is a mixture of geothermal brine (~50%), condensate and cooling water (Gudfinnsson and Óskarsson, 2012).

3.3 Lágar, Kaldársel and Hrísey cold groundwater sample areas

Kaldársel is located in the Hafnarfjördur area in southwest Iceland. This spring is located where tectonic fissures cross low hills of pillow lava breccia, and is most likely the main aquifer (Sigbjarnarson, 1982). This area is protected as it provides the Hafnarfjördur municipal water supply for drinking purposes. Lágar is situated about 5 km northwest of the Svartsengi power plant. In 1976, Hitaveita Sudurnesja Ltd. (now HS Orka) constructed the first phase of six of its existing cogeneration power plants at Svartsengi on the Reykjanes peninsula. The plant uses geothermal steam for power generation and produces hot water by heating cold water from Lágar with geothermal water in thermal exchangers and by injecting geothermal steam. The hot water is used for space heating, swimming and industrial purposes. The cold water from Lágar is also used for drinking water in the neighbouring communities of Grindavík and Reykjanesbaer. The water is pumped from a freshwater lens that floats atop a more saline water body (Gudfinnsson and Óskarssons, 2012). Hrísey is an island in the Eyjafjördur fjord in N-Iceland, and is a remnant of an old plateau of lavas that covered the area before the fjord was carved out by glaciers on either side of the island. The cold water comes from a 130 m deep well that was drilled in 1987 and produces from a fresh water layer atop more saline water. The well supplies the hamlet on the island with drinking water.

3.4 Kalmanstjörn and Saudárkrókur seawater sample areas

The seawater wells at Kalmanstjörn are situated in the Reykjanes peninsula, a few km north of the Reykjanes power plant. These wells are rather shallow (50-60 m deep), drilled very near the coast, and draw seawater from the surrounding lava and hyaloclastite formations. The water is used as cooling water for the Reykjanes power plant. Saudárkrókur is the largest town in northwest Iceland and the second largest town on the north coast of Iceland, with a population of about 2600. The seawater pipeline from which this sample is drawn is used by a local shrimp factory.

3.5 Fluid chemistry

The chemical composition of geothermal water from low-temperature geothermal boreholes, geothermal brines, heated water used for district heating pipelines, and cold water from springs and the sea, used in this report is given in Appendix I. The concentration of all elements is in mg/l. Geothermal waters from Laugar, Urridavatn, Reykjabraut, Reykir, Ósbrekka, and Hrolleifsdalur have been characterised as follows: low temperature (61.9 to 88.2°C), fresh (185 to 596 mg/l TDS), alkaline (9.29 to 10.22 of pH), and soft (6.3 to 51.8 mg/l of total hardness or TH as $CaCO_3$), and contains Ca^{2+} (2.5 to 20.5 mg/l), SO_4^{2-} (6.01 to 149 mg/l), HCO_3^- (9.8 to 27.7 mg/l); Na^+(35.5 to 153 mg/l) and Cl^- (8.4 to 191mg/l). The relative ion concentration level for cations is the same in all the geothermal water samples, namely $Na^+ > Ca^{2+} > K^+ > Mg^{2+}$. $Cl^-$is the predominant anion for Laugar, Urridavatn and Hrolleifsdalur, SO_4^{2-} is the predominant anion for Reykjabraut, and $HCO_3^-$is the predominant anion for Ósbrekka. Brine waters from Reykjanes and Svartsengi have been characterised as follows: salty (27600 and 12958 mg/l of TDS), neutral (7.76 and 6.75 of pH) and very hard (4860 and 1540 mg/l THas $CaCO_3$), contains Ca^{+2} (526 and 617mg/l), SO_4^{2-} (1790 and 15.2 mg/l), HCO_3^- (73.5 and 10.9 mg/l), Na^+(8650 and 3940 mg/l) and Cl^- (15810 and 7510 mg/l). The relative ion concentration level for cations is $Na^+ > Mg^{2+} > Ca^{2+} > K^+$ for Reykjanes, and $Na^+ > Ca^{2+} > K^+ > Mg^{2+}$ for Svartsengi. For anions, it is $Cl^- > SO_4^{2-} > HCO_3^-$ for both. Sea water from Saudárkrókur and Kalmanstjörn has been characterised as follows: cold (8.6 and 8.3°C), salty (15400 and 30682 mg/l of TDS), slightly alkaline (8.6 and 8.3 of pH) and very hard (6540 and 5200 mg/l of TH as $CaCO_3$), contains Ca^{2+} (728 and 341mg/l), SO_4^{2-}(2060 and 2240 mg/l), HCO_3^- (10.8 and 113.7 mg/l); Na^+(8260 and 8720 mg/l) and Cl^- (16350 and 16190 mg/l). The relative ion concentration levels for cations and anions are the same in both sea water samples, which is $Na^+ > Mg^{2+} > Ca^{2+} > K^+$ and $Cl^- > SO_4^{2-} > HCO_3^-$. Cold groundwater from Kaldársel, Hrísey and Lágar has been characterised as follows: cold (3.4 to 5.7°C), fresh (88 to 178 mg/l of TDS), neutral to alkaline (7.02 to 8.94 of pH) and soft (20 to 57.7 mg/l of TH as $CaCO_3$), contains Ca^{2+} (24.9 to 9.08 mg/l), SO_4^{2-} (2.4 to 10.4 mg/l), HCO_3^- (28.3 to 42.3 mg/l); Na^+(9.39 to 39.5 mg/l) and Cl^- (8.4 to 80.4 mg/l). The relative ion concentration level for cations is the same in all the cold water samples, namely; $Na^+ > Ca^{2+} > Mg^{2+} > K^+$. HCO_3^- is the predominant anion for Kaldársel and Hrísey, whereas Cl^- is the predominant anion for the Lágar water sample. The heated water for the district heating system of Hitaveita Sudurnesja is characterised as follows: low temperature (70°C), fresh (165 mg/l of TDS), alkaline (9.01 of pH) and soft (47.8 mg/l of TH as $CaCO_3$), contains Ca^{2+} (7.89 mg/l), SO_4^{2-} (10.2 mg/l), HCO_3^- (13.9 mg/l), Na^+(32.5 mg/l) and Cl^- (74.7 mg/l). The relative ion concentration levels for cations and anions are $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ and $Cl^- > HCO_3^- > SO_4^{2-}$. This water actually comes from the Lágar cold groundwater. The chemical composition did not change much after being heated except for the pH value, which increased from 7.46 to 9.01, due to degassing of CO_2, which decreased from 13.5 to 10.5 mg/l.

The chloride-sulphate-bicarbonate ternary diagram was used for distinguishing between the different types of water described by Giggenbach (1991). According to Giggenbach, chloride rich waters are general found near the up-flow zone of geothermal systems. High sulphate steam-heated waters are generally encountered over the more elevated parts of a field. The degree of separation between data points from high chloride and bicarbonate waters may give an idea of the relative degree of interaction of the carbon dioxide charge of the fluid at lower temperatures, and of the bicarbonate concentrations, which increase with time and the distance travelled underground. The $Cl–SO_4–HCO_3$ ternary plot (Figure 2) shows that the geothermal waters from Laugar and Hrolleifsdalur are chloride waters, and the waters from Urridavatn and Reykir are mixed chloride-sulphate and chloride-sulphate-bicarbonate waters, respectively. Geothermal water from Ósbrekka tends toward the bicarbonate corner, possibly suggesting a peripheral nature of thermal water, whereas geothermal water from Reykjabraut is classified as a sulphate water. Brine waters from Reykjanes and Svartsengi, sea waters from Saudárkrókur and Kalmanstjörn, and heated water from Hitaveita Sudurnesja, plot close to the chloride corner and close to the field of mature geothermal water although that is certainly not the case. Water from the cold spring in Lágar also plots close to mature geothermal water, but the other two samples from Kaldársel and Hrísey plot in the peripheral water of bicarbonate type. The difference between the Lágar water and the Kaldársel and Hrísey water is most likely due to slight mixing with the underlying seawater in Lágar.

The geothermal waters from Laugar, Urridavatn, Reykjabraut, Reykir, Ósbrekka, and Hrolleifsdalur appear to be in equilibrium at temperatures less than 100° to 120°C, according to the Na–K–Mg ternary plot of Giggenbach (1988) (Figure 3). They all fall within the full equilibrium field. The reservoir temperatures indicated by the calculated chalcedony geothermometer are close to the measured temperatures but the sodium-potassium geothermometer gives considerably lower values. One brine sample from Svartsengi falls into the full equilibrium field; the other one from Reykjanes, along with the sea water samples, falls under the partially equilibrated and mixed water field. All spring water from Kaldársel, Hrísey and Lágar and the heated water from Hitaveita Sudurnesja form a group at the Mg corner, which means they are immature waters. This is not unexpected as these are groundwater samples, not geothermal water.

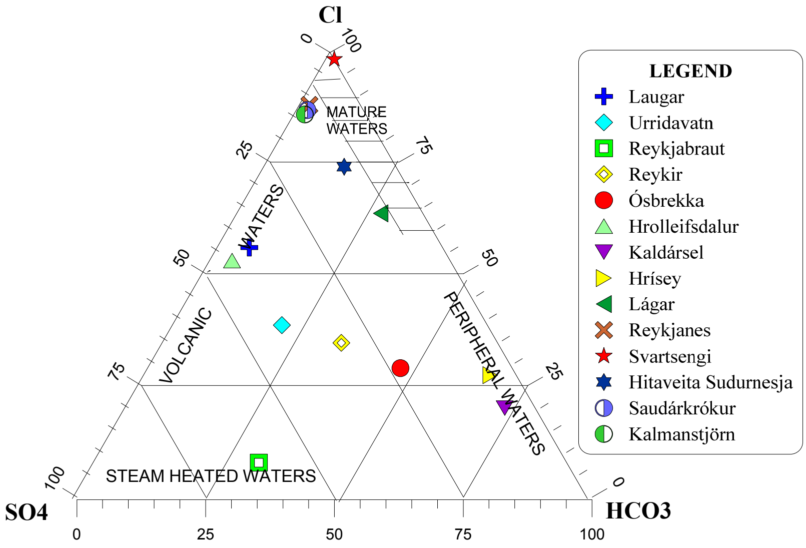

FIGURE 2: Cl–SO_4–HCO_3 ternary plot of all the water samples

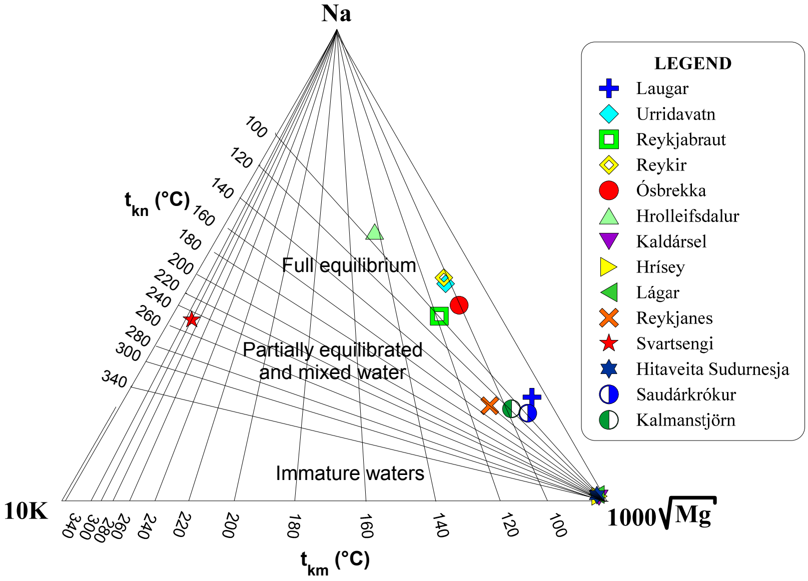

FIGURE 3: Na–K–Mg ternary plot of all the water samples

4. CHEMICAL ASSESSMENT FOR SPACE HEATING APPLICATIONS

The most important direct applications of geothermal fluid in Iceland is space heating which includes district heating systems, greenhouse and soil heating, heating of swimming pools, drying of fish, vegetables and food products, and other industrial purposes where direct heat applications are necessary. Almost 90% of all houses in Iceland are currently heated by geothermal water. Low-temperature geothermal fields are the main source of water for this utilization, although geothermally heated groundwater is also common. Corrosion and scaling problems have occurred in some cases. Sometimes, scaling and corrosion processes are interactive and complex. There is no single index for the interpretation of these processes.

Corrosion has been experienced in association with water containing dissolved oxygen at temperatures less than 80°C, and with carbon dioxide in water below 100°C with high concentrations of chloride. An inadvertent intrusion of oxygen into geothermal water may lead to greatly accelerated corrosion. An increase of dissolved oxygen can reduce hydrogen sulphide (H_2S) or vice versa. For this reason, geothermal steam is usually injected into heated groundwater, causing H_2S in the steam to remove the dissolved oxygen and, thus, protect pipelines from corrosion. The primary effects of carbon dioxide in geothermal systems involve carbonate species and pH changes. Waters with pH below 6.5 are likely to be severely or extremely corrosive to steel and moderately corrosive to alloys such as brass. Theoretically, a high uniform corrosion rate is due to the presence of carbon dioxide and sodium chloride up to about 80°C. There is significant localized damage, at least to iron and steel, when the carbon dioxide concentration exceeds 20 mg/l. Chloride ions cause the local breakdown of passive films and increase the solubility of iron in geothermal water by forming highly soluble complexes with the ferric ion (Elguedri, 1999).

Icelandic geothermal water is normally not corrosive due to its low dissolved oxygen level (<0.003 mg/l) and high pH value (>9) (Richter et al., 2007). All the geothermal water samples from Laugar, Urridavatn, Reykjabraut, Reykir, Ósbrekka, and Hrolleifsdalur and the district heating water from Hitaveita Sudurnesja were high in pH value (>9) and low dissolved oxygen concentrations (<0.001 mg/l), except for the samples from Laugar and Ósbrekka, with 0.10 and 0.06 mg/l of dissolved oxygen, respectively. Problems due to corrosion have been encountered in the communities that use water from those two fields. The pH values in brine water from Reykjanes and Svartsengi are 7.7 and 6.7, respectively, which are suitable values, but the CO_2 content is higher in Reykjanes with a concentration of 65.8 mg/l. Chloride concentrations are also very high in the samples from Reykjanes and Svartsengi. The CO_2 value in the samples from Reykjabraut is 21.2 mg/l, which is slightly higher than the damaging mark of 20 mg/l; all other samples have lower values, excluding cold waters which were not considered for corrosion assessment.

Troublesome scaling can be encountered during the utilization of geothermal fluid, although in most cases there are ways to control it. The most common precipitates from low-temperature geothermal fluids are calcium carbonate ($CaCO_3$), amorphous silica (SiO_2) and magnesium silicate ($MgSiO_3 \cdot H_2O$). The solubility of calcite increases with decreasing temperature. Therefore, cooling of geothermal water does not cause calcite scaling. But if the water boils or mixes with saline water, calcite scales may form. The mixing of the inflow from two or more different sources, with different chemistries and temperature, often affects the solubility of calcite towards super saturation. In this case, equilibrium may occur, again precipitating calcite.

Deposition of magnesium silicate may form when fresh water is mixed with geothermal water. The groundwater is high in magnesium compared to geothermal water which, on the other hand, is high in silica. The mixing of geothermal water with fresh groundwater results in high magnesium concentrations. The solubility of magnesium silicates is very low at high pH values. Therefore, high magnesium and high pH values are favourable for magnesium silicate scaling. To determine the scaling potential, the saturation indices (log Q/K) were calculated using the computer program WATCH (Bjarnason, 1994) for the measured temperature, and by cooling the samples down to 25°C from the measured temperature in 5°C intervals. The speciation technique was only applied to the hot water samples.

Saturation indices were calculated for the amorphous silica, calcite and magnesium silicate (chrysotile) minerals. A positive saturation index for a mineral means that the solution is super saturated with respect to that particular mineral and, theoretically, this means it would start to precipitate. However, production data for low-temperature geothermal waters in Iceland show that calcite normally does not instantaneously precipitate until the log Q/K value reaches more than about 0.40 (Bai Liping, 1991).

Calculated calcite saturation indices vs. temperature are shown in Figure 4. The figure shows that there does not appear to be a risk of calcite scaling in any of the geothermal waters from Laugar, Urridavatn, Reykjabraut, Reykir, Ósbrekka, and Hrolleifsdalur or the heated water from Hitaveita Sudurnesja (HS) or the brine water from Svartsengi. In the sample from Reykjanes, the saturation index of calcite was higher than the 0.32 value at a temperature above 50°C. For a saturation index between 0.32 and 0.50, calcite scaling may or may not occur, depending on other factors (Bai Liping, 1991). On the other hand, supersaturation of magnesium silicate (chrysotile) was calculated in the water samples from Laugar, Reykir, Ósbrekka, Reykjanes, and HS above 25°C, and from Reykjabraut only above 60°C (Figure 5). This may cause scaling. The geothermal brine water sample from Svartsengi showed a risk of amorphous silica scaling at temperatures below about 73°C (Figure 6).

To observe the scaling potential after mixing geothermal water with cold water, the mixing of cold groundwater (5.7°C) from Lágar and hot geothermal brine water (99°C) from nearby Svartsengi power plant was calculated. The fractions of the cold water in the mixture were 63% and 90%, intended to yield mixture temperatures of 40 and 15°C, which are optimum temperatures for balneotherapeutic and aquaculture applications, respectively. The mixing ratios were calculated using Equation 1. The chemical composition of the mixed water was determined assuming a pH value of 6.75, which is the value of the Svartsengi sample, due to its higher buffer capacity. The calculated saturation indices (log Q/K) for amorphous silica, calcite and magnesium silicate (chrysotile) of mixed water were calculated using the WATCH program. At 40°C, the log(Q/K) for amorphous silica, calcite and chrysotile were -0.17, -1.14 and -7.00, respectively, all negative. At 15°C, the log(Q/K) values were -0.39, -18.56 and -9.88, respectively, which are also negative. Therefore, there should be no risk of amorphous silica, calcium carbonate or magnesium silicate precipitation in this mixed water.

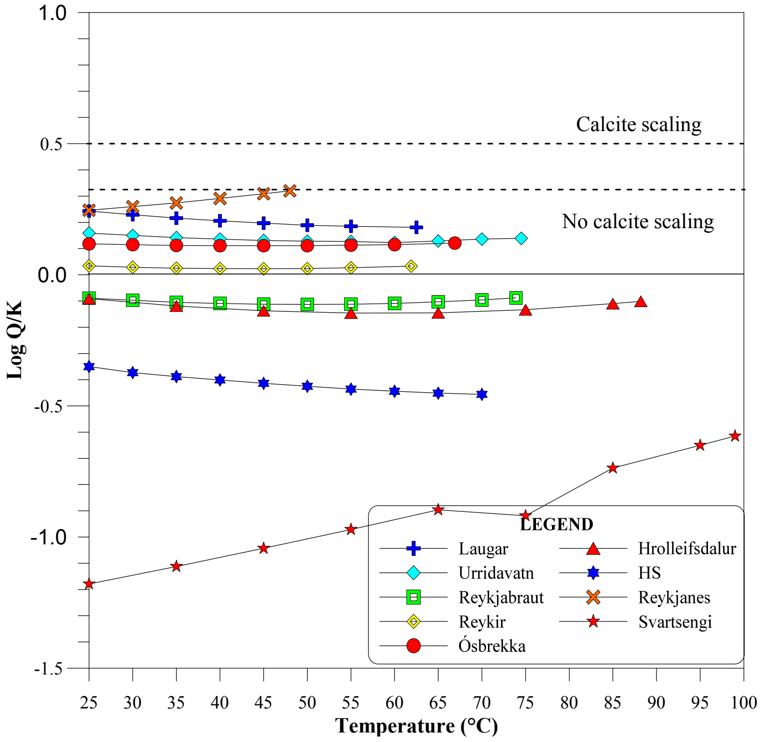

FIGURE 4: Calcite saturation index

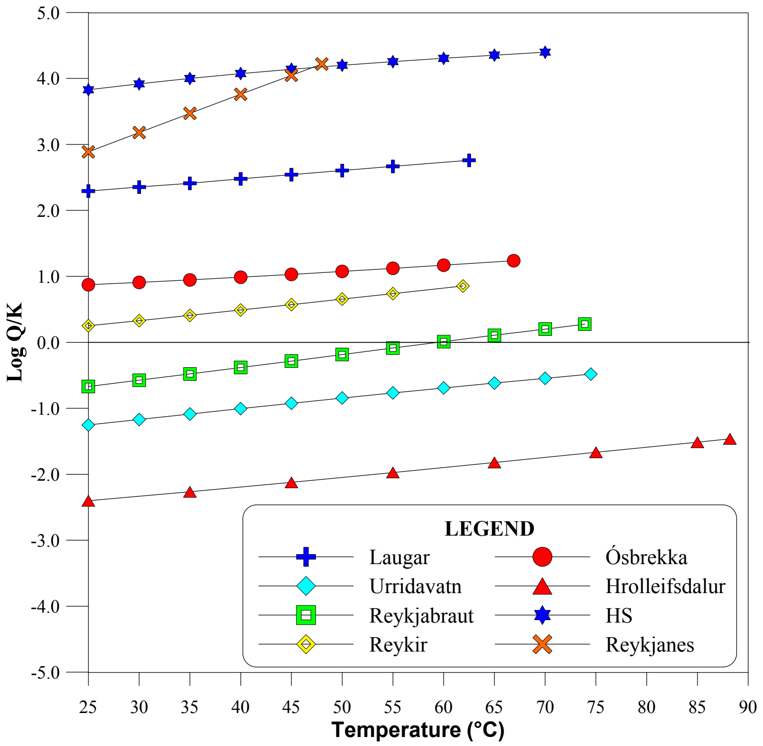

FIGURE 5: Magnesium silicate (chrysotile) saturation index

$$X \cdot 5.7 + (1 - X) \cdot 99 = 40 \qquad (1)$$

or,

$$X = 63\,\% \qquad (2)$$

where X = Cold water fraction.

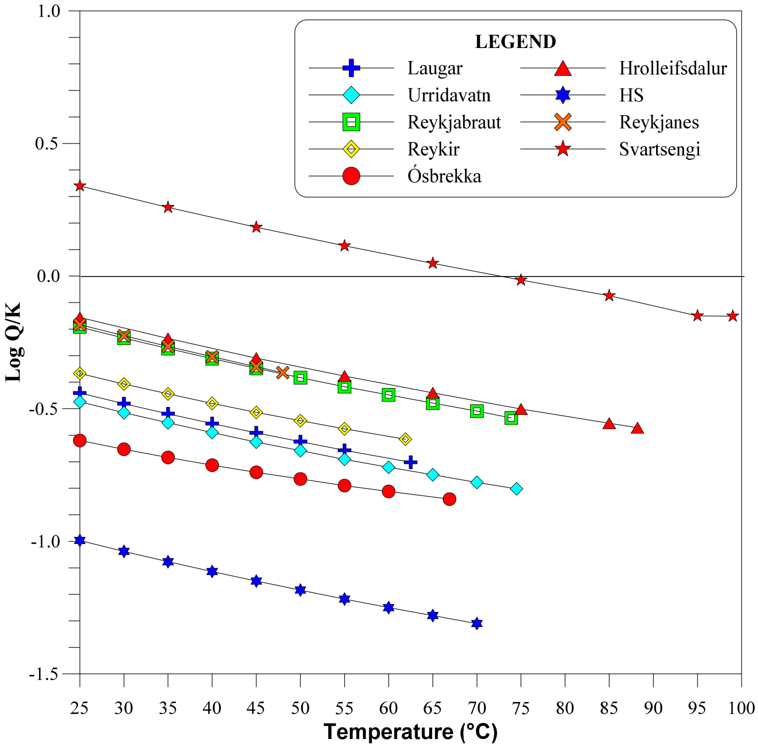

FIGURE 6: Magnesium silicate saturation index from Svartsengi high-temperature field

5. CHEMICAL ASSESSMENT FOR BALNEOTHERAPEUTIC APPLICATIONS

Geothermal fluid in balneotherapy is the oldest known type of application in Iceland. This culture goes back to ancient times. In Iceland, there are numerous swimming pools, several hot springs as well as recreation centres such as the Blue Lagoon, Mývatn Nature Baths, and the Nauthólsvík geothermally heated beach, which are visited by tens of thousands of guests every year. Improving health and appearance, getting away from stress to refresh and revitalize the body and mind are the main reasons for taking a geothermal water bath, and this culture is an important part of Icelandic life.

Thermal water having curative properties is termed as mineral water. Though there is no internationally accepted definition of mineral water, certain common criteria are found in all commonly used definitions. According to Komatina (2004), mineral water can be classified on the basis of total mineralization, ion and gas composition, content of active therapeutic components, acidity or alkalinity and temperature. According to the classification of the International Society of Medical Hydrology, the Societe International de Technique Hydrothermale (SITH), the International Association of Spas, Health Resort and Balneology and the German Health Resorts Association, a water source can be classified as curative if it possesses one or more of the following properties: more than 1500 mg/l of TDS, 20 mg/l of Fe (iron metal water), 1 mg/l of I (iodine mineral water), 1 mg/l of H_2S (hydrogen sulphide water), 18 nCi/l (nano-curie) of radon (radon water), 1 mg/l of fluoride (fluoride rich water) and if the temperature exceeds 27°C.

The actions of the geothermal water on humans are generated by three factors: thermal, chemical and mechanical factors. The net benefit of immersion in mineral water is probably the result of a combination of these factors (Sukenik et al., 1999). A water temperature of 36-37°C has various beneficial healing effects such as increasing the heart rate and cardiac flow, decreasing blood pressure, controlling contractions and muscular spasms by relaxing skeletal muscles and reducing soft tissue pain

(Fracas, 2005). The evaluation for balneotherapeutic applications of all water samples, as well as for the mixed water, is given in Table 2. A mixed water composition was calculated using 37% geothermal water at a temperature 99°C from Svartsengi and 63% cold water at a temperature 5.7°C from Lágar, so that the mixed water temperature was 40°C, which is an optimal temperature for balneotherapeutic applications. Mineral waters that are classified on the basis of temperature and a balneotherapeutic standpoint, fall into one of the following groups: cold (below 20°C), hypothermal (20-37°C), thermal (37-42°C), and hyperthermal (above 42°C) (Matz et al., 2003). According to this classification, all the geothermal waters, brine waters and heated water are hyperthermal. It is evident that the effects of thermal water are increased vasodilation in the veins of the, skin thereby accelerating the metabolic processes and oxygen supply and improving blood circulation in the cells of the skin (GTC and VO, 1988).

TABLE 2: Chemical parameters of all the water samples compared with the standards

Parameters	**Unit**	**EU (2009) and US spa standards**	**Sample codes**														
			1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
pH	**-**	7.2 -7.6	**E**	**E**	**E**	**E**	**E**	**E**	**E**	**B**	S	**E**	**B**	**E**	S	**E**	**B**
Temperature	°C	29-35	**E**	**E**	**E**	**E**	**E**	**E**	**B**	**B**	**B**	**E**	**E**	**E**	**B**	**B**	S
EC	µS/cm	>2308	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	NA	NA	**B**	S	NA	NA
TDS	mg/l	>1500	**B**	**B**	**B**	**B**	**B**	**B**	NA	**B**	**B**	S	S	**B**	S	S	S
Ca	mg/l	>150	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	S	S	**B**	S	S	S
Mg	mg/l	>50	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	S	**B**	**B**	S	S	**B**
Na	mg/l	>200	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	S	S	**B**	S	S	S
K	mg/l	0-90	S	S	S	S	S	S	S	S	S	**E**	**E**	S	**E**	**E**	**E**
F	mg/l	>1.0	**B**	**B**	S	S	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**
Cl	mg/l	>200	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	S	S	**B**	S	S	S
SO_4	mg/l	>200	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	S	**B**	**B**	S	S	**B**
HCO_3	mg/l	>600	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**
H_2S	mg/l	>1.0	**B**	**B**	S	**B**	NA	**B**	**B**	NA	**B**	**B**	**B**	**B**	NA	**B**	**B**
Al	mg/l	0.02	S	S	S	S	S	S	S	**B**	**B**	**B**	S	**B**	**B**	**B**	**B**
As	mg/l	6 x 10^{-6}	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**
Ba	mg/l	0.08	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	S	S	**B**	S	S	S
B	mg/l	0.08	S	S	S	S	B	S	NA	**B**	**B**	S	S	S	**B**	S	S
Cd	mg/l	3 x 10^{-6}	**B**	S	**B**	**B**	**B**	**B**	**B**	S	**B**	**B**	**B**	**B**	S	**B**	**B**
Cr	mg/l	35 x 10^{-5}	**B**	**B**	**B**	**B**	S	S	S	B	S	S	S	S	**B**	S	S
Cu	mg/l	5 x 10^{-6}	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
Fe	mg/l	>1.0	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**
Hg	mg/l	7 x 10^{-6}	**B**	**B**	**B**	**S**	**B**	S	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**
Mn	mg/l	0.023	**B**	**B**	**B**	**B**	**B**	S	**B**	**B**	**B**	S	S	**B**	S	**B**	S
Pb	mg/l	<4.0	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
Sr	mg/l	5.3	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	**B**	S	**B**	**B**	S	S	**B**
Zn	mg/l	<5.0	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S

1: Laugar; 2: Urridavatn; 3: Reykjabraut; 4: Reykir; 5: Ósbrekka; 6: Hrolleifsdalur; 7: Kalársel; 8: Hrísey; 9: Lágar; 10: Reykjanes; 11: Svartsengi; 12: Hitaveita Sudurnesja (HS); 13: Saudárkrókur; and 14: Kalmanstjörn; 15: Mixed water (40°C); S: Suitable for balneotherapeutic use; E: Exceeding the standard value; B: Below the standard value; NA: No available data

The chemical factors determine the curative properties of water for skin disease and other kinds of therapeutic uses (Manuel, 2010). In this study, the physicochemical parameters, including trace elements, were compared with the standards for spas in the European Union (2009) and the USA. In comparison with the standard limits, it should be noted here that the standard usually refers to the minimum value, except in the case of Pb and Zn for which it defines a maximum value. Figure 7 shows that one spring sample from Lágar and one sea sample from Saudárkrókur showed pH values within the standard limit of 7.2-7.6. Other samples showed either higher or lower pH. The pH has a direct impact on users only at very low or very high values. Primarily, irritation of the skin and eyes appears to be linked to high or low pH. Water with high pH could have an adverse effect on hair by causing the hair fibres to swell and by cleaving the cystine bridges between adjacent polypeptide chains of the hair protein. The graph in Figure 8 compares the relevant physicochemical parameters of all water samples with the standard values. In terms of TDS, brine waters from Reykjanes and Svartsengi, sea waters from Saudárkrókur and Kalmanstjörn and mixed water are mineral rich waters (TDS>1500 mg/l), suitable for balneological purposes. These samples are also rich in Na^+, Ca^{2+}, Mg^{2+}, Cl^- and SO_4^{2-} except for the SO_4^{2-}concentration in Svartsengi, as well as in the mixed water which was below the standard value. Others samples show lower than the recommended values of the above mentioned parameters. Ca^{2+}, Mg^{2+}, Na^+, Cl^-, and SO_4^{2-} are the most common constituents for waters considered to have therapeutic properties (Skapare, 2001).

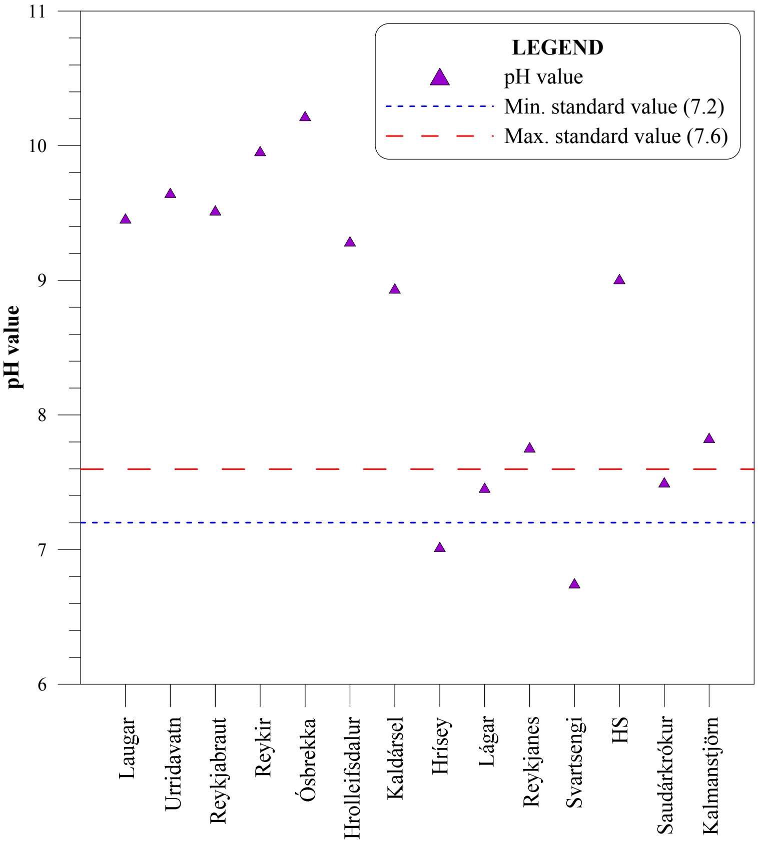

FIGURE 7: pH values compared with the EU (2009) and US spa standards

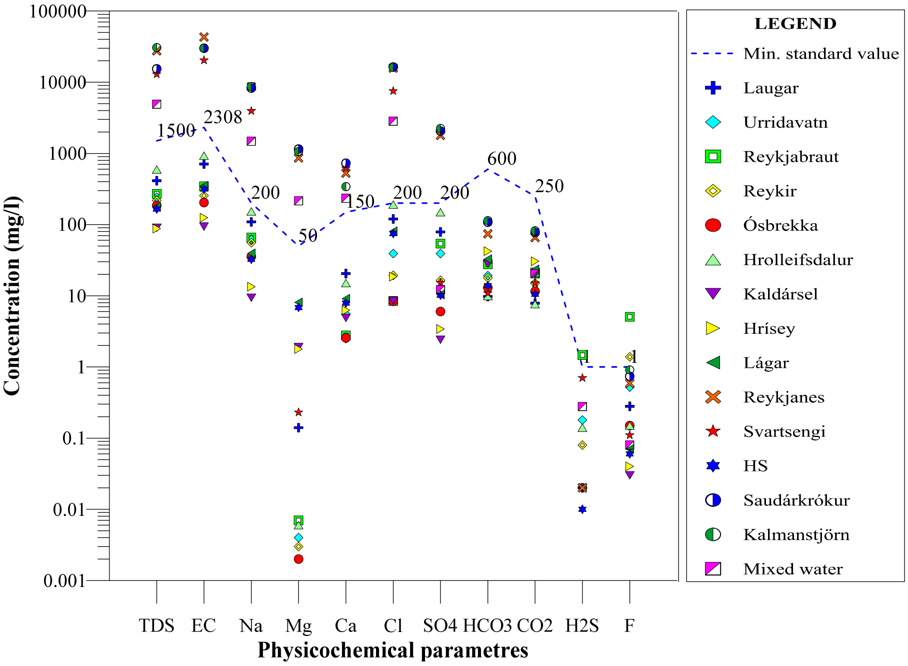

FIGURE 8: Physicochemical parameters compared with the EU (2009) and US spa

Among the various mineral salts present in geothermal water, HCO_3^- is known to be important, but all the samples contained less than the minimum amount of HCO_3^- (600 mg/l), and the same applied to CO_2. However, therapeutic activities of CO_2 water baths (700 to 1300 mg/l) are explained by a synergism between hydrostatic pressure and the chemical properties of CO_2 which acts directly on the blood vessels of the skin, causing vasodilation and increased oxygen utilization (Hartmann et al., 1997). Waters from Reykjabraut and Reykir are mineral waters in terms of F^- content. The F^- concentrations of these two samples were 5.08 and 1.39 mg/l, respectively.

The main diseases recommended for treatment by mineral water are as follows: degenerative joint diseases of the locomotive system, nervous system functional disorders, overweight problems, etc. (Bojadgieva et al., 2002). Hydrogen sulphide (H_2S) affects the microcirculation in the body, markedly dilating peripheral vessels and enhancing vascular motion (Skapare, 2001). The sulphur that penetrates the skin is oxidized and evokes various physiological responses in the skin, such as vasodilation in the microcirculation; it also has an analgesic influence on the pain receptors, and inhibits the immune response. It also interacts with oxygen radicals in the deeper layers of the epidermis; it may be transformed into pentathionic acid which could be the source of the antibacterial and antifungal activity of sulphur water (Matz et al., 2003). Only the sample from Reykjabraut contained 1.47 mg/l of H_2S, making it suitable for this category.

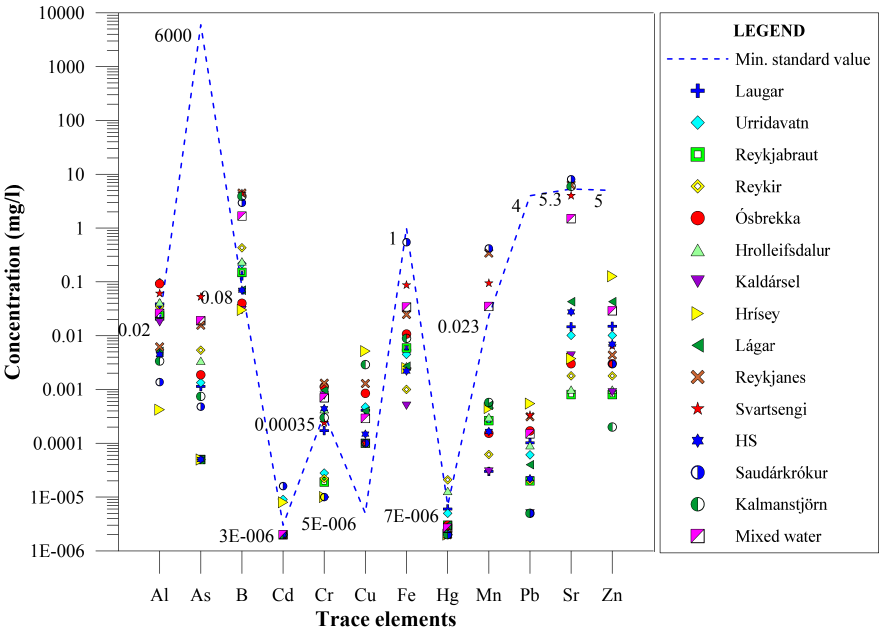

FIGURE 9: Trace element concentrations compared with the EU (2009) and US spa standards

Trace elements such Al, As, Cu Fe, Mn and Zn give medicinal properties to mineral water (Saman, 2000). Figure 9 shows the concentrations of trace elements in comparison with standard values. All geothermal waters, brine water from Svartsengi and the mixed water contained higher values of Al then the minimum required standard value of 0.02 mg/l, suitable for balneotherapeutic use. Samples from Urridavatn, Saudárkrókur and Hrísey showed suitable concentrations of Cd, and Ósbrekka, Hrolleifsdalur, Reykjanes, Hitaveita Sudurnesja (HS) showed suitable concentrations of Cr. In terms of Hg, Reykir and Hrolleifsdalur showed the presence of permissible concentrations. Almost all the waters, including the mixed water, were characterised by a high concentration of B, except for the geothermal water from Ósbrekka, the district heating water from HS and the waters from cold springs, where the B values were less than 0.08 mg/l. Brine waters from Reykjanes and Svartsengi, mixed water and one sea water sample from Saudárkrókur showed Mn values above the minimum required value of 0.02 mg/l, and sea waters from Saudárkrókur and Kalmanstjörn and brine water from Reykjanes showed Sr values that were above the minimum required value of 5.3 mg/l. In all water samples, Pb and Zn values were within the permissible limits of 4 and 5 mg/l, respectively.

6. CHEMICAL ASSESSMENT FOR AGRICULTURAL APPLICATIONS

The suitability of water for irrigation purposes depends upon the effects of the various chemical constituents. The chemical composition of water varies, depending on the origin of the water as well as time and space. Generally, all types of natural water contain dissolved salts due to the interaction of water and rock. The combinations of different types of salts present in the water limit the suitability of the water for irrigation purposes. The concentration of salts and other dissolved chemical substances increases with evaporation. High concentrations of some of these chemical substances are toxic to plants. The general parameters for assessing the irrigation water quality are: total salinity determined from electrical conductivity (EC), relative proportions of Na^+, sodium adsorption ratio (SAR) and boron toxicity. However, a number of trace elements can be found in water which may further limit its use for irrigation purposes.

6.1 Electrical conductivity (EC) and sodium percentage (% Na^+)

When evaluating irrigation water, the primary water quality concern is usually salinity due to its effect on both the plants and soil. Most salinity problems in agriculture result from salts carried by water for irrigation. Water with high salinity is toxic to plants. However, salinity alone does not determine the suitability of water for irrigation water, other factors must be considered. Electrical conductivity (EC) is a good measurement of saline hazards to crops. Total dissolved solid (TDS) is sometimes referred to as the total salinity.

TABLE 3: Irrigation water classification based on EC and TDS

Class	**Category**	**Electrical conductivity (µS/cm)**	**TDS (mg/l)**
Class 1	Excellent	<250	<175
Class 2	Good	250 to 750	175 to 525
Class 3	Permissible	750 to 2000	525 to 1400
Class 4	Doubtful	2000 to 3000	1400 to 2100
Class 5	Unsuitable	>3000	>2100

Five classes of irrigation water based on EC and TDS are defined in Table 3 (Texas A&M University, 2003). In terms of EC and TDS, all the water samples from low-temperature geothermal boreholes, springs and heated water are within the excellent or good water classes with EC values from 21.4 to 709 µS/cm and TDS values from 88 to 414 mg/l, except for one sample from a low-temperature geothermal borehole in Hrolleifsdalur which falls under the permissible water class with EC and TDS value of 926 µS/cm and 596 mg/l, respectively. Samples from sea and geothermal brine water have TDS in the range from 12958 to 30682 mg/l. Consequently, all the samples from sea and brine water are unsuitable for irrigation use.

Not only EC but also the relative proportion of Na^+ and K^+ are very important in classifying irrigation water. The primary effect of a high relative proportion of Na^+ is a reduction in the osmotic activity of plants, thus less absorption of water and nutrients from the soil. Therefore, water with low EC but a relative high Na^+ concentration may be considered less suitable for irrigation than water with the same measured EC but a more balanced diet of cations. The relative proportion of Na^+ concentrations in irrigation water is usually denoted as % Na^+ and can be determined by the formula (Wilcox, 1955) given below, where the concentrations are expressed in meq/l:

$$\%\,\mathrm{Na} = \frac{(\mathrm{Na}^+ + \mathrm{K}^+) \times 100}{(\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+} + \mathrm{Na}^+ + \mathrm{K}^+)} \tag{1}$$

All samples were classified based on Na% and EC in the Wilcox diagram (Figure 10). The figure shows that all the samples from springs in Kaldársel, Hrísey and Lágar and the heated pipeline sample from HS are in the excellent to good water classes. Samples from the low-temperature geothermal fields in Laugar, Urridavatn, Reykir, Reykjabraut, and Ósbrekka fall under permissible to doubtful, and Hrolleifsdalur belongs to the doubtful to unsuitable water classes for irrigation. Samples from brine and sea water were not plotted in this diagram due to their extremely high values; all of those waters are unsuitable for this application. A comparison of Figure 10 and Figure 3 shows that mature geothermal water would, in most cases, be considered unsuitable for irrigation due to the high Na^+ ratio.

6.2 Sodium adsorption ratio (SAR)

The sodium adsorption ratio (SAR) is an important parameter for determining the suitability of groundwater for irrigation. It is like the % Na^+, a measure of alkali or sodium hazard which relates to an infiltration problem. The higher the SAR values in the water, the greater the risk of Na^+ adsorption to the soil, which leads to the development of an alkali soil. When the concentration of Na^+ is high in irrigation water, Na^+ tends to be adsorbed to clay particles, displacing magnesium and calcium ions, reducing the soil's permeability and eventually resulting in soil with poor internal drainage. Ca^{2+} and Mg^{2+} are important due to their counter effects to sodium. Continued use of water with a high SAR value leads to a breakdown in the physical structure of the soil. When the soil is dry, it becomes hard and compact and eventually impervious to water penetration. Fine textured soil, especially high in clay, is most subject to this action. It can be calculated from the concentrations of Na^+, Ca^{2+} and Mg^{2+} according to Hem (1989):

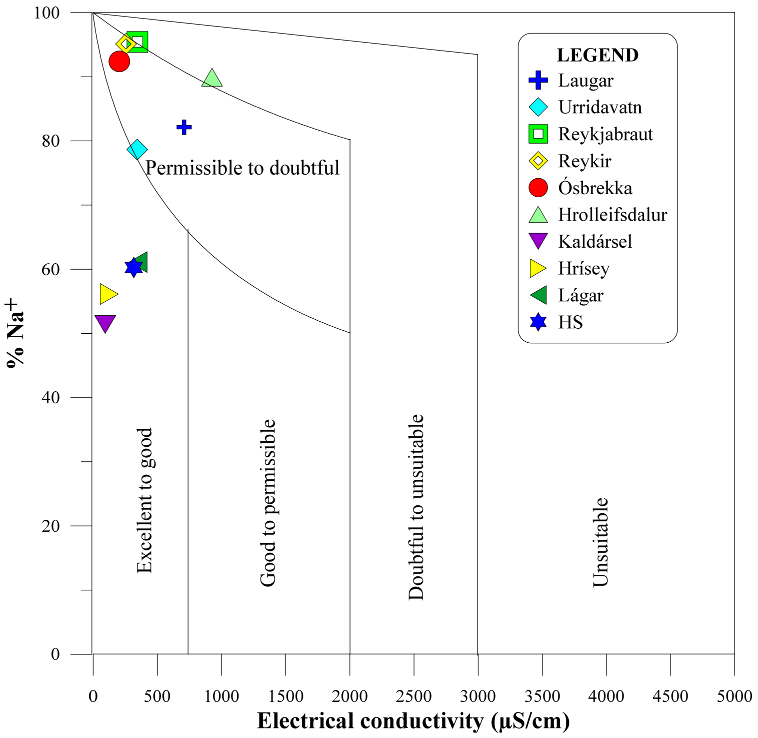

FIGURE 10: Suitability of irrigation water (from Wilcox, 1955)

$$\mathrm{SAR} = \frac{Na^+}{\sqrt{\frac{Ca^{2+}+Mg^{2+}}{2}}} \qquad (2)$$

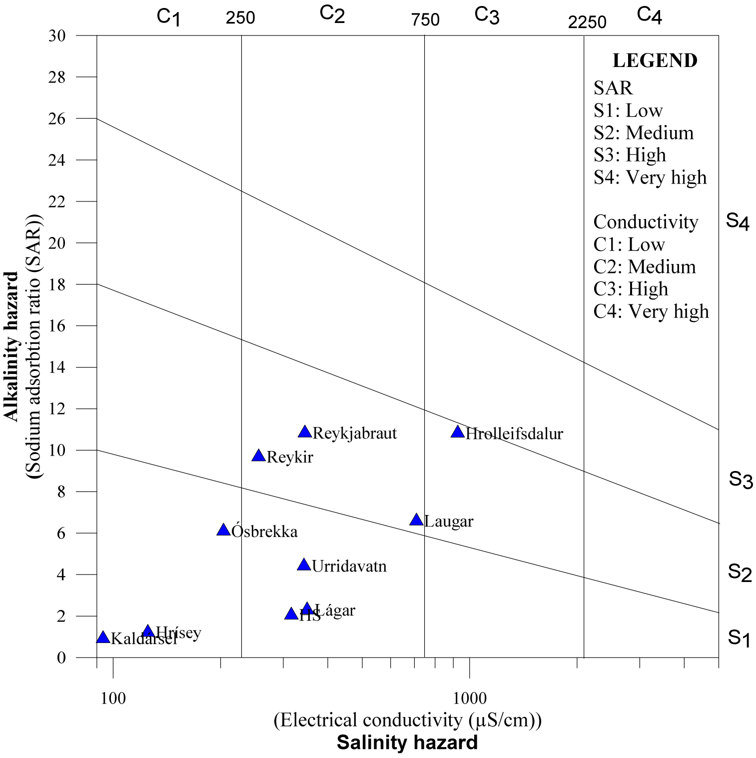

FIGURE 11: Classification of irrigation water (from Richard, 1954)

The plot of the data on the SAR diagram (Richard, 1954), in which EC is taken as the saline hazard and SAR as the alkaline hazard, is shown in Figure 11. Geothermal water from Ósbrekka shows low hazard in terms of both alkalinity and salinity, Urridavatn shows a low alkalinity hazard but a medium salinity hazard, Laugar, Reykjabraut and Reykir show medium alkalinity and salinity hazards and Hrolleifsdalur shows medium alkalinity but a high salinity hazard. Samples from spring water in Hrísey and Kaldársel show low alkalinity and salinity hazard, while Lágar shows low alkalinity but medium salinity hazard. The sample from Hitaveita Sudurnesja (HS) district heating water shows a medium alkalinity and salinity hazard.

6.3 Boron toxicity

A number of elements in water can cause toxic reactions to plants when present in high concentrations. Boron is the greatest concern after sodium. Boron is present in water as boric acid, which may be toxic to plants even at very low concentrations. It can also accumulate in the soil. The high boron concentration in many geothermal systems is derived from boron rich rock. When the rock within the crust becomes sufficiently heated, boron is extracted into the surrounding formation water, and moves to the surface through faults and fractures (Smith, 2002). Plant species differ in their tolerance to boron. Some of them are listed with tolerance in Table 4. Samples from sea water in Saudárkrókur and Kalmanstjörn and geothermal brine water from Reykjanes and Svartsengi have high concentrations with 4.5, 4.4, 2.9 and 3.9 mg/l of boron, respectively (Figure 12). Other samples appear to be within the recommended limit of 1 mg/l of B for sensitive plants. Boron toxicity causes different effects on plants, such as altered metabolism, reduced root cell division, lower leaf chlorophyll content and photosynthetic rates (Nable et al., 1997). However, turf grass is not particularly sensitive to high levels of boron. Table 5 gives a summary of the water suitability for irrigation.

TABLE 4: Plant tolerance of boron (modified after Texas A&M University, 2003)

Sensitive (1.0 mg/l of B)	**Semi-tolerant (2.0 mg/l of B)**	**Tolerant (3.0 mg/l of B)**
Walnut	Sunflower	Athel
Navy bean	Potato	Asparagus
Plum	Cotton	Palm
Pear	Tomato	Datepalm
Apple	Sweet pea	Sugarbeet
Grape	Robin rose	Mangel
Persimmon	Olive	Gardenbeet
Cherry	Barley	Alfalfa
Peach	Wheat	Gladiolus
Apricot	Corn	Broadbean
Blackberry	Oat	Onion
Orange	Pumpkin	Turnip
Avocado	Bell pepper	Cabbage
Grapefruit	Sweet potato	Lettuce
Lemon	Limabean	Carrot

TABLE 5: Suitability of water for irrigation based on several classifications

Value	**Water class**	**Sample location**
Based on electrical conductivity (EC) (µS/cm)		
<250	Excellent	Ósbrekka, Kaldársel and Hrísey.
250-750	Good	Laugar, Urridavatn, Reykjabraut, Reykir, Lágar and HS.
750-2000	Permissible	Hrolleifsdalur.
2000-3000	Doubtful	-
>3000	Unsuitable	Reykjanes, Svartsengi, Saudárkrókur and Kalmanstjörn.
Based on total dissolve solid (TDS) value (mg/l)		
<175	Excellent	Hrísey and HS.
175-525	Good	Laugar, Urridavatn, Reykjabraut, Reykir, Ósbrekka and Lágar.
525-1400	Permissible	Hrolleifsdalur.
1400-2100	Doubtful	-
>2100	Unsuitable	Reykjanes, Svartsengi, Saudárkrókur and Kalmanstjörn.
Based on alkalinity hazard or sodium adsorption ratio (SAR) (Richards,1954)		
<10	Low	Laugar, Urridavatn, Reykir, Ósbrekka, Kaldársel, Hrísey, Lágar & HS.
10-18	Medium	Reykjabraut and Hrolleifsdalur.
18-26	High	-
>26	Very high	Reykjanes, Svartsengi, Saudárkrókur and Kalmanstjörn.
Based on boron concentration (mg/l)		
<1.00	Excellent	Laugar, Urridavatn, Reykir, Reykjabraut, Ósbrekka, Hrolleifsdalur, Hrísey, Lágar and HS.
1.00 to 2.00	Good	-
2.00 to 3.00	Permissible	-
3.00 to 3.75	Doubtful	-
>3.75	Unsuitable	Reykjanes, Svartsengi, Saudárkrókur and Kalmanstjörn.

6.4 Trace elements

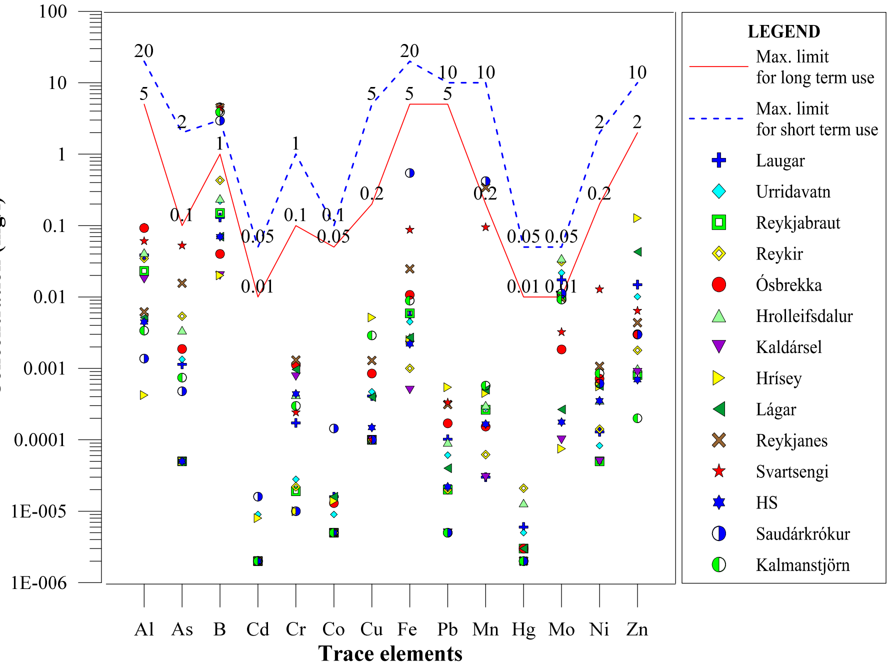

FIGURE 12: Trace element concentrations compared with recommended limits

Some trace elements such as copper (Cu), iron (Fe), manganese (Mn), zinc (Zn), molybdenum (Mo) and nickel (Ni) have been considered plant nutrients for a long time. They must be available in soil for good growth and production. If the soil is not able to supply them to the plants, they will show deficiency symptoms and growth will be affected as well as production. However, sometimes trace elements such as arsenic may be taken up in high amounts and accumulate in plants (bioaccumulation). This applies particularly to trace elements in the form of organic compounds and accumulates in tissues after being dissolved. High concentrations of trace elements are not only hazardous for plants and soil but, through the food chain, hazardous for human health, too. In Figure 12, the values of trace elements in all the samples were compared with the recommended limits given by Rowe and Abdel-Magid (1995) for irrigation water.

High concentrations of aluminium (Al) inhibit root growth (Delhaiz and Ryan, 1995). The recommended value for Al is 5 mg/l for short term and 20 mg/l for long term irrigation. Al concentrations are within the recommended limit in all the water samples. Arsenic (As) is non-essential and is generally toxic to plants; it may trigger a sequence of reactions leading to growth inhibition, disruption of photosynthetic and respiratory systems (Grag and Singla, 2011). All the samples are within the recommended limit of 0.1 mg/l of As for long term irrigation use. High concentrations of chromium (Cr) give rise to severe chlorosis, necrosis and a host of other growth abnormalities and anatomical disorders (Samantaray et al., 1996). Cadmium (Cd) interferes with the metabolic processes within plants. Cr and Cd concentrations in all the water samples were lower than the maximum recommended limit of 0.1 mg/l and 0.01 mg/l, respectively, for long term irrigation use. High concentrations of copper (Cu), manganese (Mn), and zinc (Zn) result in chlorosis, a reduction in leaf size, foliage and necrosis. Both the samples from geothermal brine in Reykjanes and Svartsengi and one sample from the sea water in Saudárkrókur, had Mn concentrations of 0.34, 0.94 and 0.40 mg/l, respectively, exceeding the maximum recommended value of 0.02 mg/l for long term irrigation use. But, they are within the limits for short term use. Four out of six samples that were collected from low-temperature boreholes in Laugar, Urridavatn, Reykir and Hrolleifsdalur had Mo concentrations of 0.02, 0.02, 0.03 and 0.03 mg/l, respectively; one sample from seawater in Saudárkrókur had a Mo concentration of 0.01 mg/l, which is at the margin of the recommended value of 0.01 mg/l for long term irrigation use. Mo toxicity is not thought to be significant to plants and does not produce harmful effects. All the low-temperature samples were within the limits for short term irrigation use (0.05 mg/l) with respect to Mo. Concentrations of other measured elements were within the recommended limits for both short and long term irrigation purposes.

7. CHEMICAL ASSESSMENT FOR AQUACULTURAL APPLICATIONS

According to the Food and Agriculture Organization, aquaculture is understood to mean the farming of aquatic organisms including fish, molluscs, crustaceans and aquatic plants. The term aquaculture is only applied to fish farming in this paper. Conditions are excellent in Iceland with regard to unpolluted seawater, abundant spring water and economical geothermal water. The main limiting factor in locating a fish farm is the availability of suitable water. Suitable water for the desired species means proper ionic, gaseous and metal content as well as temperature. Geothermal water may be utilized in three ways in aquaculture: direct use in a fish pond, mixing with cold water, and heating a fish pond by using a heat exchanger. A handful of fish production facilities are presently using geothermal water, in part, or totally for fish culture. In the utilization of warm water of geothermal origin, temperature regulation is of prime importance. A constant water supply of suitable temperature leads to increased fish production. According to the Líndal diagram (Líndal, 1973), it is recommended that the temperature of the geothermal water be in the range between 20 and 66°C for potential use in aquaculture. In cold countries, including Iceland, besides cold water species, geothermal water makes the farming of warm water species viable. Each fish species has a different temperature at which optimal development occurs, but a common optimal temperature is 15°C (Svobodova et al., 1993). In addition to the water samples, a water mixture, composed of 10% geothermal water from Svartsengi and 90% cold water from Lágar, yielding a temperature of 15°C, was evaluated for the suitability of aquaculture applications. In addition to temperature, physicochemical parameters as well as trace element content of the water are important when evaluating the suitability of the water for aquacultural applications. In Table 6, all the samples were compared with the standard values provided by Svobodova et al. (1993); Wedemeyer (1977), and Piper (1982).

TABLE 6: Comparison of all the water samples with the aquaculture water quality standards (modified from Svobodova et al., 1993; Wedemeyer, 1977; and Piper, 1982)

Water quality for aquaculture			**Sample codes**														
Parameters	**Min. value (mg/l)**	**Max. Value (mg/l)**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
pH*	6.5	8.5	**E**	**E**	**E**	**E**	**E**	**E**	**E**	S	S	S	S	**E**	S	S	S
TDS	-	3000	S	S	S	S	S	S	NA	S	S	**E**	**E**	S	**E**	**E**	S
TH *	10	400	S	S	**B**	**B**	**B**	S	S	S	S	**E**	**E**	S	**E**	**E**	S
Alkalinity *	10	400	**B**	S	S	S	S	**B**	S	S	S	S	**B**	S	S	S	S
Al	-	0.52	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
As	-	3	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
Cd	-	0.0002	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
Cr	-	7.5	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
Cu	-	0.01	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
Fe	-	0.2	S	S	S	S	S	S	S	S	S	S	S	S	**E**	S	S
Hg	-	0.002	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
Mn	-	0.01	S	S	S	S	S	S	S	S	S	**E**	**E**	S	**E**	S	S
Ni	-	0.1	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
Pb	-	0.7	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
Zn	-	0.1	S	S	S	S	S	S	S	**E**	S	S	S	S	S	S	S
DO	> 6	-	**B**	**B**	**B**	**B**	**B**	**B**	**B**	NA	NA	NA	NA	NA	**B**	NA	NA
CO_2	-	10	S	**E**	**E**	**E**	**E**	S	**E**	**E**	**E**	**E**	**E**	**E**	**E**	**E**	**E**
H_2S	-	0.002	S	**E**	**E**	**E**	S	**E**	NA	NA	NA	NA	**E**	**NA**	NA	S	NA

1: Laugar; 2: Urridavatn; 3: Reykjabraut; 4: Reykir; 5: Ósbrekka; 6: Hrolleifsdalur; 7: Kaldársel; 8: Hrísey; 9: Lágar; 10: Reykjanes; 11: Svartsengi; 12: Hitaveita Sudurnesja (HS); 13: Saudárkrókur; 14: Kalmanstjörn; 15: Mixed water (15°C); S: Suitable for potable water; E: Exceeding the maximum permissible limit; B: Below minimum permissible limit; and NA: No available data; pH*: Unitless; TH and alkalinity *: mg/l as $CaCO_3$..

7.1 Physicochemical parameters

Fish are cold blooded creatures and their body temperature is more or less the same as that of the water in which they live, usually no more than 0.5 to 1°C above or below. The metabolic and immune system of the majority of fish species has an optimum performance at a water temperature of about 15°C (Svobodova et al., 1993). Cold-water fish can maintain a similar metabolic rate at comparatively low temperature, but above 20°C they usually became less active and consume less food. Raising the temperature of the water lowers the saturation levels of dissolved gases. Consequently, heated water is supersaturated in dissolved gases and is deleterious to the fish (Robert, 1975). Super saturation of dissolved gases may cause fish death as a result of blockage of major arteries and the erosion of fins. For salmonids, the optimal growing temperature is 10°C (Fridleifsson et al., 1995). Water temperature also influences the initiation and course of a number of fish diseases. The samples from cold springs and sea water ranged from 3.4 to 8.6°C. All other geothermal water samples ranged from 48 to 99°C. Considerable progress can be achieved in warm water fish cultures using geothermal water. Techniques for water temperature control enable maintaining optimal conditions so that the fish can fully utilize their growth potential to achieve maximum weight gains. The pH balance is essential to fish metabolism. The optimal pH range is from 6.5 to 8.5. Values above 9.2 and below 4.8 can damage and kill some species such as salmonids. Water pH can be changed when mineral acids and hydroxides or other acidic or alkaline substances are discharged or leach into water courses, ponds or lakes.

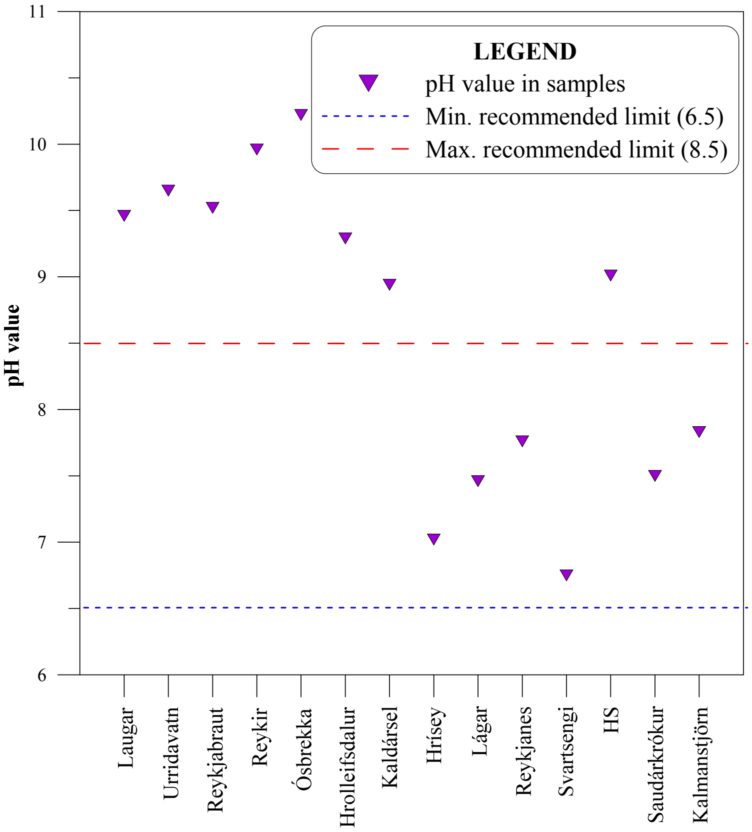

FIGURE 13: pH values of the selected samples compared with the standards

Samples from all low-temperature boreholes in Laugar, Urridavatn, Reykjabraut, Reykir, Ósbrekka, and Hrolleifsdalur had elevated pH values ranging from 9.29 to 10.22, which is higher than the optimal range (Figure 13). The high pH values of low-temperature geothermal water are due to interaction with the basaltic host rock. The sample from Kaldársel and the heated water sample from HS had less alkaline pH, 8.94 and 9.01, respectively. The pH values in all other samples were within the optimal limit, ranging from 7.04 to 7.83. Total hardness (TH) is an important factor relating to the growth of the fish. Hard water is usually well buffered while soft water is usually less buffered. Soft water may cause bone deformities due to a lack of Ca. Water can be classified as soft (0 to <75 mg/l), moderately hard (75 to 150 mg/l), hard (150 to 300 mg/l) and very hard (>300 mg/l) in terms of TH with $CaCO_3$. Samples from sea and brine waters were very hard, range from 4360 to 6540 mg/l, whereas samples from low-temperature geothermal and spring waters were soft, ranging from 6.25 to 57.7 mg/l in terms of TH of $CaCO_3$. The hardness value for mixed water was 205 mg/l of $CaCO_3$, which is hard water. Alkalinity is also important in fish farming because it protects the fish from a rapid change in pH values. It has the capacity to neutralise acid without lowering the pH value. This measure of an acid-neutralizing capacity is important in figuring out how buffered the water is against sudden changes in the pH value. The

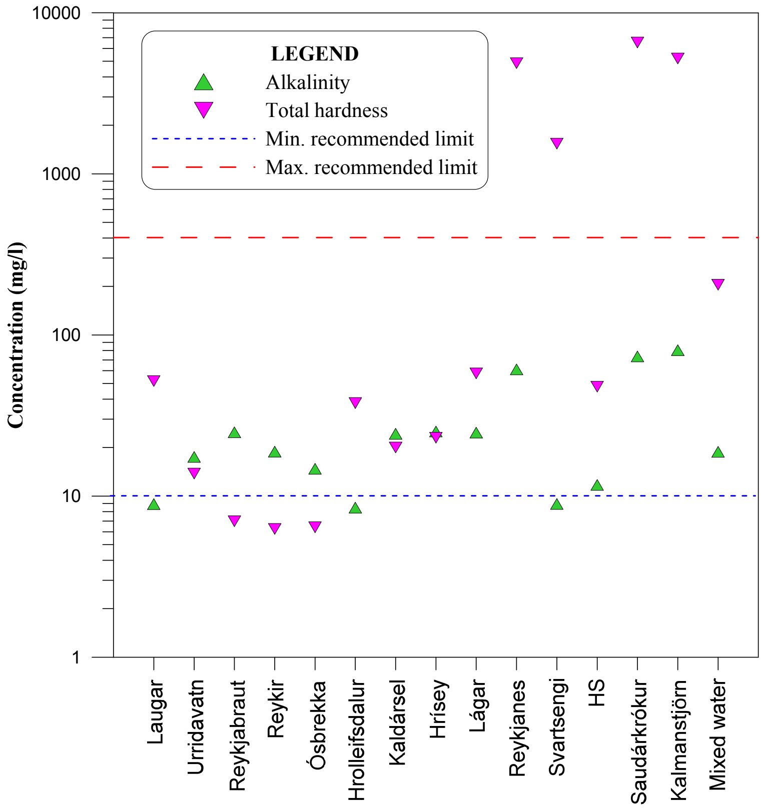

FIGURE 14: Alkalinity and hardness (as $CaCO_3$) of the selected samples compared with the standards

maximum and minimum limits for both hardness and alkalinity are 10 and 400 mg/l as $CaCO_3$. Samples from Reykjanes, Svartsengi, Saudárkrókur, and Kalmanstjörn appeared to be above the limit in terms of TH; samples from Laugar, Hrolleifsdalur and Svartsengi appeared to be below the limit in terms of alkalinity. To some extent, the high pH of the samples makes up for the low alkalinity. Other samples were within the standard limit of both the TH and alkalinity (Figure 14).

Dissolved oxygen (DO) is a crucial water quality parameter in both flow and circulation of aquaculture systems. Hypoxia, or oxygen depletion, is a phenomenon that occurs in aquatic environments as dissolved oxygen becomes less available. Fish exposed to oxygen deficient water do not take food, gasp for air, gather at the inflow to ponds where the oxygen levels are higher, become torpid, fail to react to irritation, lose their ability to escape capture and ultimately die. Significant differences in oxygen demand are found for different species, for example salmonids have a higher requirement for oxygen (8 to 10 mg/l) than other species. The major parameters for assessing the oxygen requirements of fish are temperature, the average individual weight, and the total weight of fish per unit volume of water. Oxygen requirements increase at a higher temperature (e.g. an increase in water temperature from 10 to 20°C at least doubles the oxygen demand), a higher total weight of fish per unit volume of water can lead to increased activity and, thus, increased respiration as a result of overcrowding. The oxygen requirements of fish also depend on other factors, including the temperature, pH and CO_2 level in the water. The recommended minimum DO requirement is 6 mg/l. DO, in all the low-temperature geothermal water samples, was less than 0.01 mg/l. The sea water sample measured in Saudárkrókur showed 0.05 mg/l O_2. DO values in all the other water samples were unavailable, but it may be assumed that the geothermal water has less than 0.001 mg/l of O_2. However, this problem can be solved by aerating the water with O_2.

High concentrations of H_2S are very toxic to fish; the lethal concentration for different species ranges from 0.4 (salmonids) to 4 mg/l (carp, tench and eel). H_2S exerts its toxicity by forming sulphides with the active groups of different metallo-enzymes in cell and blood pigments, thereby interrupting cellular respiration (Miron and Kristensen, 1993). The toxicity of H_2S decreases with increasing water pH because of a reduction in the ratio of the non-dissociated toxic H_2S to the less toxic HS^- ions. The optimum concentration should be less than 0.002 mg/l. In Figure 15, four samples out of six samples from low-temperature geothermal water showed H_2S values ranging from 0.08 to 1.47 mg/l, higher than the optimum range (0.002 mg/l); two samples show less than 0.03 mg/l. On the other hand, those samples had some dissolved O_2, so it is very unlikely that there is also H_2S in the samples. Samples from brine water in Svartsengi and the mixed water showed 0.7 and 0.1 mg/l of H_2S, respectively, not suitable for aquaculture. The H_2S values in all other samples were less than 0.03 mg/l, but exact values are unknown; therefore, comparison with the optimum value is difficult. H_2S reacts with O_2 to form

SO_4, so that the small amounts of H_2S present in the low-temperature geothermal water may be removed, either by aerating or dilution with cold air-saturated water.

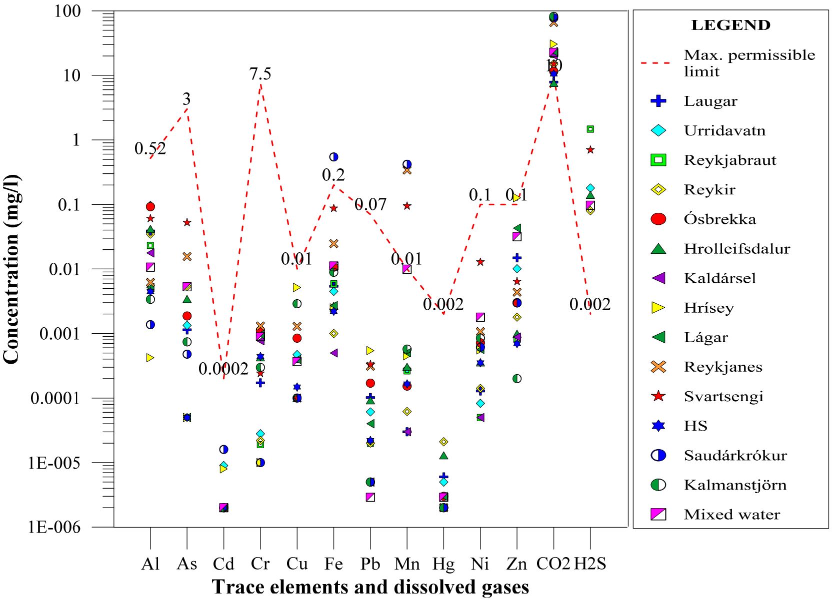

FIGURE 15: Trace elements and dissolved gas concentrations compared with the standards

The toxic action of carbon dioxide (CO_2) is either direct or indirect. Direct action is an excess of CO_2, which can cause a reduction in CO_2 diffusion from the fish blood into the respiratory water. However, CO_2 rarely causes direct toxicity in fish. The indirect effect is its influence on the pH value. The free CO_2 released during respiration reacts with the water, producing carbonic acid (H_2CO_3), and the pH value is lowered and limits the capacity of the fish blood to carry oxygen by lowering the blood pH at the gills. The maximum tolerable range of CO_2 is 10 mg/l. All the kinds of water sampled showed higher concentrations of CO_2 ranging from 15 to 82 mg/l, except for two samples from the geothermal waters in Laugar and Hrolleifsdalur. The concentrations of CO_2 in Laugar and Hrolleifsdalur were 7.9 and 7.6 mg/l, respectively.

7.2 Trace element toxicity

The metals found to be of the greatest importance for fish are aluminium (Al), chromium (Cr), iron (Fe), nickel (Ni), copper (Cu), zinc (Zn), arsenic (As), cadmium (Cd), mercury (Hg) and lead (Pb) (Svobodova et al., 1993). The graph in Figure 15 shows how these metals compare with standard values. Starting at a concentration of 0.1 mg/l, Al is toxic to fish in acidic, un-buffered waters. It influences gill permeability and damages the surface cells of the gill. Al is mainly toxic to fish at pH values 5.0 to 5.5. Al ions accumulate on the gills and clog them with a slimy layer which limits breathing. High concentrations of Al cause reduced growth and consequently the productivity of a fish farm is reduced. The tolerable limit of Al is as low as 0.5 mg/l. In all the water samples and mixed water, the concentrations of Al were less than 0.1 mg/l which is suitable for fish. Fe is vital to the life of all aquatic creatures. Fe is not deadly to any aquatic animals at normal levels, but at higher levels when iron does not dissolve in water, fish cannot process all the iron they take in from water or food. The iron can build up in the internal organs of fish, eventually killing them. The standard limit of Fe contents for fish is determined based on the fish type. In all fish species, it is generally accepted that the concentration of Fe should not exceed 0.2 mg/l; but for salmonids, the limit should not exceed 0.1 mg/l. The concentrations of Fe were less than 0.1 mg/l in all water samples along with the mixed water, except for one seawater sample from Saudárkrókur in which the Fe concentration was 0.55 mg/l. Fe, as well as Al, toxicity may be augmented with increasing acidity. Even in slightly acidic water, the increase in the concentrations of these metals will make the water more harmful to fish (Vuorinen et al., 1998). Precipitation of iron compounds and tufts of the iron bacteria in the water reduces the gill area for respiration.

The recommended limit for Mn is up to 0.01 mg/l. Brine waters from Reykjanes, Svartsengi, and the sea water form Saudárkrókur showed higher values of Mn. However, Mn toxicity in fish is not extensive. As may accumulate in large quantities in fish tissues. Therefore, it can enter into the human body through the food chain. All the water samples and mixed water had a low concentration of As with values less than 0.01mg/l. High concentrations of Ni compounds are of medium toxicity to fish. According to the standard value, Ni concentrations should be less than 0.1 mg/l. The toxic exposure to Ni turns mucus and lamellae in the gill chambers to a dark red colour, reduces breathing and may cause liver damage, depending on the accumulation in the tissues. Ni concentrations in all the samples were less than 0.01 mg/l, including the mixed water.

High concentrations of Cu and Zn in the water can be harmful, although at lower levels they are essential elements for fish. The characteristic symptoms of toxicity caused by copper ions and compounds are breathing difficulties. The maximum admissible Cu concentration in water for the protection of fish is in the range of 0.001 to 0.01 mg/l, depending on the physical and chemical properties of water and on the species of fish (Svobodova et al., 1993). All water samples and the mixed water contained less than the maximum admissible value of Cu concentrations, and are consequently considered safe in terms of Cu toxicity. Zn poisoning of fish is most frequently encountered; small fish are extremely sensitive to Zn. The poisoning effects on fish are similar to those found for copper. Zn toxicity in fish can be greatly influenced by both water hardness and the pH value (Everall et al., 1989). All the water samples and the mixed water were within the permissible limit of 0.1 mg/l for Zn, except a slightly higher concentration, 0.13 mg/l, in one sample from a cold water well in Hrísey.

Cd effects are similar to that of other toxic metals; Cd can cause damage to the reproductive organs, as well as to the central nervous system. The maximum admissible Cd concentration in water is 0.0002 mg/l. Cd concentrations recorded in all the water samples and the mixed water were less than 0.00001 mg/l. Consequently, all the water samples are suitable in terms of Cd.

Hg can cause damage to some vital tissues and organs in fish and may also have a harmful effect on reproduction by reducing egg production. For fish, in general, the maximum admissible concentration of Hg has been suggested to be as low as 0.002 mg/l. All water samples and the mixed water had much lower values of Hg (<0.00002 mg/l).

Pb toxicity is characterised by damage to the gills, so fish are killed by suffocation. The maximum admissible Pb concentration in water is 0.007 mg/l. The contents of Pb in all the water samples and the mixed water were within the permissible limit. The toxicity of Cr is similar to Pb. The concentrations of Cr appeared to be very low (<0.00001 mg/l) in all the water samples.

8. CHEMICAL ASSESSMENT FOR INDUSTRIAL APPLICATIONS

Diverse water quality is required for different types of industries. However, food drying and processing is the most important hot water consuming industrial sector in Iceland. The industries within this sector are: fish, meat, vegetable and potato industries; the dairy industry; beverage and breweries industry, and the margarine and fat industry. The food industries have a high demand for potable water due to the wide variety of components added to the product during processing where water comes into contact with the product. An EU directive has strictly prohibited the use of non-potable water in food industries. In Iceland, about 95% of the country's potable water is untreated groundwater, extracted from springs and boreholes, and less than 5% from the surface (Gunnarsdóttir, 2012). The largest groundwater resources are in the volcanic zone and the high porosity of surface layers and bedrock is often characterized by thin layers of soil. The natural geochemistry of ground and surface water, resulting from interaction with rocks, creates widespread health problems in many parts of the world. The deficiency, excess or imbalances of different chemical species present in potable water are well known to have an influence on human health. Therefore, it is important to evaluate the chemical characteristics of potable water. At the same time, the chemical composition of groundwater is important for decision makers when it comes to the selection of sites for geothermal reinjection wells, in order to avoid affecting the quality of the groundwater. The World Health Organization (WHO), European Union (EU) and other organizations have set guidelines with recommended levels for different chemical species in potable water. The concentrations of all the chemical species of all the water samples were compared with WHO (2004) guidelines for potable water (Table 7).

TABLE 7: Water quality of all the water samples compared with the WHO (2004) guidelines

Parameters	**WHO (2004) guidelines**		**Sample codes**													
	Most desirable limit (mg/l)	**Max. Allowable limit (mg/l)**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
pH *	-	6.5-8.5	**E**	**E**	**E**	**E**	**E**	**E**	S	**E**	S	S	S	**E**	**E**	S
TDS	500	1500	S	S	S	S	S	S	NA	S	S	**E**	**E**	S	**E**	**E**
Ca	75	200	S	S	S	S	S	S	S	S	S	**E**	**E**	S	**E**	**E**
Mg	50	150	S	S	S	S	S	S	S	S	S	**E**	S	S	**E**	**E**
Na	-	200	S	S	S	S	S	S	S	S	S	**E**	**E**	S	**E**	**E**
K	-	12	S	S	S	S	S	S	S	S	S	**E**	**E**	S	**E**	**E**
F	>0.05	<1.5	**B**	S	S	S	**B**	S	**B**	**B**	**B**	**E**	**B**	**B**	**B**	S
Cl	200	600	S	S	S	S	S	S	S	S	S	**E**	**E**	S	**E**	**E**
SO_4	200	400	S	S	S	S	S	S	S	S	S	**E**	S	S	**E**	**E**
H_2S	0.05	0.1	S	**E**	**E**	**E**	NA	**E**	S	NA	S	S	**E**	S	NA	S
Al	-	0.2	S	S	S	S	S	S	S	S	S	S	S	S	**E**	S
As	-	0.01	S	S	S	S	S	S	S	S	S	**E**	**E**	S	**E**	S
Ba	-	0.7	S	S	S	S	S	S	S	S	S	S	**E**	S	S	S
Cd	-	0.003	S	S	S	S	S	S	S	S	S	S	S	S	S	S
Cr	-	0.05	S	S	S	S	S	S	S	S	S	S	S	S	S	S
Cu	-	2	S	S	S	S	S	S	S	S	S	S	S	S	S	S
Fe	-	0.3	S	S	S	S	S	S	S	S	S	S	**E**	S	**E**	S
Hg	-	0.001	S	S	S	S	S	S	S	S	S	S	S	S	S	S
Mn	-	0.05	S	S	S	S	S	S	S	S	S	S	**E**	S	S	S
Mo	-	0.07	S	S	S	S	S	S	S	S	S	S	S	S	S	S
Ni	-	0.02	S	S	S	S	S	S	S	S	S	S	S	S	S	S
Pb	-	0.01	S	S	S	S	S	S	S	S	S	S	S	S	S	S
Zn	-	3	S	S	S	S	S	S	S	S	S	S	S	S	S	S
B	-	0.0.5	S	S	S	S	S	S	NA	S	S	S	**E**	S	**E**	**E**

1: Laugar; 2: Urridavatn; 3: Reykjabraut; 4: Reykir; 5: Ósbrekka; 6: Hrolleifsdalur; 7: Kaldársel; 8: Hrísey; 9: Lágar; 10: Reykjanes; 11: Svartsengi; 12: Hitaveita Suðurnesja (HS); 13: Saudárkrókur; and 14: Kalmanstjörn; S: Suitable for potable water; E: Exceeding the WHO guideline values; B: Below WHO guideline values; and NA: No available data; pH*: Unitless.

8.1 Physicochemical parameters

The water samples from the springs in Kaldársel, Hrísey and Lágar and from sea water in Saudárkrókur and Kalmanstjörn are cold water with temperatures ranging from 3.4 to 8.6°C. Low-temperature geothermal waters from Laugar, Urridavatn, Reykjabraut, Reykir, Ósbrekka, and Hrolleifsdalur, heated water from Hitaveita Sudurnesja, and brine waters from Reykjanes and Svartsengi are hot waters with temperatures ranging from 48 to 99°C. Temperature has an impact on the solubility of a number of inorganic constituents and chemical contaminants that may have impact on health. Warm water temperatures may enhance the growth of micro-organisms and may increase problems related to colour, odour and taste. Figure 16 shows that the pH values of low-temperature geothermal boreholes vary between 9.29 and 10.22, which indicates the extent of the interaction between the hot water and the basaltic rocks; these pH values are higher than the desirable range (6.5 to 8.5) according to WHO (2004). In addition, one sample collected from a spring in Kaldársel and the heated pipeline from HS showed higher pH values than the desirable range. The values were 8.94 and 9.01, respectively. The pH values in all the other samples were within the desirable range. However, the Icelandic and EU regulations on

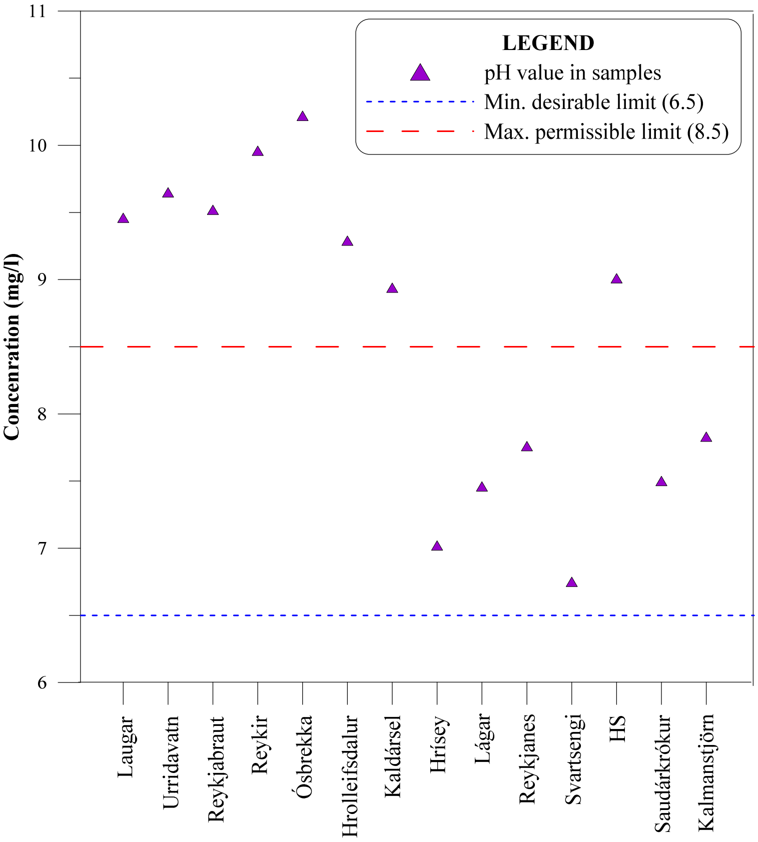

FIGURE 16: pH values compared with the guidelines

potable water allow a pH of 6.5 to 9.5. The pH has no direct impact on consumers but it does affect the effectiveness of water disinfection and clarification. Low pH may cause corrosion of water mains and pipes in water supply systems, as well as an increase in bacterial growth. Failure to minimize corrosion can result in the contamination of drinking-water and adverse effects on its taste and appearance.

All the physicochemical parameters were compared with WHO (2004) guidelines. According to the guidelines, a total dissolve solid (TDS) value of 500 mg/l is the most desirable and up to 1000 mg/l is the maximum permissible limit for potable water. Figure 17 shows that the TDS values ranged from 185 to 596 mg/l in the low-temperature geothermal waters so these waters are within the permissible limit. Samples from springs and heated water range from 88 to 178 mg/l, which is also within the desirable limit. All the samples from the brine and sea water showed much higher values of TDS, ranging from 15400 to 30682 mg/l. TDS greater than 1000 mg/l results in a salty taste, and water with extremely low TDS may be considered unacceptable because of its flat and insipid taste (WHO, 2004). The high TDS in potable water may cause gastrointestinal irritation in humans. The concentrations of Ca^{2+} in brine and sea waters range from 341 to 728 mg/l, higher than specified as most desirable and way beyond the maximum permissible limit of 75 and 200 mg/l, respectively. Ca^{2+} concentrations in other samples varied from 2.5 to 20.5 mg/l.

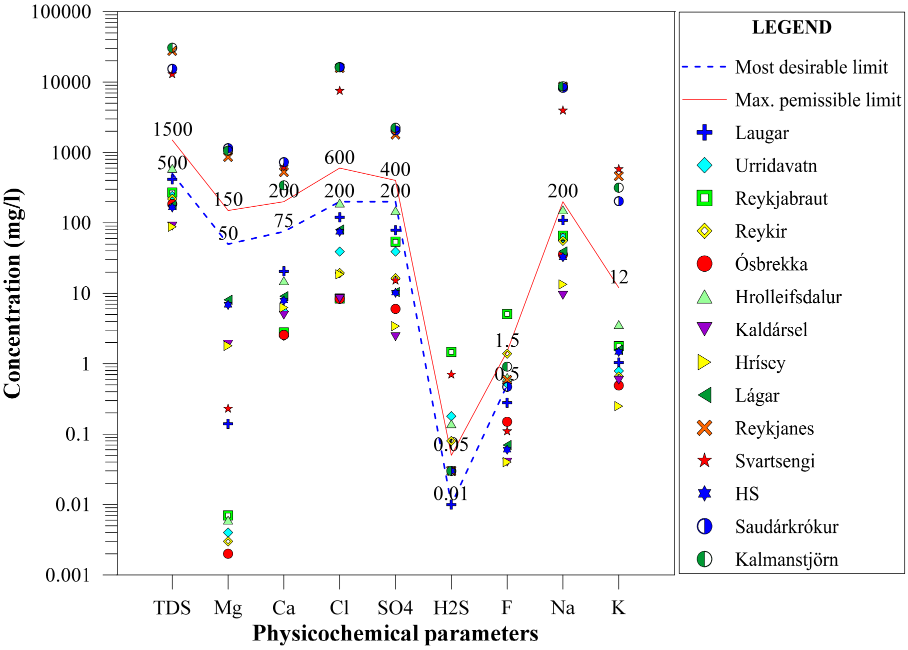

FIGURE 17: Physicochemical parameters compared with the guidelines

The concentrations of Mg^{2+} in both the samples from sea water from Saudárkrókur and Kalmanstjörn were more than ten times higher than the desirable limit of 50 mg/l. One sample from brine water in Reykjanes showed a Mg^{2+} concentration of 0.23 mg/l, which is within the desirable limit for potable water but the other sample from Svartsengi had a higher Mg^{2+} concentration of 864 mg/l. The concentrations of Mg^{2+}in the rest of the samples were within the permissible limit. Both Ca^{2+} and Mg^{2+} are essential to human health. Low intakes of Ca^{2+} have been associated with risks of osteoporosis, nephrolithiasis, colorectal cancer, hypertension, coronary artery disease, insulin resistance and obesity (WHO, 2006). When the absorbed Ca^{2+} is in excess of need, the excess is excreted by the kidney in most healthy people. A low Mg^{2+} level in the human body has been associated with endothelial dysfunction, increased vascular reactions, high circulating levels of reactive protein and decreased insulin sensitivity (WHO, 2006). The major effect of excess Mg^{2+} intake is renal insufficiency associated with a significant decrease in the ability to excrete magnesium. Potable water with high concentrations of Mg^{2+} with high SO_4^{2-} may have a laxative effect, although consumers may adapt to these levels as exposure continues (WHO, 2011). In general, an increase of both Ca^{2+} and Mg^{2+} concentrations in water results in an increase in the total hardness (TH).

Water can be classified as soft (< 75 mg/l), moderate (75 to 150 mg/l), hard (150 to 300 mg/l) and very hard (>300 mg/l), based on the TH as $CaCO_3$ (Sawyer and McCarty, 1967). Samples collected from brine and sea water fell under the very hard water class. Other samples from low-temperature geothermal boreholes, springs and heated pipeline fell under the soft water class. Long term consumption of hard water may cause urological problem or urolithiasis, pre-natal mortality, cancer and cardiovascular disorders (Agrawal and Jagetai, 1997). A guideline value of 200 mg/l was established by WHO, based on taste considerations. Samples from brine and sea water have high concentrations of Na^+, ranging from 3940 to 8720 mg/l. Na^+ concentrations in the samples from low-geothermal boreholes, springs and heated pipelines were within acceptable limits, ranging from 9.39 to153 mg/l. The excess of Na^+ is thought to cause hypertension, congenial diseases and kidney disorders, but there is no firm evidence that can support the theory (WHO, 2004).

As per the standard guidelines, the maximum permissible limit for K^+ is 12 mg/l. The K^+ concentrations range from 0.25 to 3.6 mg/l in all the water samples, except in the brine and sea waters where it ranges from 203 to 579 mg/l. The high concentrations of K^+ in brine waters are due to the fact that both geothermal brines originate from seawater.

The most desirable limit for Cl^- is 200 mg/l and the maximum permissible limit is 600 mg/l. The concentrations of Cl^- in all samples were lower than the most desirable limit, ranging between 8.36 and 191 mg/l, except in the brine and sea water samples, which ranged between 7510 and 16350 mg/l. A high concentration of Cl^- in drinking water causes a salty taste and has a laxative effect.

The concentrations of SO_4^{2-} are also high in brine and sea water, ranging from 1790 to 2240 mg/l, except for one sample from a brine water sample from Svartsengi which had a SO_4^{2-} concentration of 15.2 mg/l. Samples from all other sources had a SO_4^{2-} concentration of between 2.41 and 149 mg/l, within the most desirable limit of 200 mg/l. SO_4^{2-} ingestion in excess of the maximum allowable limit of 400 mg/l in potable water may have gastrointestinal effects (WHO, 2004).

The F^- content in all the water samples ranged from 0.05 to 5.08 mg/l. F^- is an essential element for health. Deficiency or low concentration (<0.5 mg/l) in potable water leads to dental caries. However, a high intake of F^- over 1.5 mg/l may cause skeletal and dental fluorosis (WHO, 1998). Therefore, it is essential to a have a safe limit of F^- concentrations in between 0.5 and 1.5 mg/l in potable water. Samples from low-temperature boreholes in Urridavatn, Reykir and Hrolleifsdalur showed F^-concentrations within the recommended guidelines, Laugar and Ósbrekka showed lower concentrations of F^- of 0.28 and 0.15 mg/l, respectively, and Reykjabraut showed a higher concentration, 5.08 mg/l, than the recommended limit for F^-.

All the spring waters and heated water of HS showed lower values for F^- (< 0.07 mg/l) than the recommended limit. F^- concentrations in the sea water samples appeared to be within the permissible limit. F^- concentration in one brine water sample from Reykjanes was within the permissible limit, but the one from Svartsengi was lower than the permissible limit. The concentrations of these two samples were 0.59 and 0.11 mg/l, respectively.

The taste and odour thresholds of hydrogen sulphide (H_2S) in water were estimated to be between 0.05 and 0.1 mg/l. The rotten eggs odour of hydrogen sulphide may be noticeable in the distribution system due to oxygen depletion. Almost all the waters from the low-temperature boreholes exceeded the value of the taste and odour threshold except for two samples from Laugar and Ósbrekka which showed less than a 0.03 mg/l concentration of H_2S. The brine water sample from Svartsengi showed a higher value of 0.7 mg/l of H_2S concentration. All other samples showed less than 0.03 mg/l of H_2S concentration.

8.2 Trace elements

The levels of trace elements in water and their significance in terms of health are of particular importance in potable water. Some elements are non-essential to human health and above certain limits they are toxic, such as aluminium (Al), arsenic (As), cadmium (Cd), mercury (Hg), lead (Pb), boron (B), silver (Ag), radium (Ra), radon (Rn) and uranium (U). However, some elements are essential at trace levels but can exhibit toxic properties in excess levels of concentrations such as beryllium (Be), vanadium (V), chromium (Cr), manganese (Mn), iron (Fe), cobalt (Co), nickel (Ni), zinc (Zn), selenium (Se), molybdenum (Mo), antimony (Sb) and barium (Ba). Many other elements have no effect on human health. The comparison between all the measured trace element concentrations in all the water samples with the WHO (2004) guideline is given in Figure 18.

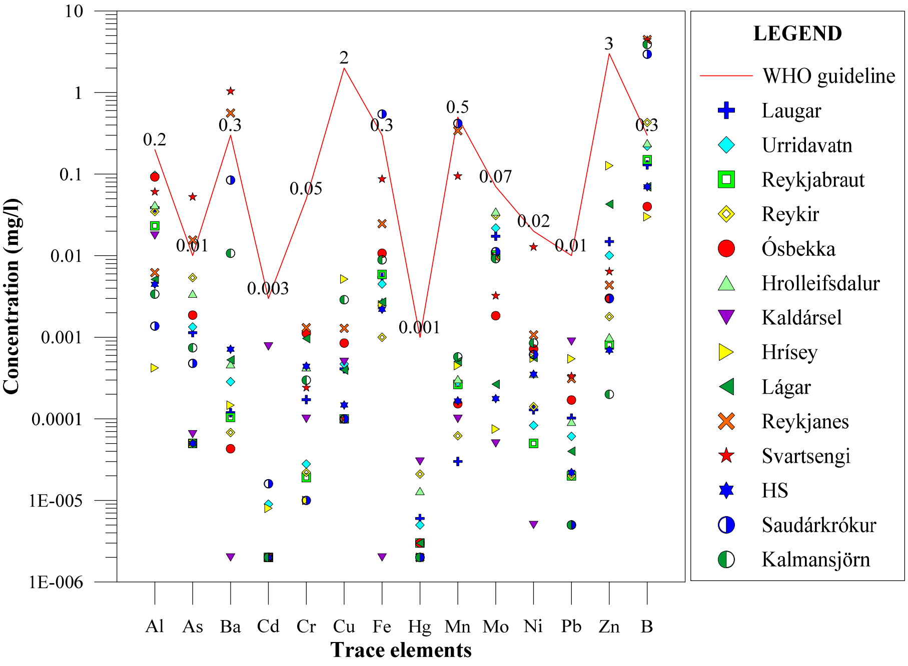

FIGURE 18: Trace element concentrations compared with the guidelines

There is no health-based guideline value recommended for Al. However, a concentration of Al of 0.2 mg/l in drinking-water provides a compromise between the practical use of Al salts in water treatment and discoloration of distributed water (WHO, 1998). The metabolism of Al in humans is not well understood; it is poorly absorbed and most of the absorbed Al is rapidly excreted in urine. Al concentrations in all the waters were within the recommended limit.

The tolerable limit for As is 0.01 mg/l for humans. The As concentrations were higher than the guideline value in the brine waters from Reykjanes and Svartsengi. The As concentrations of these two samples were 0.015 and 0.05 mg/l, respectively. All other water samples had As concentrations of less than 0.005 mg/l. The common symptom of chronic As poisoning is conjunctivitis, melanosis, depigmentation and keratosis. The connection between As exposure and skin and internal cancers is well established (Dissanyaake and Chandrajith, 1999). Numerous studies have examined the risk of cancers associated with arsenic ingestion through potable water. There is overwhelming evidence that consumption of high levels of arsenic through potable water was causally related to the development of cancer at several sites (WHO, 2004).

Ba is present as a trace element in both igneous and sedimentary rocks. A health-based guideline value of 0.7 mg/l was derived for barium, based on concerns regarding the potential of Ba to cause hypertension (WHO, 2001). One brine water sample from Reykjanes had a Ba concentration of 0.56 mg/l, which is within the tolerable limit; another brine water sample collected from Svartsengi contained 1.04 mg/l of Ba, which is higher than the tolerable limit. All other samples had Ba concentrations of less than 0.1 mg/l. It should be noted that excess water-soluble Ba may cause hypertension (WHO, 2004).

The tolerable limit of B is 0.5 mg/l. B concentrations were high for both the brine and sea waters. B concentrations from brine water in Reykjanes and Svartsengi were 4.47 and 4.40 mg/l, respectively. From sea water samples in Saudárkrókur and Kalmanstjörn, B concentrations were 2.95 and 3.90 mg/l, respectively. Concentrations in all the other water samples were less than the maximum tolerable limit, range from less than 0.03 to 0.43 mg/l. Naturally occurring boron was present in water, primarily as a result of leaching from rocks and soils containing borates and boro-silicates (WHO, 1998). B can accumulate in bodies and may infect the stomach, liver, kidney and brain of the human body. B is rapidly and almost completely absorbed by the human body. Long-term exposure of humans to B compounds leads to mild gastrointestinal irritation (WHO, 1998).

Fe is a central component of haemoglobin in the blood. Excessive intake has no serious impact on health. There is usually no noticeable taste at concentrations below 0.3 mg/l Fe. The sea water sample from Saudárkrókur and the brine water sample from Svartsengi had slightly higher concentrations of Fe than is recommended in terms of taste. The sample from Svartsengi was also slightly elevated in Mn. Mn is one of the most abundant metals in the earth's crust and usually occurs together with Fe. It is an essential trace element for humans. Neuro-toxic effects due to excessive intake of Mn in potable water have been observed (WHO, 2004). The values of all other measured elements were within the permissible limits.

9. SUMMARY AND CONCLUSIONS

Water from different sources is of different types and is variable in chemical composition due to mixing with sea water, volcanic activity, geothermal alteration, water-rock interaction and various other factors. From 14 samples from different sources, geothermal waters showed various types of water such as chloride, bicarbonate and mixed chloride-sulphate and chloride-sulphate-bicarbonate type and appeared to be fully equilibrated. The brine and sea waters were of chloride type and were either in full or partial equilibrium with rock. Spring and heated waters were, in all cases, considered to be immature waters, even though chloride might be the dominant cation.

Geothermal waters from Laugar and Ósbrekka may be corrosive in space heating applications, due to the presence of dissolved oxygen. The brine characteristics from Reykjanes and Svartsengi are also corrosive, due to carbon dioxide, especially the water from Reykjanes. In some cases, scaling may occur. Amorphous silica can precipitate from the brine water from Svartsengi when cooled to below 73°C. Several geothermal waters from low-temperature geothermal fields and geothermally heated water showed the possibility of magnesium silicate scaling. No scaling should was observed after mixing Lágar cold groundwater and Svartsengi hot brine water at 15°C and 40°C, with 63% and 90% cold water fractions, respectively. A summary of the results is given in Table 8.

TABLE 8: Summary of the results

Sample location	Space heating applications	Balneotherapeutic applications	Agricultural applications	Aquaculture applications	Industrial applications
Laugar	P	S	P	US	S
Urridavatn	S	S	P	US	US
Reykjabraut	P	S	P	US	US
Reykir	P	S	P	US	US
Ósbrekka	P	S	P	US	US
Hrolleifsdalur	S	S	US	US	US
Reykjanes	P	S	US	US	US
Svartsengi	US	S	US	US	US
Hitaveita Sudurnesja (HS)	P	US	S	US	S
Lágar	NA	US	S	S	S
Kaldársel	NA	US	S	P	S
Hrísey	NA	US	S	S	S
Kalmanstjörn	NA	S*	US	S	US
Saudárkrókur	NA	S*	US	S	US
Mixed water	S	S	NA	US	NA

S: Suitable; S*: Suitable after heating; P: Permissible; US: Unsuitable; and NA: Not assessed.

For the assessment of balneotherapeutic applications, waters from brine and sea are classified as mineral waters, along with some geothermal waters such as from Reykir and Reykjabraut, in terms of H_2S and fluoride. All geothermal waters are suitable for balneotherapeutic applications in terms of temperature. However, sea waters are not thermal waters, but mineral rich in terms of TDS. They can be used either after heating with geothermal water in thermal heat exchangers, or by mixing with geothermal water. Reykjanes and Svartsengi brine waters are considered to be well matched with spa specifications, as is the mixed water that results from mixing 63% cold groundwater with geothermal brine water; consequently, these waters are suitable for balneotherapeutic use.

For the assessment of the quality of irrigation water, EC, TDS, sodium percent, SAR, boron toxicity and trace elements are important parameters. Temperature was not considered for this evaluation. According to EC, TDS, sodium percent and SAR, all springs and heated water fell under the excellent to good water class. All geothermal waters are permissible for agricultural purposes, except water from the Hrolleifsdalur geothermal area, which is considered unsuitable for irrigation. All geothermal, cold and heated groundwater are suitable, in terms of boron and trace elements. Brine and sea waters are not suitable for irrigation purposes in terms of EC, TDS, sodium percent, SAR and boron values.

Various physicochemical parameters (excluding temperature), dissolved gas and trace element concentrations in water were considered in assessing the water's suitability for aquaculture. None of the geothermal waters were considered suitable for aquaculture due to high pH. Spring and sea waters are suitable for aquaculture, though some exceed the limits for hardness, CO_2, Fe and Mn, which have no major effects on fish. H_2S concentrations in geothermal and brine waters are higher than the maximum recommended limit. H_2S concentrations are also high after mixing brine water with 90% cold water. Consequently, geothermal, brine and mixed waters are not suitable for aquaculture, unless aerated with O_2 to remove H_2S.

For the assessment of the water quality for the applications of drinking or food processing industries, the WHO guidelines were followed. Waters from all springs and the heated pipeline are of potable quality in terms of all physicochemical parameters and trace elements except for pH. None of the sea and brine waters are potable due to high salinity. Most of the geothermal waters are not suitable in terms of pH, H_2S and, in some cases, fluoride and boron.

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APPENDIX I: Chemical composition of all the water samples

Parameters	**Laugar**	**Urridavatn**	**Reykjabraut**	**Reykir**	**Ósbrekka**	**Hrolleifsdalur**	**Kaldársel**	**Hrísey**	**Lágar**	**Reykjanes**	**Svartsengi**	**HS**	**Saudárkrókur**	**Kalmanstjörn**
Location type	Borehole	Borehole	Borehole	Borehole	Borehole	Borehole	Spring	Spring	Spring	Pipeline	Pipeline	Pipeline	Pipeline	Borehole
Water type	Low-T	Low-T	Low-T	Low-T	Low-T	Low-T	Cold	Cold	Cold	Brine	Brine	Heated	Sea	Sea
Temperature^1	62.5	74.5	73.9	61.9	66.9	88.2	3.5	3.4	5.7	48	99	70	8.6	8.3
pH^2	9.46	9.65	9.52	9.96	10.22	9.29	8.94	7.02	7.46	7.76	6.75	9.01	7.5	7.83
pH-Temperature^1	22.2	21.3	22.1	19.6	20.5	22	21.7	21.4	21.6	22	22.3	22.7	22.5	22.1
EC at 25°C^3	709	343	345	256	204	926	93.7	125.1	350	-	-	316	30000	-
CO_2	7.87	15	21.2	15	11.5	7.6	20.4	30.5	23.5	65.8	15	10.5	77.8	82
H_2S	<0.03	0.18	1.47	0.08	<0.03	0.14	<0.03	-	<0.03	<0.03	0.7	<0.03	-	<0.03
O_2	0.1	<0.001	<0.001	<0.001	0.06	<0.001	-	-	-	-	-	-	0.05	-
B	0.13	0.22	0.15	0.43	0.04	0.24	-	<0.03	0.07	4.47	4.4	0.07	2.951	3.9
SiO_2	57.5	59.3	104.7	98.3	77.8	102	23.4	16.4	14.8	79.1	256	13.2	13.8	8.1
Na	109	61.3	65.8	55.7	35.5	153	9.39	13.4	39.5	8650	3940	32.5	8260	8720
K	1.04	0.79	1.77	0.66	0.49	3.6	0.582	0.25	1.58	461	579	1.47	203	316
Mg	0.14	0.004	0.007	0.003	0.002	0.006	1.9	1.79	8.1	864	0.23	6.85	1150	1060
Ca	20.5	5.52	2.78	2.5	2.56	15.1	4.89	6.27	9.08	526	617	7.89	728	341
F	0.28	0.52	5.08	1.39	0.15	0.64	<0.05	0.04	0.07	0.59	0.11	0.06	0.47	0.91
Cl	120	39.1	8.44	19.4	8.36	191	8.44	18.6	80.4	15810	7510	74.7	16350	16190
SO_4	78.8	39.1	54.2	16.4	6.01	149	2.41	3.41	10.4	1790	15.2	10.2	2060	2240
Al	0.0389	0.0968	0.0232	0.0347	0.0923	0.0418	0.0177	0.000422	0.00513	0.0062	0.0607	0.00446	0.00137	0.00338
As	0.00114	0.00134	<0.00005	0.00538	0.00187	0.00342	<0.00005	<0.00005	<0.00005	0.0156	0.0525	<0.00005	0.000478	0.000743
Ba	0.000119	0.000285	0.000104	0.000068	0.000043	0.000467	0.000065	0.000147	0.000529	0.561	1.04	0.000714	0.0844	0.0107
Cd	<0.000002	0.000009	<0.000002	<0.000002	<0.000002	<0.000002	<0.000002	0.000008	<0.000002	<0.000002	<0.000002	<0.000002	0.000016	<0.000002
Co	0.000016	0.000009	<0.000005	<0.000005	0.000013	<0.000005	<0.000005	0.000014	0.000016	<0.000005	<0.000005	<0.000005	0.000144	<0.000005
Cr	0.000172	0.000028	0.000019	0.000022	0.00112	0.000428	0.000771	<0.00001	0.000968	0.00131	0.000241	0.000441	<0.00001	0.000298
Cu	0.00041	0.000471	<0.0001	<0.0001	0.000848	<0.0001	<0.0001	0.00517	0.000397	0.00129	<0.0001	0.000148	<0.0001	0.00289
Fe	0.0054	0.0045	0.0059	0.001	0.0107	0.0027	0.0005	0.0025	0.0027	0.0247	0.0871	0.0022	0.545	0.0089
Hg	0.000006	0.000005	0.000003	0.000021	0.000003	0.000013	<0.000002	<0.000002	0.000003	<0.000002	0.000002	<0.000002	<0.000002	<0.000002
Mn	<0.00003	0.000282	0.000264	0.000062	0.000153	0.000306	<0.00003	0.000451	0.000505	0.341	0.0945	0.000166	0.419	0.000574
Mo	0.0173	0.0218	0.0102	0.0311	0.00184	0.0348	0.0001	0.000075	0.000266	0.00963	0.00322	0.000177	0.0112	0.0092
Ni	0.000129	0.000083	<0.00005	0.000141	0.000718	0.000356	<0.00005	0.000558	0.000566	0.00107	0.0128	0.000352	0.000614	0.000851
Pb	0.000102	0.000061	0.00002	0.00002	0.00017	0.000092	<0.000005	0.000545	0.00004	0.000311	0.000333	0.000022	<0.000005	<0.000005
Sr	0.0146	0.0296	0.0444	0.00382	0.00869	0.0439	0.00427	0.00375	0.0305	6.32	3.99	0.0276	8.06	5.95
Zn	0.0149	0.0101	0.000805	0.00179	0.00301	0.000998	0.000885	0.127	0.0428	0.00437	0.0064	0.000695	0.00297	<0.0002
TDS	414	241	270	219	185	596	-	88	178	27600	12958	165	15400	30682

1: °C; 2: Unitless; 3: µS/cm and other element concentrations are in mg/l.