UNITED NATIONS UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME
Orkustofnun, Grensásvegur 9,
IS-108 Reykjavík, Iceland

Reports 2010
Number 31

CHEMICAL ASSESSMENT OF WATER PROSPECTS FOR DIRECT APPLICATIONS IN NICARAGUA

Manuel A. Vanegas Carvajal
National Autonomous University of Nicaragua, León (UNAN-León)
Faculty of Science and Technology, Department of Chemistry
León
NICARAGUA
manuel_vanegas29@yahoo.es

ABSTRACT

The chemical water quality of 30 samples from Nicaragua and 8 samples from Iceland were used to evaluate the potential for different direct-use applications. All the samples were classified according to the ternary Cl-SO_4-HCO_3 plot for chloride, sulphate, and bicarbonate water types. These samples showed a very variable chemical composition, influenced by water-rock interaction and geothermal alteration. Different water quality guidelines were used for the assessment of the prospect water according to different cascading applications. The water quality of the data sets were compared with the WHO (2008) drinking water standards; with many samples exceeding the optimum levels for parameters such as Na, Cl, SO_4, and TDS, and some samples breaching the drinking water guideline in trace elements such as arsenic. The European Union mineral water classification was used for balneological purposes, as well as a classification basis on pH and temperature; all the samples were compared with ten times the drinking water standards (applicable for recreational waters) and only a few samples were above these limits. For aquacultural purposes, the samples were evaluated according to physicochemical parameters such as temperature, pH, alkalinity and hardness, and to the inorganic toxicant constituents. Many samples exceeded the generally recommended values for fish culture in H_2S, Zn, Fe, Mn, and Al; and some exhibited higher Cr and As levels than the recommended limits. The water sample data were also classified on the basis of salinity and boron toxicity, and evaluated with respect to the minor and trace elements. The main problem in the samples was the high boron concentrations which limited the water's usefulness as irrigation water. Finally, the samples were chemically assessed for industrial uses, for example the pulp and paper industry; according to US EPA (2004) water quality guidelines, with many samples not being suitable for this purpose.

1. INTRODUCTION

Geothermal water contains a wide variety and concentration of dissolved constituents that make it a very good prospect for different applications such as balneology, agriculture, aquaculture, industrial processes and space/district heating. Aquacultural and balneological applications require geothermal fluids at the lowest temperature. However, these waters must satisfy the norms prescribed for different chemical and physicochemical parameters. The water quality plays an important role in the

water classification for different applications or specific requirements. The simplest chemical parameters often quoted to characterise geothermal waters are the total dissolved solids (TDS) that give a measure of the amount of chemical salts dissolved in the water and pH which is a measure of the acidity or alkalinity of the waters (Wright, 1991). The main problem for irrigation waters is the high concentration of total dissolved solids which are composed of soluble salts which can cause decreased plant growth and salt burns on the leaves (Gandouzi, 1999). Another important parameter to take into consideration is the toxic trace element concentration in water. Even though these elements are part of the earth's crust, they are not essential to humans. However, in some cases these elements can be balneologically effective; from a balneological standpoint, trace elements could have pharmacological applications. Some trace elements, called micronutrients, are required in low quantities by plants and their deficiency as their toxicity can cause devastating effects (Gandouzi, 1999). The suitability of geothermal water for fish culture can only be suggested, using a few postulated guidelines. According to those, some elements are essential for fish growth while others are very toxic; also trace elements can be concentrated in fish to levels unsafe for human consumption (Roberts, 1975). In industry, the main concern is metal corrosion and inorganic scale formation arising from the use of water under different conditions and in different processes (El-Manharawy and Hafez, 2003).

Nicaragua is a country with abundant water resources. About 10% of its territory consists of superficial waters but, in the long term, this resource could be decreasing due to indiscriminate deforestation. In addition, there has been significant contamination of these resources as a result of human activities, mainly industrial activities to the point where many shallow aquifers have been affected; this is a very important problem that needs to be addressed. As a result, it is necessary to find new water resources. An important resource is the great amount of water that is extracted from the earth and utilized in different geothermal power plants to produce electrical energy. In order to use this water for direct use, it is necessary to evaluate its quality through the chemical composition. Groundwater contains more dissolved solids than surface water; in general, this chiefly reflects their longer contact times with rocks at elevated temperatures, and their isolation from dilution by fresh precipitation. Sulphate is a more important species in groundwater than in surface water, and the concentration of metals such as Fe and Mn are higher in groundwater than in surface waters (Langmuir, 1997).

The aim of the present work is to study the chemical characteristics of surface and geothermal water to determine its suitability as a source of water for different applications such as: drinking water, agriculture, aquaculture, balneology and industrial applications. The chemical composition of the water is very important in order to assess its quality and its possible uses as well as to detect the presence of contaminants and determine the appropriate treatment for later uses.

In Nicaragua, studies have been conducted to determine the geochemical characterisation of the water in various geothermal fields (CNE, 2001), as well as to geochemically characterise the surface water and groundwater around Managua (Parello et al., 2008). However, no antecedents of direct heat applications were found, so the present work will be helpful in developing future projects with low-temperature geothermal resources in Nicaragua, as well as cascaded uses of the water from geothermal fields under exploitation. The geothermal resources in the country have been developed for electric power generation only; at least no direct uses were reported for the World Geothermal Congress 2010 held in Bali, Indonesia (Lund et al., 2010).

2. GEOTHERMAL RESOURCES

Geothermal energy is extracted from the natural heat within the Earth. Immense amounts of thermal energy are generated and stored in the Earth´s core, mantle and crust. At the base of the continental crust, temperatures are believed to range from 200 to 1,000°C, and at the centre of the earth the

temperatures may be in the range of 3,500-4,500°C. The heat is transferred from the interior to the surface mostly by conduction, and this conductive heat flow makes the temperature rise with increasing depth in the crust, on average 25-30°C/km. Geothermal production wells are commonly more than 2 km deep, but rarely much more than 3 km at present (Fridleifsson et al., 2008).

Exploitable geothermal systems occur in a number of geological environments. They can be divided broadly into two groups depending on whether they are related to active volcanism or not. High-temperature fields (>180°C) are usually related to active volcanism, mainly along so-called plate boundaries. There, the crust is highly fractured and thus permeable to water, and heat resources are readily available. These resources are used mostly for conventional power production. In such areas magmatic intrusions, sometimes with partly molten rock at temperatures above 1000°C, situated at a few kilometres depth under the surface, heat up the groundwater (Fridleifsson et al., 2008). The other group of geothermal systems is the low-temperature fields (< 180°C), mostly used for direct application of thermal energy. These geothermal resources are often unrelated to volcanoes and can be divided into four types: a) Resources related to deep circulation of meteoric water along faults and fractures; b) Resources in deep high-permeability rocks at high hydrostatic pressure; c) Resources in high-porosity rocks at pressures greatly in excess of hydrostatic (i.e. "geopressured") pressure; and d) resources in hot but dry (low-porosity) rock formations. All these, with the exception of type c), can also be associated with volcanic activity. Types c) and d) are not commercially exploited as yet (Fridleifsson et al., 2008).

2.1 Geothermal utilisation

Geothermal utilisation is commonly divided into two categories, i.e. electricity production and direct application. Conventional electric power production is commonly limited to fluid temperatures above 180°C, but considerably lower temperature can be used with the application of binary fluids (outlet temperature commonly about 70°C). The ideal inlet temperatures into buildings for space heating is about 80°C, but by application of larger radiators in houses/or the application of heat pumps or auxiliary boilers, thermal waters with temperatures only a few degrees above the ambient temperature can be used beneficially (Fridleifsson et al., 2008).

2.2 Geothermal direct uses

Direct or non-electric utilisation of geothermal energy refers to the immediate use of the heat energy rather than to its conversion to some other form such as electrical energy. The main types of direct application include swimming, bathing and balneology (therapeutic use), space heating and cooling, agriculture (mainly greenhouse heating and some animal husbandry), aquaculture (mainly fish ponds), industrial processes, and heat pumps for cooling (Lagat, 2010). Direct uses do not include applications where the geothermal energy is used in generating electricity (Tylor, 2005). But the combination of direct-use with electric power production is a positive strategy for the development of direct-use applications, especially industrial uses. One of the main attractions of this strategy is that relatively high-temperature fluid from the waste stream of a geothermal electric plant is produced without assuming the economic risks and costs related to the drilling of a conventional geothermal well (Tylor, 2005).

The Líndal diagram is widely used in the geothermal community to depict temperature as a guideline for direct applications. The diagram shows several current and potential uses of geothermal energy, ranging from fish farming and soil heating at low temperatures, through space heating and drying at intermediate temperatures, to electric power generation and industrial processing at high temperatures as shown in Figure 1 (Líndal, 1973). Based on update papers submitted to the World Geothermal Congress 2010 covering the period 2005 to 2009, papers from 70 countries were received, 66 of which reported some geothermal direct uses, with 12 additional countries added from other sources giving a

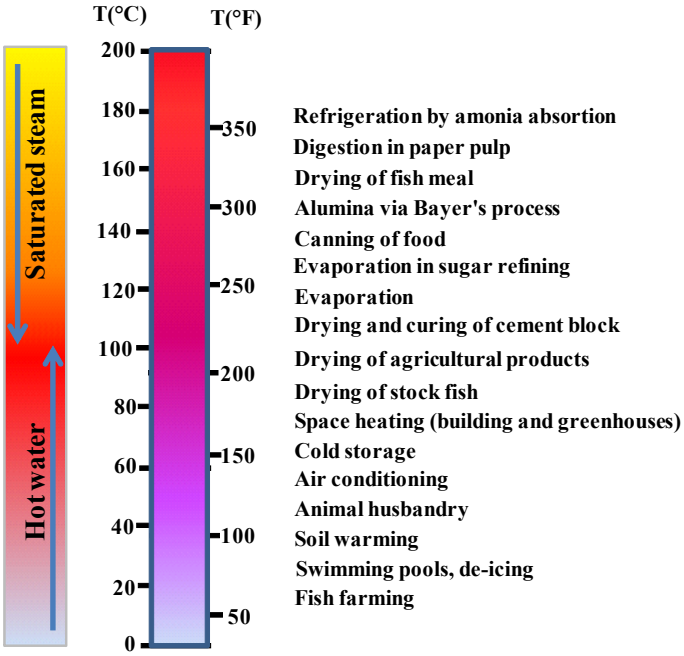

FIGURE 1: Líndal diagram - current and potential uses of geothermal energy (Líndal, 1973)

total of 78 countries. That is an increase of six countries since the World Geothermal Congress of 2005; these countries are Bosnia & Herzegovina, El Salvador, Estonia, Morocco, South Africa and Tajikistan (Lund et al., 2010).

Aquacultural, spa and pool applications require geothermal fluids of the lowest temperature (25-95°C), space heating and greenhouse requirements are in the range of 50-95°C, and industrial processes need the highest temperatures, over 95°C (Tylor, 2005). However, there are opportunities for lower temperature usage in most industrial processes, through heat recovery within the process itself and, unless the steam is consumed in the process, no boiler make-up water heating is required (Rafferty, 2003).

In agriculture, geothermal water is used mainly as a source of heat and moisture. Agricultural applications make direct use of geothermal water, using it to heat and water plants, warm greenhouses, or to dry crops (Tylor, 2005). Numerous commercially marketable crops have been raised in geothermally heated greenhouses in Hungary, Russia, New Zealand, Japan, Iceland, China and the U.S. These include vegetables, such as cucumbers and tomatoes, flowers, houseplants and tree seedlings (Freeston, 1996). In these countries, the climate is very cold almost all year; however, it is possible to create an acclimatised environment in other countries in which the temperature is more or less stable (Lagat, 2010). In countries with tropical climates, such as Kenya, a greenhouse heating system for flower growth has been reported. There, geothermal wells, which are not suitable for power production, supply warmth and CO_2 for greenhouses (Bertani, 2010). Tunisia reports the use of low-enthalpy resources for irrigation and heating greenhouses. Countries such as El Salvador, Guatemala and México are currently using geothermal energy for drying fruits; Guatemala is also applying geothermal energy to concrete curing (Lund et al., 2010).

Aquaculture involves the raising of freshwater or marine organisms in a controlled environment to enhance production rates (Lund, 2009). The aim of geothermal aquaculture is to adjust water temperature to an optimum temperature for animal growth. Species typically raised include carp, catfish, bass, tilapia, mullet, eels, salmon, sturgeon, shrimp, lobster, crayfish, crabs, oysters, clams, scallops, mussels and abalone (Aligan, 2010). Typical water chemistry for a fish farm is: 7.8 pH, 980 ppm Na, 46 ppm K, 132 ppm Ca, 33 ppm Mg, and 65 ppm SiO_3. All of these, as well as nitrogenous waste from the fish and chlorine levels (from municipal water supplies), are water chemistry factors that can affect fish growth (Tylor, 2005). Using geothermal heat allows better control of pond temperature, thus optimising growth. Fish breeding has been successful in Japan, China and the U.S. (Freeston, 1996). The most important factors to consider are the quality of the water and disease. If geothermal water is used directly, concentrations of dissolved heavy metals (fluorides, chlorides, arsenic, and boron) must be considered (Lagat, 2010).

Drinking and bathing in geothermal water, and using the mud precipitates on the skin are thought to give certain health benefits. Geothermally heated swimming pools often have a desirable temperature of 27-32°C. However, this will vary from culture to culture by as much as 5°C. If the geothermal water is higher in temperature, then some sort of mixing or cooling by aeration or in a holding pond is

required to lower the temperature. If the geothermal water is used directly in the pool, then a flow through process is necessary to replace the "used" water on a regular basis. In many cases, the pool water must be treated with chlorine, thus, it is more economical to use a closed loop for the treated water and have the geothermal water provide heat through a heat exchanger (Lund, 2009).

Industrial applications mostly need a higher temperature than that for space heating, greenhouses and aquacultural projects. Examples of industrial operations that have used geothermal energy are: heap leaching operations to extract precious metals in the USA (110°C), dehydration of vegetables in the USA (130°C), diatomaceous earth drying in Iceland (180°C), and pulp and paper processing in New Zealand (205°C). Drying and dehydration may be the two most important processing uses of geothermal energy. A variety of vegetable and fruit products can be considered for dehydration using geothermal temperatures such as onions, garlic, carrots, pears, apples and dates (Lund, 2009).

3. DESCRIPTION OF THE STUDY AREAS

The geothermal areas were selected to cover both types of geothermal fields, with high and low enthalpy. Also taken into consideration were the location of these areas with respect to the communities or cities, and the high potential for direct use due to accessibility, as in the case of San Jacinto – Tizate geothermal field, Apoyo caldera and Mombacho volcano areas. The sample selection in these areas was done taking into account the expected geochemical composition of the samples due to the geological setting and the historical data. The Icelandic geothermal fields were selected considering both high- and low-enthalpy geothermal fields and the special chemical characteristics of the diluted geothermal waters; some Icelandic samples were expected to be similar to samples from Nicaragua. These could be used for potential comparison purposes since Iceland is a country with much experience in direct-heat uses in greenhouses, fish drying, etc.

3.1 Nicaragua geothermal areas

3.1.1 San Jacinto – Tizate geothermal field

The San Jacinto – Tizate geothermal field (Figure 2) is located in SW-Nicaragua, in the southern part of the Chortis block, which is a unit of mainly continental crust belonging to the Caribbean plate. More precisely, the area is located within the Nicaraguan depression, which is a large subsiding area developed parallel to the Pacific Coast and Middle America Trench (CNE, 2001).

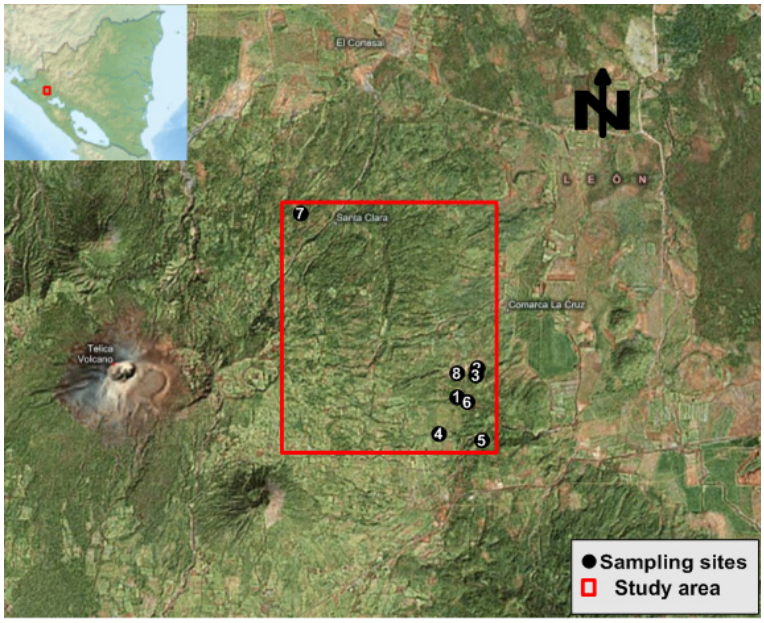

FIGURE 2: San Jacinto-Tizate Geothermal field

The geological and tectonic history of the western region of Nicaragua has been strictly related to the geodynamic evolution of the pacific continental margin, characterised by subduction of the Cocos oceanic plate beneath the Caribbean continental plate (CNE, 2001).

The perforations made in the San Jacinto – Tizate geothermal field have provided extensive information about the underground stratigraphy of the area. The lithological samples of the wells

present a sequence of different units ranging from recent volcanic products from the active mountain range over older volcanic rocks to volcano-sedimentary rocks of the tertiary.

Geochemical information provided by the geothermal wells drilled in San Jacinto – Tizate suggests that the deeper and hotter fluid found in the area is Na-Cl type water with 2,700 mg/l of Cl at 300°C and an approximately neutral pH, which is typical of hydrothermal systems of moderately high temperatures developed in young volcanic rocks. The test data from the wells and the gas chemistry suggest that the site is dominated by the liquid phase (CNE, 2001).

Shallow ground water in the geothermal reservoir shows dilute Ca cation mixing composition, HCO_3, and a chloride content of 40 mg/l; much of these waters are influenced thermal activity, with temperatures varying from 25 to 50°C, derived from mixing processes with steam and/or acid sulphate waters (CNE, 2001). Figure 2 shows the sampling sites and Table 1 summarises the sample description.

TABLE 1: Sample description

Code	Sample description	Geothermal field	Resource type
1	Geothermal well SJ4	San Jacinto – Tizate	High-enthalpy
2	Geothermal well SJ5	San Jacinto – Tizate	High-enthalpy
3	Cyclone separator "brine"	San Jacinto – Tizate	High-enthalpy
4	Domestic well Estación de bombas	San Jacinto – Tizate	High-enthalpy
5	Domestic well Porfirio Carrero	San Jacinto – Tizate	High-enthalpy
6	Domestic well close to SJ-4	San Jacinto – Tizate	High-enthalpy
7	Domestic well El Ñajo	San Jacinto – Tizate	High-enthalpy
8	Spring ojo de agua	San Jacinto – Tizate	High-enthalpy

3.1.2 Apoyo caldera and Mombacho volcano areas

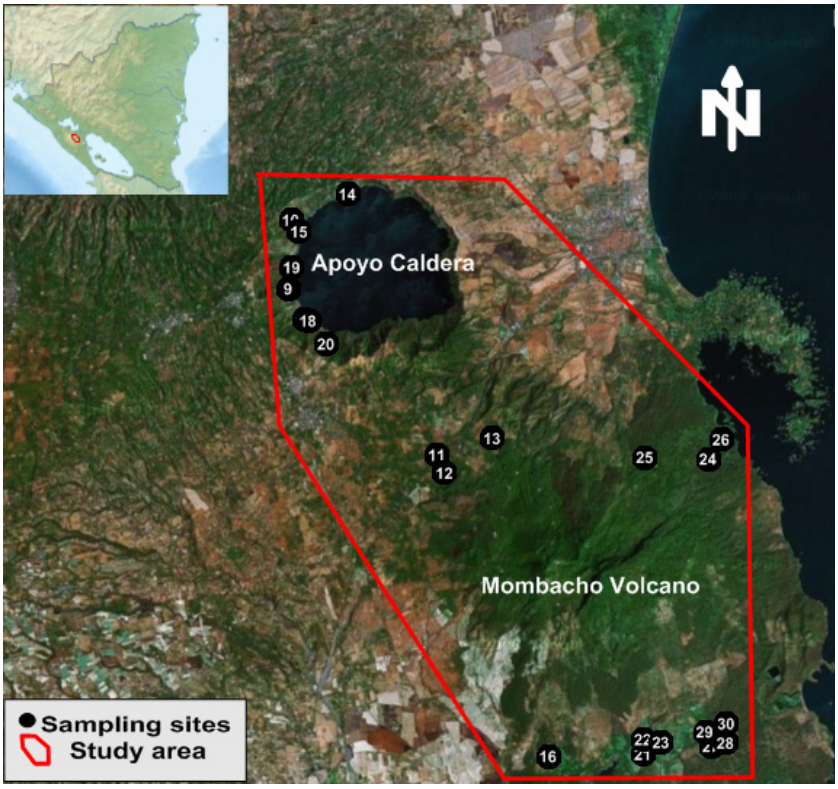

FIGURE 3: Apoyo caldera and Mombacho volcano

The Apoyo caldera and Mombacho volcano (Figure 3) are part of the Masaya-Granada-Nandaime geothermal field. This area has been studied previously as well as other geothermal areas in Nicaragua. The results of these studies are summarised in the geothermal master plan of Nicaragua 2001. This area is located northwest of Nicaragua Lake.

The Apoyo caldera and Mombacho volcano are aligned in a NW-SE direction in the central part of the area mentioned above; the Apoyo caldera is in the central part and the Mombacho volcano is in the southeast part of the area. The Apoyo caldera was formed by a collapsed volcanic structure. Inside the

caldera there is a lagoon, and it has walls of 100 to 450 m height. The collapsed structure consists of basaltic and andesitic lavas and a pyroclastic series with intercalations of basaltic lavas (CNE, 2001).

The Mombacho volcano is a strata volcano 50 km^3 in volume with an elevation of 1,340 m; it is characterised by lavas flows intercalated with pyroclastic products and two large landslides of rocks from the top on the northeast and southeast sides of the volcano. What is known as the Mombacho "main crater" is the space formed by the landslide of rocks to the southeast. The volcanism of the Mombacho volcano seems to be younger than that of the Apoyo collapse (CNE, 2001).

The superficial hydrothermal manifestations in the area are comprised of strong fumaroles of volcanic type in the Masaya complex. The temperature of the fumeroles reaches up to 99°C at the Mombacho volcano top. The Mombacho fumaroles have hydrothermal characteristics with magmatic influence; the gas geothermometers suggest temperatures above 300°C. South of these fumaroles there are several springs with temperatures of 54°C. Further south is another group of hot springs with temperatures of about 60°C. At the northern part of the volcano there is a hot spring with a temperature of 38°C at an elevation of 200 m a.s.l. and another with a temperature of 55°C at the Nicaragua lake level. The chemistry of the hot springs at the highest elevations corresponds to shallow heated waters by vapour and conduction. The hot springs at the lowest elevations in the south are products of mixing shallow water with the deepest, hottest Na-Cl type components (CNE, 2001).

The maximum temperature of the hot springs located along a 4 km part of the west and southwest shores of the Apoyo lagoon is 97°C. The discharge water is Na-Cl dominated with salinity of 4000 mg/l. The correlation between Cl in the diluted cold waters and the thermal water indicate a deeper origin with a temperature of at least 220°C. The chemistry of the water of the Apoyo lagoon suggests the probable existence of thermal springs at the bottom of the lagoon (CNE, 2001). Figure 3 shows the sampling sites and Table 2 summarises sample descriptions.

TABLE 2: Sample descriptions

Code	Sample description	Geothermal field	Resource type
9	Domestic well Estancia de Adriano	Apoyo-Mombacho	Low-enthalpy
10	Domestic well Hospedaje El Cráter de Doña Ana	Apoyo-Mombacho	Low-enthalpy
11	Domestic well San Antonio en Caña Castilla	Apoyo-Mombacho	Low-enthalpy
12	Domestic well Casa de doña Cristina Gallo	Apoyo-Mombacho	Low-enthalpy
13	Domestic well Casa de Retiro Tepeyac	Apoyo-Mombacho	Low-enthalpy
14	Domestic well Villa Petra	Apoyo-Mombacho	Low-enthalpy
15	Domestic well Costa Brava. Casa de Doña Susana Dewinne	Apoyo-Mombacho	Low-enthalpy
16	Domestic well Aguas Agrias	Apoyo-Mombacho	Low-enthalpy
17	Spring El Herbazal	Apoyo-Mombacho	Low-enthalpy
18	Spring Nº 2 El Herbazal	Apoyo-Mombacho	Low-enthalpy
19	Spring C-1 Laguna de Apoyo. Sector Los Pochotes	Apoyo-Mombacho	Low-enthalpy
20	Spring El Limón	Apoyo-Mombacho	Low-enthalpy
21	River El Borbollón Mecatepe	Apoyo-Mombacho	Low-enthalpy
22	River Caliente Mecatepe	Apoyo-Mombacho	Low-enthalpy
23	Apoyo lagoon (Shore) Sector Los Pochotes	Apoyo-Mombacho	Low-enthalpy
24	Lagoon Aguas Calientes. Point 1. Granada	Apoyo-Mombacho	Low-enthalpy
25	Lagoon Aguas Calientes. Point 2. Granada	Apoyo-Mombacho	Low-enthalpy
26	Lagoon Aguas Calientes. Point 3. Granada	Apoyo-Mombacho	Low-enthalpy
27	Hot lagoon Las Plazuelas	Apoyo-Mombacho	Low-enthalpy
28	White lagoon 1 Las Plazuelas	Apoyo-Mombacho	Low-enthalpy
29	White lagoon 2 Las Plazuelas	Apoyo-Mombacho	Low-enthalpy
30	Green lagoon Las Plazuelas	Apoyo-Mombacho	Low-enthalpy

3.2 Icelandic geothermal fields

3.2.1 Krafla and Námafjall geothermal fields

The Krafla field (Figure 4) lies within the caldera of the Krafla central volcano; the volcano has erupted both basaltic and silicic magma (Jónasson, 1994). The aquifer rock is, however, largely basaltic, sub-aerially erupted lavas, sub-glacially erupted hyaloclastites as well as small intrusive bodies of basalt, dolerite and gabbro. Intrusions of granophyre also occur (Giroud, 2008).

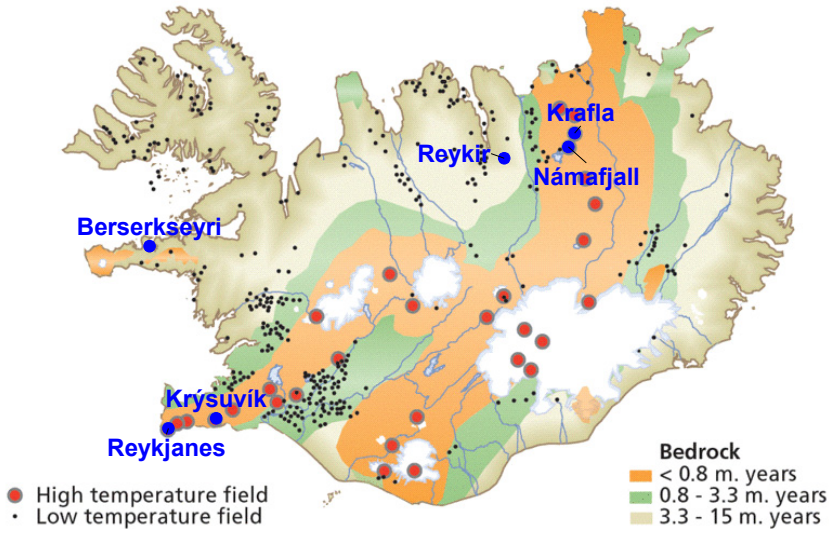

FIGURE 4: Map of Iceland showing the study areas in blue

The drilled geothermal reservoir at Krafla has been divided into two main depth zones, an upper sub-boiling zone at 190-200°C and a lower two-phase zone with temperatures of up to 350°C (Ármannsson et al., 1989; Arnórsson, 1995). Quartz geothermometer and Na-K temperatures indicate that most aquifers producing into wells in this field are below 300°C (Gudmundsson and Arnórsson, 2002; Giroud, 2008). The Námafjall field (Figure 4), which lies 8 km south of Krafla, may be regarded as a parasite system to the Krafla volcano. The 1975-84 volcanic episodes suggest that the heat source to the Námafjall geothermal system is represented by the dykes formed by magma intrusion into tensional fissures from the magma body in the roots of the Krafla system. The aquifer rock at Námafjall is the same as at Krafla except that silicic rocks are absent (Giroud, 2008).

In wells drilled at Námafjall, prior to the 1975-84 volcanic episodes, temperatures follow the boiling point curve with depth. In wells drilled in another part of the field after the 1975-84 volcanic episodes, the temperature at the top of the reservoir is sub-boiling. These low temperatures are considered to be the consequence of cold shallow groundwater incursions along fractures that were activated during the 1975-84 volcanic episodes. The maximum recorded temperature in drillholes at Námafjall is 320°C (Gudmundsson and Arnórsson, 2002). As at Krafla, geothermometers indicate that aquifers producing into wells at Námafjall have considerably lower temperatures than this maximum (Gudmundsson and Arnórsson, 2002; Giroud, 2008).

3.2.2 Reykjanes geothermal field

The Reykjanes geothermal system (high-temperature geothermal field), located on the Reykjanes peninsula (Figure 4) in SW-Iceland, is an oblique on-shore segment of the Mid-Atlantic ridge with active spreading initiated around 6-7 m.y. ago. The peninsula consists mostly of Holocene lavas protruded by hyaloclastite hills formed by sub-glacial eruptions during the last glaciation (Jakobsson et al., 1978; Clifton and Kattenhorn, 2006). In view of the geological setting, the heat source to this system is considered to be a sheeted dyke complex and the permeability is fracture controlled. Percolation of sea water into the reservoir rock has been reported on the Reykjanes peninsula. The exploited geothermal system is hosted by basaltic rocks, subglacial hyaloclastites, breccias and pillow lavas as well as tuffaceous sediments. The abundance of intrusions increases with depth. The highest temperature recorded is about 320°C at 2000 m depth. The aquifer is two phase above 1000 m but sub-boiling at greater depth (Giroud, 2008).

3.2.3 Krýsuvík geothermal field

The Krýsuvík geothermal area is located on the Reykjanes Peninsula (Figure 4). The Krýsuvík field is one of five presently active geothermal fields on the Reykjanes Peninsula. Several shallow wells were drilled in Krýsuvík during the first exploration phase. Hydrothermal alteration within the wells was reported to be similar in pattern to other high-temperature fields. Maximum temperatures were reported at 200-500 m depths. Proper upflow zones were not found. Study of the drill cuttings showed that upper Pleistocene strata are mostly composed of hyaloclastite units with thinner intervening basaltic lava units of interglacial age. Thermal waters from wells in the Krýsuvík high-temperature geothermal field display a large variation in dissolved solids (Arnórsson et al., 1975).

3.2.4 Berserkseyri geothermal field

The Berserkseyri (Figure 4) low enthalpy geothermal field is part of the Snaefellsnes geothermal area which is located in West Iceland. This area is volcanologically active and is characterised by the production of alkaline rock ranging from basaltic to trachytic in composition. (Óskarsson and Sigvaldason, 1982). The overweighing quantity of volcanic material in Snaefellsnes was produced in post-glacial times and upper Quaternary times. Geological studies indicate that volcanic activity on Snaefellsnes has, since upper Quaternary times, been confined to a narrow zone which coincides with the mountain range running along the middle of the peninsula. This zone appears to represent a structural weakness extending well into the mantle, as witnessed by the magmatic activity. However, no high-temperature fields are known in Snaefellsnes (Strelbitskaya, 2005).

3.2.5 Reykir geothermal field in Fnjóskadalur

The Reykir low-temperature geothermal area (Figure 4) is located at the head of the Fnjóskadalur valley, some 30 km southeast of Akureyri in North-Central Iceland (Árnadóttir et al., 2010). The Fnjóskadalur valley is separated from the Eyjafjördur valley (and fjord) by a low flat mountain named Vadlaheidi (highest point 854 m a.s.l.). The geothermal resource at Reykir has been known for a long time. Its surface manifestation was a series of closely spaced hot springs rising from the gravel deposits covering the floor of Fnjóskadalur valley. Formations from two different geological stages are among the key features in the area. Two lava flows east of Reykir belong to a Pliocene rock formation which lies discordantly on top of the Miocene formations. These two lava flows are separated by a sedimentary sequence (siltstones and sandstones). In some areas, these sediments contain lignite horizons. A pronounced thermal anomaly is associated with the Reykir low-temperature field. Flow testing indicates that the field is among the more powerful low-temperature geothermal systems in Iceland. Reykir is considered to sustain long term average production of 50 l/s (Árnadóttir et al., 2010). Figure 4 shows the sampling sites and Table 3 summarises the sample description.

TABLE 3: Sample descriptions

Code	Sample description	Geothermal field	Resource type
31	Geothermal water, partly seawater	Berserkseyri	Low-enthalpy
32	Dilute geothermal water	Reykir in Fnjóskadalur	Low-enthalpy
33	Wastewater	Reykjanes	High-enthalpy
34	Wastewater & discharge	Reykjanes	High-enthalpy
35	Water from silencer	Krafla	High-enthalpy
36	Water from silencer	Námafjall	High-enthalpy
37	Condensate	Reykjanes	High-enthalpy
38	Surface manifestation, near-boiling pool	Krýsuvík	High-enthalpy

4. HYDROGEOCHEMICAL PROCESSES

Geothermal systems are found with a variety of combinations of geological, physical, and chemical characteristics. The chemical characteristic of the geothermal fluid is controlled by the temperature and pressure of the reservoir, the salinity of the recharge fluid and the density of magmatic intrusions (Ármannsson and Fridriksson, 2009). It is common to classify geothermal waters according to their dominant anions HCO_3, Cl, and SO_4. The most common type for fresh groundwater is of near neutral pH bicarbonate waters, but as water reaches equilibrium in a geothermal environment, chloride commonly becomes the dominant anion. Sulphate is usually derived from magmatic origins in high-enthalpy geothermal systems. The hydrothermal alteration (triggered by the reaction of thermal waters with the country rocks) involves mineral, chemical and textural changes depending on the particular condition of both temperature and pressure. The main chemical processes from a discharging reservoir, either naturally or through utilisation, are mineral dissolution and precipitation, while the dominant physical process is boiling, although conductive cooling and mixing are also important. The constituents of thermal waters can be divided into soluble or non-reactive groups (Cl, B, Br, etc.) and rock forming species (SiO_2, Na, K, Ca, Mg, etc.), providing the basis for water classification and reservoir interpretation. The reactions involved are functions of the temperature, pressure, salinity, and host rock composition of the geothermal system. Any specific composition reflects the combined effect of initial fluid constituents, kinetics of primary mineral dissolution and secondary mineral deposition at changing temperature and pressure, vapour loss, dissolution, and mixing with fluids of different origin (Kühn, 2004).

The formation of many soluble minerals such as gypsum, sodium chloride, and calcite can result from the dissolution of different minerals; for example, the chemical reaction for weathering albite to kaolinite, and of K-feldspar to kaolinite can be resolved as (Dall´Aglio, 1991):

$$2NaAlSi_3O_8 + 2CO_2 + 3H_2O \longrightarrow Al_2Si_2O_5(OH)_4 + 2Na^+ + 2HCO_3^- + 4H_4SiO_4$$

$$2KAlSi_3O_8 + 2CO_2 + 3H_2O \longrightarrow Al_2Si_2O_5(OH)_4 + 2K^+ + 2HCO_3^- + 4H_4SiO_4$$

These reactions can also be expressed according to the following formula:

$$2KAlSi_3O_8 + 2H^+ + 9H_2O \longrightarrow Al_2Si_2O_5(OH)_4 + 2K^+ + 4H_4SiO_4$$

The resultant water would contain HCO_3^-, Na^+ (or K respectively) and SiO_2 in the ratio 1:1:2. Similar reactions for other minerals occur in the geothermal systems.

In groundwater, mineral solubility and kinetics determine the release of cations. Therefore, consideration of the availability of most soluble rock-forming minerals in the weathering zone of the bedrock is critical in establishing the initial qualities of the water. Dissolution of carbonate and silicate minerals is largely driven by the production of CO_2 within the soil zone by root respiration and bacterial metabolism on solid mineral phases within the soil (Edmunds and Shand, 2008). Different ratios of all these compounds, together with quantitative changes in the content of each element, determine the great diversity of groundwater, expressed in the existence of several thousand hydrogeochemical groundwater types (Komatina, 2004).

A spring is a concentrated discharge of groundwater appearing at the surface as a current of flowing water. Springs occur in many forms and have been classified after their cause, surrounding rock structures, discharge, temperature, or variability. Volcanic springs are associated with volcanic rocks and fissure springs result from fractures extending deep into the earth´s crust. Such springs are usually thermal (Todd and Mays, 2004).

5. CHEMICAL COMPOSITION OF FLUIDS

As mentioned above, the chemical composition of geothermal fluids is very variable. The chemistry of brine and condensate waters from geothermal utilities depends on the operating condition used for the generation of energy in different geothermal fields. On the other hand, superficial waters and shallow groundwater are influenced by geomorphology, lithology, hydrology, climate, and by hydrothermal alterations.

5.1 Nicaragua geothermal fields

5.1.1 San Jacinto – Tizate geothermal field

For the purposes of this study, a series of chemical data from between 2005 and 2008 taken from the San Jacinto geothermal field were compiled; the selected data are samples taken from the two-phase line of wells SJ4 and SJ5 which are currently producing wells; also water samples from the separator, hot springs, and shallow well waters of the zone where taken. Table 4 summarises the water type classification according to the ternary Cl-SO_4-HCO_3 plot (Figure 5).

TABLE 4: Order of the dominant major elements for the San Jacinto – Tizate geothermal field

Water type	Code of samples	Order of the major elements
Chloride	1, 2, 3,	Cations: Na > K > Ca > Mg Anions: Cl >HCO_3> SO_4 > B
	6	Cations: Na > Ca > Mg > K Anions: Cl > HCO_3 > SO_4 > B
Sulphate	7	Cations: Na > Ca > K > Mg Anions: SO_4 > Cl > HCO_3 > B
Bicarbonate	4, 5, 8	Cations: Ca > Na > Mg > K Anions: HCO_3 > SO_4 > Cl > B

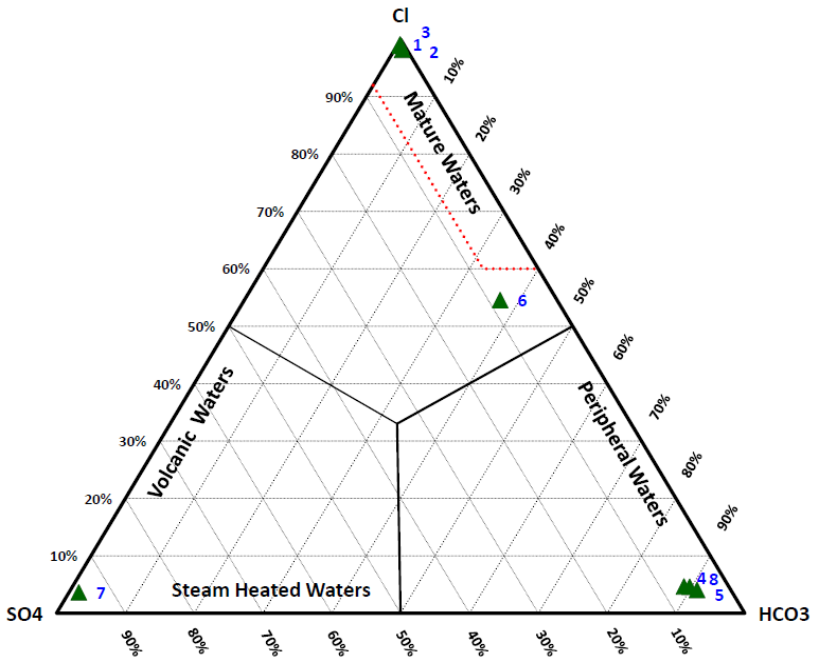

FIGURE 5: Ternary Cl-SO_4-HCO_3 (mg L^{-1}) plot of samples from San Jacinto-Tizate

The samples from San Jacinto – Tizate were classified according to their dominant anions, as shown in Figure 5. Samples 1 and 2, taken from discharge of deep geothermal wells, are chloride water type; sample 3 is also chloride water type but represents separated geothermal fluid. Sample 6 is of chloride water type, and comes from a domestic well close to geothermal well SJ4. Sample 7 is sulphate water type, being steam-heated groundwater. Samples 4, 5 (groundwater) and 8 (spring) are bicarbonate water type. These waters are common on the margin of the field with high CO_2 reactivity (Kühn, 2004). The chemical composition of the San Jacinto – Tizate geothermal field is shown in Table 5.

TABLE 5: Chemical composition of geothermal waters: brine, groundwater and springs in the San Jacinto – Tizate geothermal field

Parameters	Codes							
	1	2	3	4	5	6	7	8
T (°C)	211.40	186.70	26.16	27.67	36.18	48.00	52.90	29.77
pH	7.57	7.34	7.50	6.89	7.08	6.50	5.44	7.15
EC (µs/cm)	11471.61	9916.27	11430.00	282.82	303.97	1283.50	490.60	312.80
Na (mg/l)	2157.39	1830.91	2103.40	18.15	17.66	166.60	59.60	16.34
K (mg/l)	428.46	367.52	414.36	6.02	4.50	17.25	20.50	4.35
Ca (mg/l)	61.28	38.84	56.88	26.35	28.43	101.70	44.50	32.75
Mg (mg/l)	0.02	0.01	0.02	9.05	9.48	30.52	7.96	10.74
Cl (mg/l)	3848.39	3258.73	3775.80	7.49	6.44	274.34	7.86	8.24
SO_4 (mg/l)	20.81	23.61	23.60	10.48	7.82	41.53	206.65	10.20
NO_3 (mg/l)	-	-	-	8.62	10.59	39.73	0.81	8.59
HCO_3 (mg/l)	14.29	38.05	20.26	143.31	145.32	186.96	3.11	160.71
SiO_2 (mg/l)	696.92	682.94	705.06	97.47	101.07	125.95	192.50	113.03
B (mg/l)	44.23	46.30	48.07	0.07	0.07	1.90	0.06	0.07
Li (mg/l)	5.51	4.68	5.40	0.04	0.05	0.05	0.05	0.04
As (mg/l)	4.88	3.97	4.84	0.01	0.01	0.01	0.01	0.01
Al (mg/l)	0.45	0.60	0.51	0.09	0.27	0.06	0.19	0.07
Rb (mg/l)	3.15	2.81	3.72	0.05	0.05	0.05	0.05	0.04
Cs (mg/l)	0.04	0.05	0.03	0.01	0.01	0.01	0.01	0.01
Sb (mg/l)	0.05	0.01	-	0.01	0.01	-	-	0.01
Pb (mg/l)	0.01	0.01	-	-	-	-	-	-
Fe (mg/l)	0.05	0.10	0.21	0.03	0.15	0.12	0.35	0.07
Zn (mg/l)	0.04	0.03	0.06	-	-	-	-	-
Cu (mg/l)	0.05	0.05	0.05	-	-	-	-	-
H_2S (mg/l)	0.01	0.01	0.01	-	-	-	-	-
NH_3 (mg/l)	0.05	0.21	-	0.06	0.06	-	-	0.12

1: Geothermal well SJ4; 2: Geothermal well SJ5; 3: Cyclone separator "brine"; 4: Domestic well Estación de bombas; 5: Domestic well Porfirio Carrero; 6: Domestic well close to SJ-4; 7: Domestic well El Ñajo; 8: Spring Ojo de agua.

5.1.2 Apoyo caldera and Mombacho volcano areas

A total of 22 samples were taken in the Apoyo caldera and Mombacho volcano geothermal areas. The analytical data given in Table 6 were provided by the Ministry of Energy and Mines of Nicaragua. These samples come from different sources such as groundwater, springs, streams, and from the Apoyo lagoon. The sampling campaign was in November 2009. All the analytical data were plotted in the ternary diagram (Figure 6). The concentration of cations and anions of each group is variable; the order of the dominant major elements is summarised in Table 7.

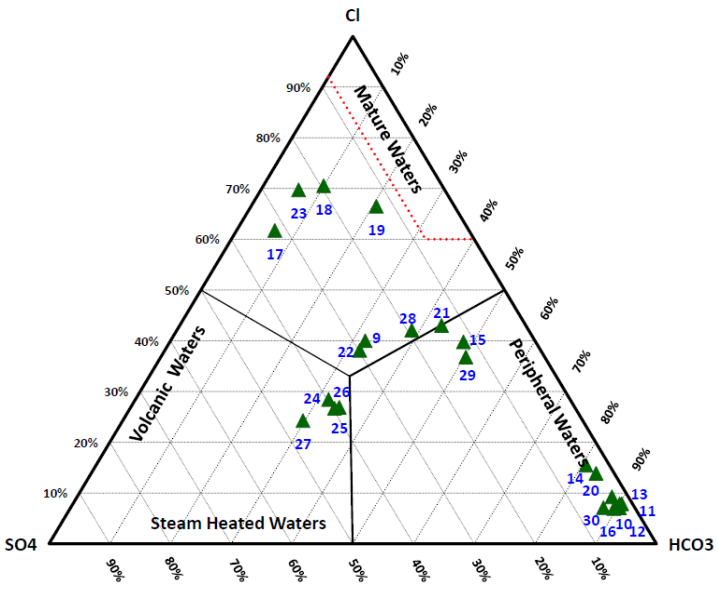

FIGURE 6: Ternary Cl-SO_4-HCO_3 (mg L^{-1}) plot for Apoyo caldera and Mombacho volcano data

TABLE 6: Chemical composition of groundwater and surface water for the Apoyo caldera and Mombacho volcano areas

Codes	T°C	pH	EC (µs/cm)	TDS (mg/L)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Mg (mg/L)	Cl (mg/L)	SO_4 (mg/L)	CO_2 (mg/L)	SiO_2 (mg/L)	B (mg/L)	Li (mg/L)	As (mg/L)	Rb (mg/L)	Cs (mg/L)	Fe (mg/L)	Cu (mg/L)
9	43.4	6.92	3790	1721	594.40	50.80	95.30	28.90	514.88	359.14	519.20	86.88	9.29	1.26	0.008	0.135	0.001	0.953	0.003
10	29.8	7.63	374	180	25.10	6.60	28.50	9.47	10.00	5.11	136.40	75.11	<0.1	0.01	0.005	0.016	0.005	0.013	0.002
11	29.5	6.95	305	151	14.91	4.70	23.80	10.60	8.00	2.89	129.36	93.52	<0.1	0.00	0.001	< 0.010	0.002	0.015	0.004
12	28.4	7.02	291	147	16.19	4.50	19.50	9.30	8.00	1.80	112.64	92.23	<0.1	0.00	0.000	< 0.010	0.001	0.015	0.001
13	27.7	6.83	310	155	13.70	4.50	25.20	12.30	9.00	2.42	139.48	94.59	<0.1	0.00	0.000	< 0.010	0.001	0.006	0.001
14	30.4	8.25	481	230	82.60	11.40	2.10	0.85	27.99	6.95	149.16	69.76	0.57	0.12	0.072	0.017	0.003	0.019	0.002
15	25.0	7.43	871	422	79.10	12.50	58.70	17.20	126.97	37.86	168.52	71.26	1.16	0.07	0.017	0.026	0.001	0.024	0.006
16	28.3	6.05	462	218	18.60	4.80	42.70	19.00	10.00	7.26	384.56	94.16	<0.1	0.02	0.001	< 0.010	0.019	0.005	0.001
17	67.0	6.24	5980	2710	970.20	100.70	161.80	20.80	1214.73	628.28	273.68	199.88	13.35	3.60	-	0.579	0.003	0.083	0.008
18	59.0	6.56	6350	2780	944.30	103.60	105.90	10.60	1409.68	389.51	312.40	240.54	10.95	3.52	-	0.670	0.002	0.214	0.004
19	31.6	8.09	5650	2643	845.10	125.10	83.10	25.70	1374.69	265.48	437.36	32.31	13.30	1.63	-	0.761	0.001	0.008	0.002
20	28.5	6.45	280	145	14.80	5.90	30.00	7.00	12.00	2.59	132.44	91.16	<0.1	0.01	0.002	< 0.010	0.015	0.014	0.001
21	49.3	6.16	2360	913	207.50	34.50	139.00	62.60	319.93	103.00	786.72	144.66	3.93	0.29	-	0.090	0.002	0.008	0.002
22	42.0	6.81	1854	828	172.90	31.70	98.00	37.60	259.94	203.04	292.16	151.51	3.06	0.30	-	0.134	0.177	0.018	0.001
23	56.8	7.17	6580	2761	961.20	2.50	125.80	14.40	1369.69	471.67	139.48	132.25	8.99	1.48	-	0.309	0.001	0.018	0.003
24	37.3	6.65	1604	704	142.50	118.30	126.90	28.20	170.79	238.72	286.00	156.65	1.82	0.13	-	0.077	0.013	0.123	0.004
25	35.2	6.78	1531	658	134.40	32.90	101.80	25.70	154.13	222.02	270.16	145.09	1.82	0.13	-	0.066	0.008	0.020	0.002
26	44.3	6.49	1558	654	135.10	28.60	97.50	25.90	154.13	228.65	328.68	145.73	1.73	0.13	-	0.056	0.004	0.022	0.001
27	43.5	6.70	1502	651	131.20	37.00	86.90	24.10	133.30	252.74	232.76	160.50	1.45	0.19	0.156	0.128	0.004	0.008	0.003
28	42.5	5.99	1612	723	142.90	18.70	92.10	36.70	220.78	100.82	650.32	125.73	2.68	0.26	-	0.066	0.018	0.008	0.002
29	32.0	6.17	730	352	57.70	9.10	48.20	18.90	84.98	29.96	296.56	98.23	0.81	0.10	-	0.023	0.019	0.012	0.002
30	33.9	8.88	394	204	29.40	8.90	25.00	12.30	13.75	3.99	136.40	83.89	<0.1	0.11	-	< 0.010	0.002	0.016	0.003

9: Domestic well Estancia de Adriano; 10: Domestic well Hospedaje El Cráter de Doña Ana; 11: Domestic well San Antonio in Caña Castilla; 12: Domestic well Cristina Gallo house; 13: Domestic well Retiro Tepeyac house; 14: Domestic well Villa Petra; 15: Domestic well Costa Brava Susana Dewinne house; 16: Domestic well Aguas Agrias (dump); 17: Spring El Herbazal; 18: Spring Nº 2 El Herbazal; 19: Spring C-1 Apoyo lagoon, Los Pochotes Sector; 20: Spring Río El Limón; 21: River El Borbollón Mecatepe; 22: River Caliente Mecatepe; 23: Apoyo lagoon (shore), Los Pochotes Sector; 24: Lagoon aguas calientes, Point 1 Granada; 25: Lagoon aguas calientes, Point 2, Granada; 26: Lagoon aguas calientes, Point 3, Granada; 27: Hot lagoon Las Plazuelas; 28: White lagoon 1 Las Plazuelas; 29: White lagoon 2 Las Plazuelas; 30: Green lagoon Las Plazuelas.

5.2 Iceland geothermal fields

Analytical data of six different geothermal fields from Iceland were taken into consideration for this study: Berserkseyri, Reykir in Fnjóskadalur, Reykjanes, Krafla, Námafjall and Krýsuvík. The nature of these fluids is variable: geothermal water, separated water, wastewater and water from a hot spring. The data were taken from the ISOR database, except the Krýsuvík data (Markússon, 2009). The chemical constituents for the fluids are listed in Table 8. All data was picked for comparative purposes with respect to geothermal direct uses.

TABLE 7: Order of dominant major elements for de Apoyo caldera and Mombacho volcano

Water type	Code of samples	Order of the major elements
Chloride	9, 19, 22	Cations: Na > Ca > K > Mg Anions: Cl >HCO_3> SO_4 > B
	17, 18, 23, 28	Cations: Na > Ca > K > Mg Anions: Cl > SO_4 > HCO_3 > B
Sulphate	24, 25, 26, 27	Cations: Na > K > Ca > Mg Anions: SO_4 > HCO_3 > Cl > B
Bicarbonate	10, 11, 12, 13, 20	Cations: Ca > Na > Mg > K Anions: HCO_3 > Cl > SO_4 > B
	15, 21, 29, 30	Cations: Na > Ca > Mg > K Anions: HCO_3 > Cl > SO_4 > B
	16	Cations: Ca > Mg > Na > K Anions: HCO_3 > Cl > SO_4 > B
	14	Cations: Na > Ca > K > Mg Anions: HCO_3 > Cl > SO_4 > B

TABLE 8: Chemical composition of geothermal water, wastewater, and a hot spring in selected Icelandic geothermal fields

Parameters	Codes							
	31	32	33	34	35	36	37	38
T (°C)	77	88.1	-	-	100	6.4	-	95
pH	6.7	9.79	5.94	7.73	9.86	4.58	6.9	2.72
EC (µs/cm)	9630	220	-	-	1171	615	13.8	-
TDS (mg/l)	6390	216	41770	28310	1372	784	-	-
Na (mg/l)	1148	48.1	12100	6800	255	92.6	0.03	12.38
K (mg/l)	27.1	0.84	1779	418	33.3	16.3	-	0.7
Ca (mg/l)	872	1.7	2020	520	3.65	4.49	0.01	44.75
Mg (mg/l)	37.4	0.005	1.03	675	0	2.17	-	26.05
Cl (mg/l)	3120	6.57	24200	15050	66.4	55.6	0.1	8.66
SO_4 (mg/l)	471	15.7	18.4	1600	262	175	0.14	606
SiO_2 (mg/l)	149	105.8	874	82	611.7	234	0.04	169
B (mg/l)	0.48	0.08	9.95	3.3	0.98	1.64	-	0.05
Hg (mg/l)	-	-	-	0.00004	0.00002	0.00001	0.00001	-
As (mg/l)	-	0.0040	0.0990	0.1290	0.0347	0.1350	0.0003	0.0040
Pb (mg/l)	0.00006	0.00006	-	0.00108	0.00003	0.00014	-	0.00044
Cd (mg/l)	0.00001	0.00001	-	0.00005	-	0.00001	-	0.00002
Cr (mg/l)	0.00113	0.00006	0.00085	0.00045	0.00021	0.00021	-	0.0963
Al (mg/l)	0.0065	0.2180	0.0370	0.0012	1.4200	0.8320	0.0014	41.67
Mn (mg/l)	1.53	0.000193	3.84	0.295	0.0032	0.0236	0.000218	1.14
Fe (mg/l)	3.16	0.0029	1.25	-	0.039	0.603	0.016	18.76
Zn (mg/l)	0.00389	0.0151	0.00717	0.00272	0.00243	0.00378	-	0.221
Cu (mg/l)	0.000668	-	0.00121	0.00152	0.00152	0.000552	-	0.00029
Sr (mg/l)	7.1	0.00552	11	5.78	0.0221	0.011	-	0.084
H_2S (mg/l)	0.03	0.15	1.41	-	19.5	0.07	2.45	3.98
CO_2 (mg/l)	103	17.2	13.8	61.5	69.1	5.18	13.8	-

31: Berserkseyri (geothermal water), 32: Reykir í Fnjóskadalur (low-enthalpy dilute geothermal water), 33: Reykjanes (wastewater); 34: Reykjanes (wastewater & discharge); 35: Krafla (high enthalpy field, water from silencer); 36: Námafjall (high enthalpy field, water from silencer); 37: Reykjanes (condensate); 38: Krýsuvík (high enthalpy surface manifestation, near cooling pool)

According to the ternary plot of the relative abundance of chloride, sulphate and bicarbonate (Figure 7) the samples are classified on the basis of the main anions: Chloride water type (geothermal waters); Sulphate water type (steam heated); Bicarbonate water type (Table 9).

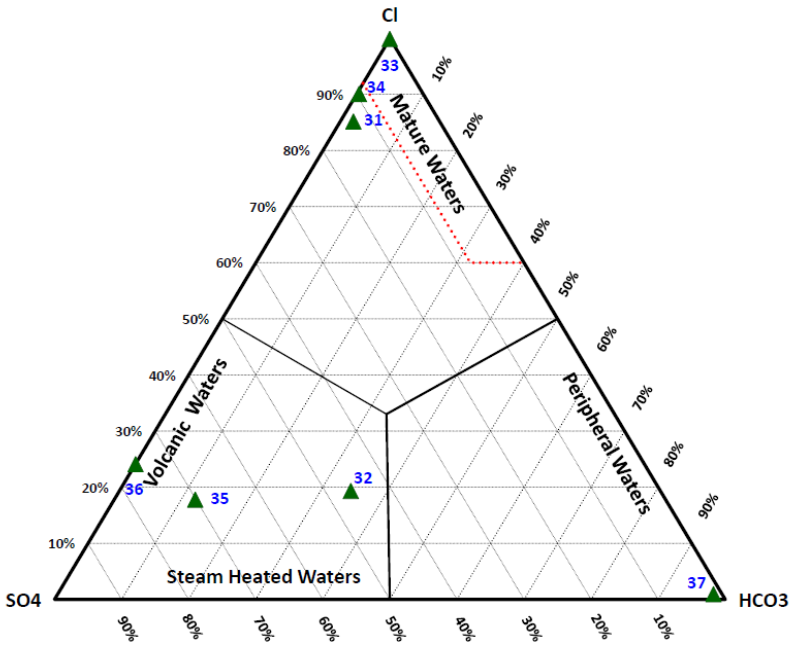

FIGURE 7: Ternary Cl-SO_4-HCO_3 (mg L^{-1}) plot for selected Icelandic geothermal fields

TABLE 9: Order of dominant major elements for the selected Icelandic geothermal fields

Water Type	Code of samples	Order of the major elements
Chloride	31	Cations: Na > Ca > Mg > K Anions: Cl > SO_4 > HCO_3 > B
	33	Cations: Na > Ca > K > Mg Anions: Cl > SO_4 > B > HCO_3
	34	Cations: Na > Mg > Ca > K Anions: Cl > SO_4 > HCO_3 > B
Sulphate	32	Cations: Na > Ca > K > Mg Anions: SO_4 > HCO_3> Cl > B
	35	Cations: Na > K > Ca > Mg Anions: SO_4 > Cl > HCO_3 > B
	36	Cations: Na > K > Ca > Mg Anions: SO_4 > Cl > B > HCO_3
	38	Cations: Ca > Mg > Na > K Anions: SO_4 > Cl > B
Bicarbonate	37	Cations: Na > Ca Anions: HCO_3 > SO_4 > Cl

6. CHEMICAL ASSESSMENT OF PROSPECTS FOR DRINKING WATER

Water coming from different natural sources contains many chemical species which are undesirable in drinking water. Sometimes these constituents have direct adverse impacts on the human health; others are responsible for turbidity or an unpleasant taste. Even when these constituents are not health related, they can be of concern with other aspects of water quality. Water with a dirty appearance or which is discoloured or with an unpleasant taste or smell could be rejected by consumers. This means that it is important to assess not only the safety measures but also the appearance of drinking water.

TABLE 10: WHO drinking water quality standards

Chemical Parameter	WHO Guideline value (mg/l)
pH	6.5-8.0*
TDS	600*
EC µS/cm	2500**
Aluminum (Al)	0.2
Antimony (Sb)	0.02
Arsenic (As)	0.01
Barium (Ba)	0.7
Boron (B)	0.5
Cadmium (Cd)	0.003
Chromium (Cr)	0.05
Chloride (Cl)	250*
Copper (Cu)	2
Fluoride (F)	1.5
Iron (Fe)	0.3*
Lead (Pb)	0.01
Manganese (Mn)	0.4
Mercury (Hg)	0.006
Molybdenum (Mo)	0.07
Nickel (Ni)	0.07
Nitrate (NO^{3-})	50
Nitrite (NO^{2-})	3
Sodium (Na)	200*
Selenium (Se)	0.01
Sulphate (SO_4)	250*
Zinc (Zn)	4*

*No health-based guideline, but for taste, odour and appearance.
**European commission, 2007.

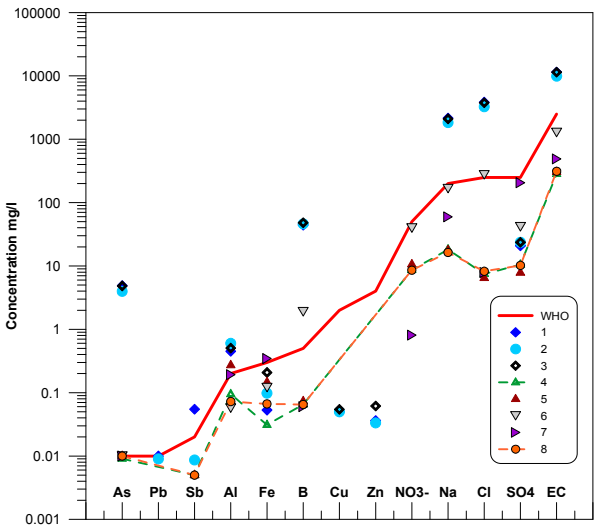

FIGURE 8: San Jacinto – Tizate data compared with WHO guideline values

For geothermal water, it is important to evaluate the chemical characteristics and compare that with the international standards for drinking water, perhaps not only for drinking purposes but for making decisions about the selection of the correct site for geothermal reinjection wells in order to avoid affecting the quality of the groundwater, which may be used for drinking. In the same manner, for balneological purposes, it is important to monitor the chemical characteristics because people sometimes consume the water while bathing or swimming.

Generally, most nations accept the standards prepared by the World Health Organization (WHO) for acceptable maximum concentrations of relevant chemicals in drinking water. The standards are summarised in Table 10 (WHO, 2008).

Some chemical parameters such as TDS, Cl, Fe, Na, SO_4, and Zn are considered to be of no concern to the health. However, despite that, they are of concern regarding taste, odour and appearance. The TDS is directly related to conductivity, so WHO only gives guideline values for TDS and not for conductivity; however, a guideline value of 2500 µS/cm is provided by the European Commission (2007). In Figure 8, the samples from San Jacinto geothermal field were compared with the WHO guidelines values. Samples 1, 2 and 3 are geothermal wells SJ4, SJ5 and brine from the separator.

These samples have been classified as chloride water type. As expected, these water types are not suitable for drinking; they exhibit high levels of conductivity, chloride, sodium, boron, and aluminium and exceed, on average, 500 times the health-based guideline values for arsenic (see Table 11). Sample 6 is also a chloride type of water; it exhibited higher boron concentrations than allowable by WHO guidelines; parameters such as arsenic, nitrate, sodium and chloride were close to this guideline. Samples 4, 5, and 8 are bicarbonate water type, suitable for drinking. But sample 8 was higher in aluminium concentrations than the guideline. However, aluminium is not a health-based guideline. Sample 7 is a sulphate water type,

slightly higher in iron concentrations than the reference value; As, Al, and SO_4 were very close to the maximum values permissible for drinking water.

The samples from Apoyo caldera and Mombacho volcano were divided into four groups. According to the origin of the samples, we have samples from groundwater, springs, river, and lagoon, and all these samples present thermal alteration. The groundwater samples are shown in Figure 9; it can be seen that there are three samples that are not suitable for drinking: samples 9, 14 and 15. Sample 9 (chloride water type) had higher values of Fe, B, Na, Cl, SO4, TDS, and electrical conductivity than the guidelines. These constituents give the water a saline taste. Boron, at high concentrations, can have physiological effects on humans. Samples 14 and 15 (bicarbonate water type) had slightly higher values for As and B than the WHO guideline while arsenic was above the recommended values for humans. Samples 10, 11, 12, 13, and 16 (bicarbonate water type) were suitable for drinking. Sample 16 had a pH of 6.05 while the guideline value is between 6.5 and 8.0, so this indicates that the pH poses here a problem for drinking purposes.

Figure 10 shows a graphical representation for samples from springs and river. The graph shows that only sample 20 (bicarbonate water type) is suitable for drinking. Samples 17, 18, and 19 (chloride water type) exceed the guideline values for TDS, electrical conductivity, boron, chloride, sodium and sulphate. Samples 21 (bicarbonate water type) and 22 (chloride water type) exceeds the guideline for TDS, boron and chloride, while sample 21 also presented slightly too high contents of sodium, exceeding the reference value for aesthetics.

Samples 23 (chloride water type), 24, 25, 26, 27 (sulphate water types), and 28 (chloride water type) exhibited a high content of TDS and boron. Sample 23

TABLE 11: Chemical parameters of all the samples compared with WHO guideline values

Chemical Parameter	Code of the samples																																							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	25	26	27	28	29	30	31	32	33	34	35	36	37	38
T (°C)	211	187	26	28	36	48	53	30	43	30	30	28	28	30	25	28	67	59	32	28	49	42	57	37	35	44	44	43	32	34	77	88	NA	NA	100	6	NA	95
pH	S	S	S	S	S	S	X	S	S	S	S	S	S	X	S	X	X	S	X	X	X	S	S	S	S	X	S	X	X	X	S	X	X	S	X	X	S	X
TDS	NA	NA	NA	NA	NA	NA	NA	NA	X	S	S	S	S	S	S	S	X	X	X	S	X	X	S	X	X	X	X	X	S	X	S	X	X	X	X	X	NA	NA
EC	X	X	X	S	S	S	S	S	X	S	S	S	S	S	S	S	X	X	X	S	S	X	X	S	S	X	S	X	S	S	X	S	X	NA	S	S	S	NA
Al	X	X	X	S	X	S	S	S	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	S	X	S	S	X	X	S	X
Sb	X	S	NA	S	S	NA	NA	S	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	X	NA
As	X	X	X	S	S	S	S	S	S	S	S	S	S	X	X	S	NA	NA	NA	S	NA	NA	NA	NA	NA	NA	X	NA	NA	NA	NA	S	X	X	X	X	X	S	S
B	X	X	X	S	S	X	S	S	X	S	S	S	S	X	X	S	X	X	X	S	X	X	X	X	X	X	X	X	X	S	S	S	X	X	X	X	NA	S
Cd	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	S	S	NA	S	NA	S	NA	S
Cr	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	S	S	S	NA	S	S	NA	X
Cl	X	X	X	S	S	X	S	S	X	S	S	S	S	S	S	S	X	X	X	S	X	X	X	S	S	S	S	S	S	S	X	S	X	X	S	S	S	S
Cu	S	S	S	NA	NA	NA	NA	NA	S	S	S	S	S	S	S	S	S	S	S	S	S	S	X	S	S	S	S	S	S	S	S	NA	S	S	S	S	NA	S
Fe	S	S	S	S	S	S	X	S	X	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	X	S	X	NA	S	X	S	X
Pb	S	S	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	S	S	X	S	S	S	NA	S
Mn	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	X	S	X	S	S	S	S	X
Hg	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	S	S	S	S	NA
Na	X	X	X	S	S	S	S	S	X	S	S	S	S	S	S	S	X	X	X	S	X	S	X	S	S	S	S	S	S	S	X	S	X	X	X	S	S	S
SO_4	S	S	S	S	S	S	S	S	X	S	S	S	S	S	S	S	X	X	X	S	S	S	X	S	S	S	X	S	S	S	X	S	S	X	X	S	S	X
Zn	S	S	S	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	S	S	S	S	S	S	NA	S

S: Suitable for drinking water; X: Exceeding the WHO guidelines values for health or aesthetics; NA: No available data; In general, no data were available for Ba, F, Mo, Ni, Se, NO^{3-}, and NO^{2-}

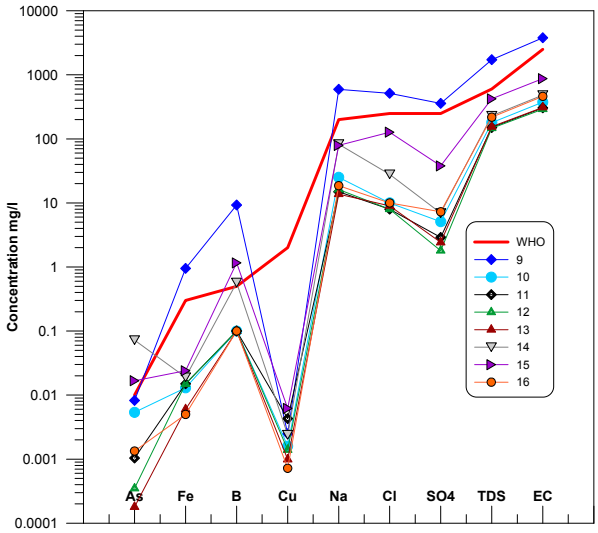

FIGURE 9: Groundwater samples (Apoyo – Mombacho) data compared with the WHO guideline values

also exhibited high values of EC, Cl, Na and SO_4. Sample 27 also presented values of arsenic and sulphate above the WHO guideline (Figure 11). Only sample 30 (bicarbonate water type) is suitable for drinking. This sample presented an alkaline characteristic (pH 8.8) but this pH has no direct impact on the consumer; however, the pH does play an important role for effective disinfection together with chloride. The pH should preferably be less than 8.0. No data were available for Al, Sb, Ba, Cd, Cr, F, Pb, Mn, Hg, Mo, Ni, NO^{3-}, NO^{2-}, Se, and Zn. Table 11 shows the water quality for all the water samples compared with the WHO guideline values for human health and aesthetics.

Figures 12 and 13 show selected data from Icelandic geothermal fields compared with WHO guidelines values. All the samples are from geothermal sources. As shown, only samples 32

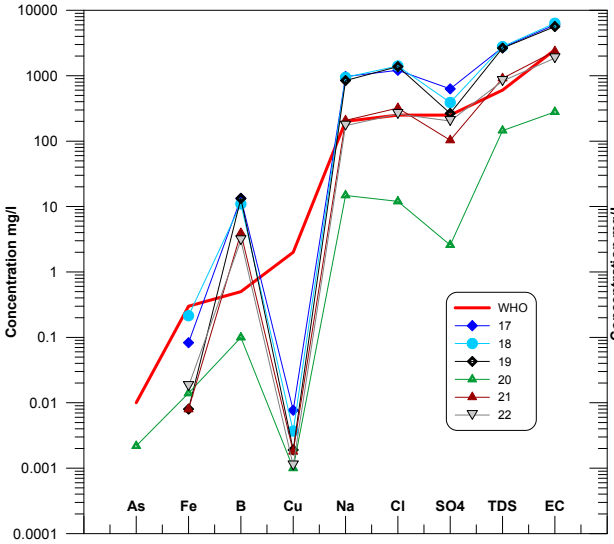

FIGURE 10: Spring and river sample data from Apoyo – Mombacho compared with WHO guideline values

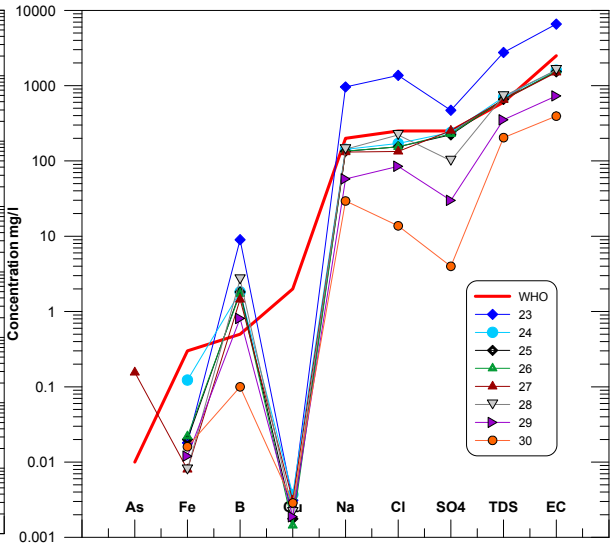

FIGURE 11: Lagoon sample data from Apoyo – Mombacho compared with WHO guideline values

(sulphate) and 37 (bicarbonate) are suitable for drinking; however, sample 32 had almost the same aluminium concentrations as the WHO aluminium practical value. This value is not considered a health-based guideline for WHO due to the uncertainty surrounding its hazards to humans. This sample also had an alkaline character (pH 9.79). Even when pH is not a health-based guideline, preferably it should be less than 8. The samples chemically suitable for drinking are from Reykir (diluted low-enthalpy geothermal water) and Reykjanes (condensed geothermal steam). The sample from Reykir (32) was selected to represent the vast low-enthalpy resources in Iceland. Sample 31 is a chloride water type (geothermal water, fresh water, seawater). It and samples 33, 34, 35, 36, and 38 are not suitable for drinking due to the presence of a high content of TDS, Cl, Fe, Mn, Na, SO4, B, Al, Cr and As, the last two elements being toxic for humans. The pH values in these samples were in the range of acidic to alkaline. Table 8 illustrates the water quality of all the water samples compared with the WHO guidelines for human health and aesthetics.

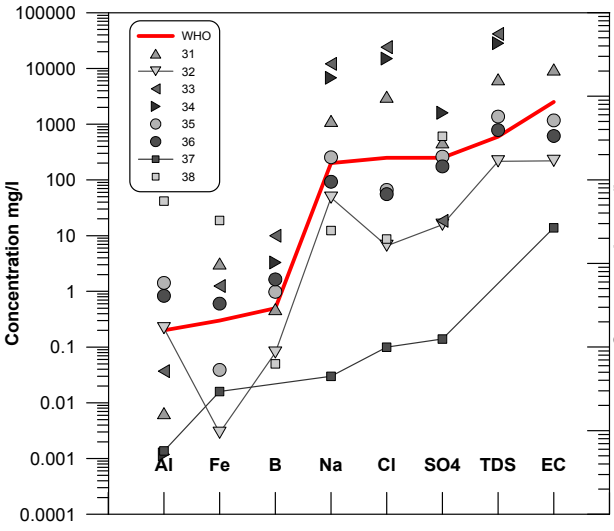

FIGURE 12: Selected samples from Icelandic geothermal fields compared with WHO guideline values

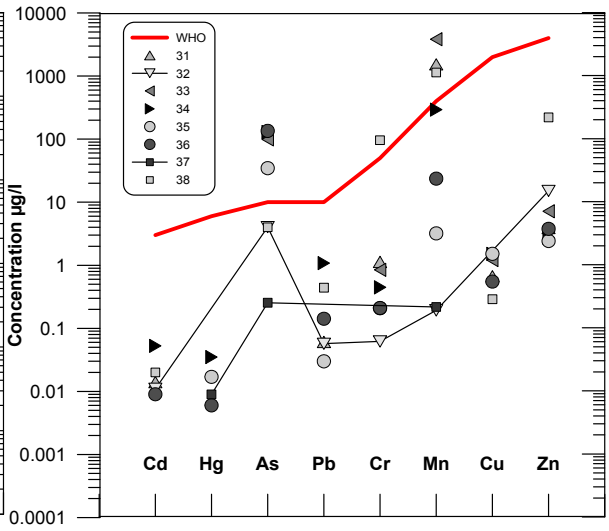

FIGURE 13: Selected samples from Icelandic geothermal fields compared with WHO guideline values

7. CHEMICAL ASSESSMENT OF PROSPECTS FOR BALNEOLOGY WATER

Water quality plays an important role in balneology, since the chemical properties of the water determine possible adverse effects on human health; water chemical properties also determine the curative properties of water for skin diseases and other kinds of therapeutic uses. According to Komatina (2004), mineral (medicinal) waters can be classified on the basis of a number of criteria such as total mineralisation, ion and gas composition, content of active therapeutic components, radioactive acidity or alkalinity, and temperature. The European Union 2009 directive has classified mineral (medicinal) waters as shown in Tables 12, 13 and 14. A similar classification of geothermal water was slightly adapted for Icelandic conditions, but based on both German and Japanese classifications for health resort water (Kristmannsdóttir, 2010). There are a number of different classifications of mineral waters on the basis of pH and temperature (Komatina, 2004) as shown in Table 15.

TABLE 12: San Jacinto – Tizate geothermal field (EU mineral water classification)

Indications	Criteria		Code of the samples							
	TDS (mg/l)	EC (µS/cm)	1	2	3	4	5	6	7	8
Very low mineral content	< 50	< 77								
Low mineral content	< 500	< 769				X	X		X	X
Intermediate mineral content	500 - 1500	769 - 2308						X		
Rich in mineral salts	> 1500	> 2308	X	X	X					
Contains bicarbonate	Bicarbonate > 600 mg/l									
Contains sulphate	Sulphate > 200 mg/l								X	
Contains calcium	Calcium > 150 mg/l									
Contains magnesium	Magnesium > 50 mg/l									
Contains fluoride	Fluoride > 1 mg/l		NA	NA	NA	NA	NA	NA	NA	NA
Contains iron	Iron > 1 mg/l									
Acidic	Carbon dioxide > 250 mg/l		NA	NA	NA	NA	NA	NA	NA	NA
Contains sodium	Sodium > 200 mg/l		X	X	X					
Suitable for low sodium diet	Sodium < 20 mg/l					X	X			X

X: Classification of the waters for all the samples; NA: No data available

TABLE 14: Selected Icelandic geothermal fields (EU mineral water classification)

Indications	Criteria		Code of the samples							
	TDS (mg/l)	EC (µS/cm)	31	32	33	34	35	36	37	38
Very low mineral content	< 50	< 77							X	NA
Low mineral content	< 500	< 769		X						NA
Intermediate mineral content	500 - 1500	769 - 2308					X	X		NA
Rich in mineral salts	> 1500	> 2308	X		X	X				NA
Contains bicarbonate	Bicarbonate > 600 mg/l		NA	NA	NA	NA	NA	NA	NA	NA
Contains sulphate	Sulphate > 200 mg/l					X				X
Contains calcium	Calcium > 150 mg/l		X		X	X				
Contains magnesium	Magnesium > 50 mg/l					X				
Contains fluoride	Fluoride > 1 mg/l		NA	NA	NA	NA	NA	NA	NA	NA
Contains iron	Iron > 1 mg/l		X		X					X
Acidic	Carbon dioxide > 250 mg/l									
Contains sodium	Sodium > 200 mg/l		X		X	X	X			
Suitable for low sodium diet	Sodium < 20 mg/l								X	X

X: Classification of the waters for all the samples; NA: No data available

Mineral waters have a balneological effect on humans as a result of the ionic composition and mineralisation. The medicinal effect of carbonated mineral water is determined by high concentrations of carbon dioxide as well as the ionic composition. The free hydrogen sulphate and hydrosulphate ions determine the medicinal properties for hydrosulphate mineral waters. Components such as iron, arsenic, manganese, aluminium, copper and zinc give medicinal properties to mineral waters. Silica precipitates also have very important medicinal properties (Komatina, 2004). The high concentration of carbon dioxide and hydrogen sulphate gases are results of oxidation processes where the dissolved oxygen in the water reacts with organic matters in the rocks or in the water itself. Dissolution processes of rocks and minerals release heavy and trace elements such as iron, manganese, cadmium, zinc, etc. giving curative characteristics to mineral waters (Saman, 2000).

There are no specific guidelines for recreational waters; however, care must be taken for bathing and swimming due to the possible ingestion of some quantities of the water's chemical constituents. Here, drinking water guidelines can be used for recreational waters. Mance et al. (1984) suggested that environmental quality standards for chemicals in recreational waters should be based on the assumption that recreational water makes only a relatively minor contribution to intake. They assumed a contribution for swimming of an equivalent of 10% of drinking-water consumption. Since most authorities (including WHO) assume consumption of 2 litres of drinking-water per day, this would result in an intake of 200 ml per day from recreational contact with water (WHO, 2003). The graph in Figure 14 shows the samples from all the study areas compared with ten times the

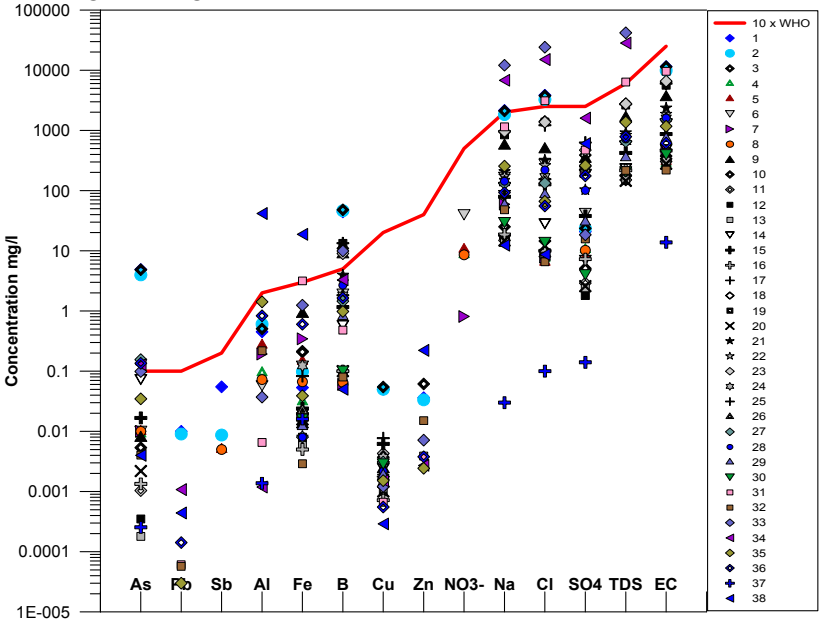

FIGURE 14: Water quality for all the samples from the studied areas compared with ten times the WHO (2008) drinking water guideline values

TABLE 13: Apoyo caldera and Mombacho volcano (EU mineral water classification)

Indications	Criteria		Code of the samples																					
	TDS (mg/l)	EC (µS/cm)	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Very low mineral content	< 50	< 77																						
Low mineral content	< 500	< 769		X	X	X	X	X	X	X				X									X	X
Intermediate mineral content	500 - 1500	769 - 2308													X	X		X	X	X	X	X		
Rich in mineral salts	> 1500	> 2308	X								X	X	X				X							
Containts bicarbonate	Bicarbonate > 600 mg/l		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Containts sulphate	Sulphate > 200 mg/l																							
Containts calcium	Calcium > 150 mg/l		X								X	X	X			X	X	X	X	X	X			
Containts magnesium	Magnesium > 50 mg/l																							
Containts fluoride	Fluoride > 1 mg/l		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
containts iron	Iron > 1 mg/l																							
Acidic	Carbon dioxide > 250 mg/l		X							X	X	X	X		X	X		X	X	X		X	X	
Containts sodium	Sodium > 200 mg/l		X								X	X	X		X		X							
Suitable for low sodium diet	Sodium < 20 mg/l				X	X	X			X				X										

X: Classification of the waters for all the samples; NA: No data available

TABLE 15: San Jacinto-Tizate geothermal field, Apoyo caldera and Mombacho volcano, and selected geothermal fields in Iceland (mineral water classification on basis of pH and temperature)

pH		Code of the samples																																				
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
Strongly acid	< 3																																					X
Acid	3.5 - 5.5							X																													X		
Weakly acid	5.5 - 6.8						X										X	X	X		X	X			X	X	X	X	X	X		X		X				
neutral	6.8 - 7.2				X	X			X	X		X	X	X									X	X													X		
Weakly alkaline	7.2 - 8.5	X	X	X							X				X	X				X															X				
Alkaline	> 8.5																														X		X			X			
Temperature/°C		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**
Cold	< 20																																				X		
Warm	20 - 37			X	X	X			X		X	X	X	X	X	X	X			X	X					X				X	X							
Thermal	37 - 42																						X		X													
Highly thermal	42 - 100						X	X		X								X	X			X	X	X			X	X	X			X	X			X			X
Superheated	> 100	X	X																																				

X: Classification of the waters for all the samples

TABLE 16: Water quality of water samples compared with ten times WHO guidelines

| Chemical Parameter | Code of the samples | | |

8. CHEMICAL ASSESSMENT OF PROSPECTS FOR AQUACULTURE

Guidelines for aquaculture are based on the experience from a number of countries around the world. Aquaculture is diverse and water quality characteristics depend on specific requirements for each species as some chemical characteristics might be good for one species, and not so good for others. The physicochemical parameters are very important in aquaculture, for example temperature affects the growth of fish, hardness is important for bone and exoskeleton. The chemical aquatic form of metals determines their effect on fish (Zweig et al., 1999).

8.1 Physicochemical parameters

Temperature has an important influence on fish, because it is closely correlated with the metabolism of fish. The higher the temperature, the greater the metabolic processes. If, for example, the fish is suddenly moved from one temperature to another that is higher or lower by more than 12°C, then the fish could experience paralysis, respiratory problems, consume less food, and finally die. Temperature also plays an important role on the initiation of some fish diseases. Geothermal waters are preferred for several applications because of the easier control of temperatures using it than for other water sources (Svobodova et al., 1993). Some fish present higher growth at extreme temperatures; these extreme temperatures are different for each species, depending on the original fish environment, if the original environment of the fish is fresh water, salt water, cold or hot water, etc. Many species suitable for aquaculture might tolerate temperatures from 5 to 36°C, but the range for maximum growth is narrower, from 25 to 30°C (ANZECC, 2000).

The optimal pH range for fish is from 6.5 to 8.5 (Figure 15). As a defence against the effects of a low or high water pH, fish can produce an increased amount of mucus on the skin and on the inner side of the gill. The pH also has significant influence on the toxic effect of a number of other substances (e.g. hydrogen sulphate, and heavy metals) on fish (Svobodova et al., 1993). Alkalinity does not affect fish directly; however, it is important because it prevents extreme pH. Hardness is important for the skeleton of fish; bone deformities and reduced growth rates may result if the water is too soft. However, hardness also affects aquaculture species through its chemical interaction with other components in water. The most efficient water for fish culture has roughly equal magnitudes of total hardness and total alkalinity (Figure 16). The general range is from 20 to 300 mg/l for alkalinity and hardness (Zweig et al., 1999).

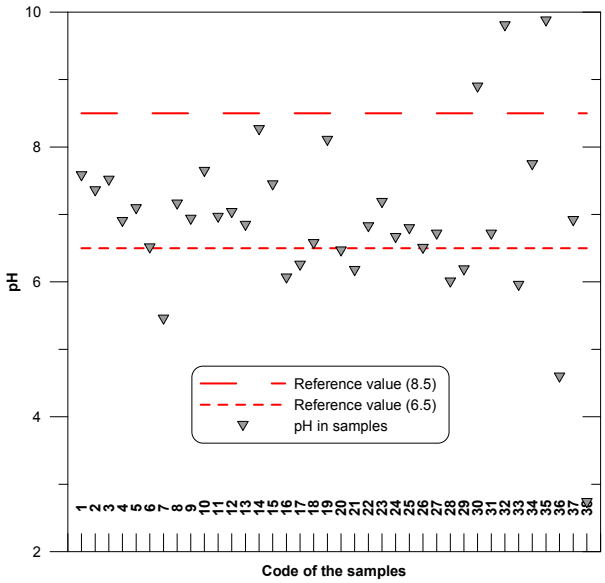

FIGURE 15: Graph showing the pH of the samples

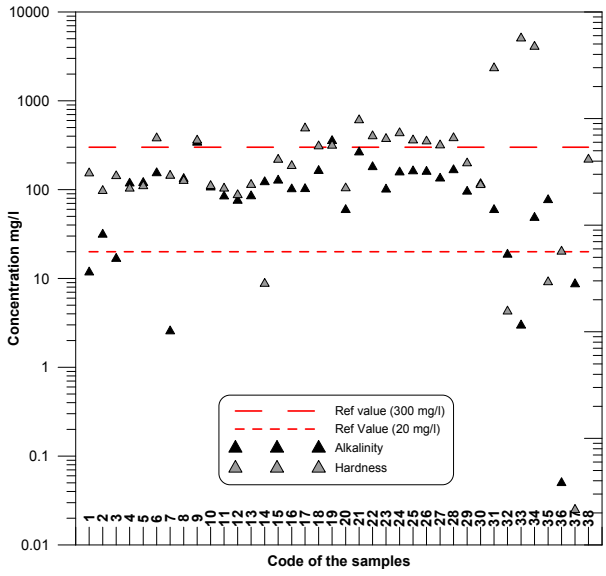

FIGURE 16: Graph showing the alkalinity and hardness in all the samples

8.2 Inorganic toxicants

Metals have the property of bioaccumulation in sediments, aquatic flora and fauna. The metals found to be of highest importance to fisheries in practice are: aluminium, chromium, iron, nickel, copper, zinc, arsenic, cadmium, mercury and lead (Svobodova et al., 1993). Table 17 summarises the recommended limit values for inorganic species provided by ANZECC (2000). The main problems for fish culture in all the samples are: H_2S, Zn, Fe, Mn, and Al (Figure 17). Hydrogen sulphide is extremely harmful to fish; the best methods for removal of hydrogen sulphide are oxidation with permanganate and dilution through water exchange. Even when there is no evidence of zinc effects on human health, zinc is toxic to aquatic organisms. Zinc can precipitate at high pH and co-precipitate with calcium carbonate. The precipitates of iron and manganese may occlude gills and cause stress or mortality to fish. The simplest method for removing zinc is to retain water for one or two days in a holding pond (Zweig et al., 1999).

TABLE 17: Summary of the recommended water quality general guidelines for inorganic species (ANZECC, 2000)

Parameter	Freshwater	Saltwater
H_2S	0.001	0.002
Hg	0.001	0.001
Zn	0.005	0.005
Fe	0.01	0.01
Mn	0.01	0.01
Cr	0.02	0.02
Al	0.03	0.01
As	0.05	0.05

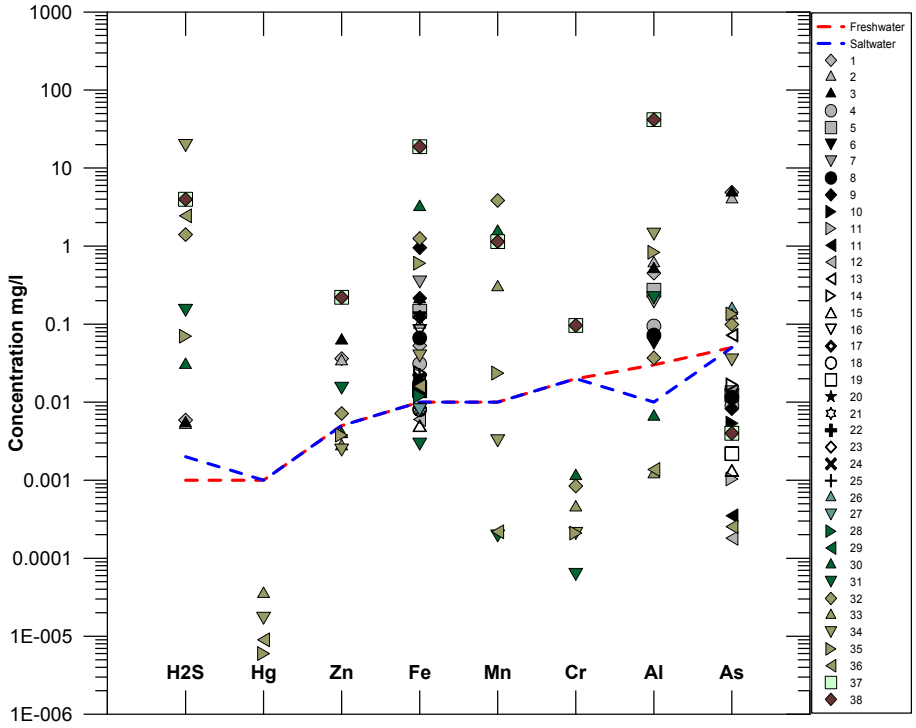

FIGURE 17: H_2S and metals in all the samples (general guidelines for H_2S and metals from ANZECC, 2000)

Trivalent chromium compounds are more toxic to fish than those in the hexavalent form; its toxicity depends on physicochemical properties of water (Svobodova et al., 1993). The maximum toxicity of aluminium on fish occurs at pH 5, where it can accumulate in fish at levels harmful for humans (Zweig et al., 1999). Arsenic and mercury may lead to the formation of organic methyl derivatives; they are accumulated in sediments and aquatic organisms. Arsenic compounds can have medium to high toxic effects on fish. Mercury compounds can cause damage to some vital tissues and organs in fish and may also affect reproduction (Svobodova et al., 1993). Table 18 illustrates the water quality of the samples.

9. CHEMICAL ASSESSMENT OF PROSPECTS FOR IRRIGATION WATER

The chemical composition of the samples was diverse with regard to water quality for irrigation purposes. Depending on its origin, waters derived from springs, streams, and wells contained considerable quantities of chemical substances to reduce crop yields and deteriorate soil fertility (Phocaides, 2007). Different kinds of salts are normally found in irrigation waters; the amounts and combinations of these substances define the suitability of water for irrigation and the likelihood of plant toxicity. Two types of salt problems exist which are very different: those associated with total salinity and those associated with sodium. Soils may be affected only by salinity or by a combination of salinity and sodium (Texas A&M University, 2003).

9.1 Salinity and sodium assessment

A preliminary step for assessing the irrigation water quality is to classify these prospects based on salinity. Salinity on its own does not define the suitability of irrigation water; it represents only a general guide and other factors must be considered (ANZECC, 2000). Table 19 summarises the different classes of irrigation water based on electrical conductivity and TDS. The sodium hazard is the effect that irrigation water containing large amounts of sodium could cause on soil; it is usually expressed as SAR (sodium adsorption ratio). SAR is related to infiltration problems and it is calculated from the ratio of sodium to calcium and magnesium (Texas A&M University, 2003):

$$\mathrm{SAR} = \frac{[\mathrm{Na}^{+}]}{\sqrt{\frac{[\mathrm{Ca}^{+2}] + [\mathrm{Mg}^{+2}]}{2}}} \qquad (1)$$

The soil structure is changed by the reaction of the sodium cation, which is the major cation dominant in waters with high salinity. The sodium cation replaces the calcium and magnesium in the soil. This cation exchange causes the deterioration of the soil structure making the soil impermeable to water and air. High concentrations of exchangeable sodium shift the pH to alkaline values,

TABLE 19: Water classification based on salinity (Texas A&M University, 2003)

Classes of waters	Electrical conductivity (µS/cm)	TDS (mg/l)
Class 1, Excellent	250	175
Class 2, Good	250-750	175-525
Class 3, Permissible	750-2000	525-1400
Class 4, Doubtful	2000-3000	1400-2100
Class 5, Unsuitable	3000	2100

TABLE 18: Water quality of water samples for aquacultural purposes

Chemical Parameter	Code of the samples																																														
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**
T (°C)	211	187	26	28	36	48	53	30	43	30	30	28	28	30	25	28	67	59	32	28	49	42	57	37	35	44	44	43	32	34	77	88	NA	NA	100	6	NA	95
Temp	X	X	S	S	X	X	X	S	X	S	S	S	S	S	S	S	X	X	S	S	X	X	X	X	S	X	X	X	S	S	X	X	NA	NA	X	S	NA	X
pH	S	S	S	S	S	X	X	S	S	S	S	S	S	S	S	S	X	S	S	X	X	S	S	S	S	X	S	X	X	S	S	X	X	S	X	X	S	X
H_2S	X	X	X	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	X	X	X	NA	X	X	X	X
Hg	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	X	S	S	S	NA
Zn	X	X	X	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	S	X	X	S	S	S	NA	X
Fe	X	X	X	X	X	X	X	X	X	X	X	X	S	X	X	S	X	X	S	S	S	X	X	X	X	X	S	S	X	X	X	S	X	NA	S	S	X	X
Mn	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	X	S	X	X	S	X	S	X
Cr	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	S	S	S	S	S	S	NA	X
Al	X	X	X	X	X	X	X	X	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	S	X	S	X	X	X	S	X
As	X	X	X	S	S	S	S	S	S	S	S	S	S	X	S	S	NA	NA	NA	S	NA	NA	NA	NA	NA	NA	X	NA	NA	NA	NA	S	X	X	S	X	S	S

S: Suitable for fish culture; X: Exceeding the general guidelines values for aquaculture; NA: No available data

reducing the availability of micronutrients such as iron and phosphor (Phocaides, 2007). The sodium hazard of water based on the SAR values is shown in Table 20.

The classification of water samples can be seen in Table 21; the classification was done according to salinity (Table 19) and the sodium hazard of water (Table 20).

TABLE 20: Sodium hazard of water based on SAR
(Texas A&M University, 2003)

SAR values	Sodium hazard of water		Comments
1 - 10	Low	A	Use on sodium sensitive crops
10 - 18	Medium	B	Amendments and leaching are needed
18 - 26	High	C	Generally unsuitable for continuous use
> 26	Very High	D	Generally unsuitable for use

9.2 Boron toxicity

The toxicity of boron is very variable in crops, but it is essential for plants in relatively low concentrations; the requirement and toxicity differ from one crop species to another (ANZECC, 2000). The classification of irrigation water in relation to its boron content and crop tolerance is shown in Table 22. Boron must be routinely analysed in irrigation water tests (Johnson and Zhang, 1990).

TABLE 22: Classification of irrigation water based on boron concentrations

Boron (mg/l)			
Classification	**Sensitive plants**	**Semi-tolerant plants**	**Tolerance plants**
Excellent	< 0.3	< 0.6	< 1.0
Good	0.4 - 0.6	0.7 - 1.3	1.0 - 2.0
Fair	0.7 - 1.0	1.4 - 2.0	2.1 - 3.0
Poor	1.1 - 1.3	2.1 - 2.5	3.1 - 3.8
Unsuitable	> 1.3	> 2.5	> 3.8

Table 23 gives the water classification for all samples, based on boron. As can be seen, the results are variable, ranging from excellent to unsuitable.

Plant species differ in their tolerance to boron. Some of them are listed with tolerance in Table 24.

TABLE 24: Plant tolerances to boron
(Johnson and Zhang, 1990)

Sensitive	Semitolerant	Tolerant
Navy Bean	Sunflower	Sugar beet
Pear	Cotton	Alfalfa
Apple	Radish	Onion
	Barley	Lettuce
	Wheat	Carrot
	Corn	
	Oats	

TABLE 21: Classification of water based on salinity and SAR
(San Jacinto-Tizate, Apoyo caldera and Mombacho volcano, and selected Icelandic geothermal fields)

Code	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
Class of water, basis on salinity (TDS or EC)	5	5	5	2	2	3	2	2	5	2	2	2	2	2	3	2	5	5	5	2	4	3	5	3	3	3	3	3	2	2	5	2	5	5	3	3	1	NA
Sodium Hazard of water, basis on SAR	D	D	D	C	B	D	D	B	D	C	B	B	B	D	D	C	D	D	D	B	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	NA	B

1: Excellent, 2: Good, 3: Permissible, 4: Doubtful, 5: Unsuitable, A: Low, B: Medium, C: High, D: Very High, NA: No data availible

9.3 Minor and trace elements

The chemical constituents in irrigation waters are diverse and can, depending on concentration, have a toxic effect on plants. Trace metals are toxic to plants but they are also important as micronutrients; the deficiency of these micronutrients can cause diseases to plants. Some symptoms shown in leaves are chlorotic and necrotic (Gandouzi, 1999). Table 25 summarises the recommended limits in reclaimed water for irrigation (Texas A&M University, 2003). As can be seen in Figure 18, boron is the main problem in many of the selected samples, both for short term as well as long term; high concentrations of boron are toxic for plants and also affect the soil, because it is absorbed on the soil surface at alkaline pH values. The high boron concentration in many geothermal systems is derived from boron-rich sediment or rocks that are metamorphosed through burial (chemical and mineralogical change of rocks by pressure, heat and water to more compact and crystalline rocks) and are incorporated into magma during volcanic events associated with subduction zones. When the rocks within the crust become sufficiently heated, boron is extracted into the surrounding formation waters (Smith, 2002).

TABLE 25: Recommended limits for constituents in reclaimed water for irrigation (Adapted from Rowe and Abdel-Magid, 1995 by Texas A&M University, 2003)

Constituent	Long term use (mg/l)	Short term use (mg/l)
Cd	0.01	0.05
Cr	0.1	1
As	0.1	2
B	0.75	2
Li	2.5	2.5
Cu	0.2	5
Pb	5	10
Mn	0.2	10
Zn	2	10
Al	5	20
Fe	5	20

Cadmium uptake by plants increases with soil acidity and soil salinity; cadmium interferes with the metabolic processes within plants. Chromium reduces crop yield, depending on the tolerance of different plant species. Arsenic inhibits the reductase enzymes in plants, destroying the chlorophyll in the foliage. Crops sensitive to sodium are also sensitive to high lithium concentrations; lithium has a similar effect on soil structure as sodium. Copper is essential in small quantities for plant growth, but at high quantities causes growth reduction.

TABLE 23: Classification of waters based on Boron
(San Jacinto-Tizate, Apoyo caldera and Mombacho volcano, and selected Icelandic geothermal fields)

Code	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
Sensitive plants	U	U	U	E	E	U	E	E	U	E	E	E	E	G	P	E	U	U	U	E	U	U	U	U	U	U	U	U	F	E	G	E	U	U	F	U	NA	E
Semitolerant plants	U	U	U	E	E	F	E	E	U	E	E	E	E	E	G	E	U	U	U	E	U	U	U	F	F	F	F	U	G	E	E	E	U	U	G	F	NA	E
Tolerance plants	U	U	U	E	E	G	E	E	U	E	E	E	E	E	G	E	U	U	U	E	U	P	U	G	G	G	G	F	E	E	E	E	U	P	E	G	NA	E

E: Excellent, G: Good, F: Fair, P: Poor, U: Unsuitable, NA: No boron data available

Low soil pH allows greater lead uptake by plants; lead can inhibit plant growth. Manganese and zinc are essential for plants; however, at high concentrations they may be highly toxic to plants, affecting the root growth in acidic soils, which increases its absorption by soil. Zinc toxicity is evidenced by chlorosis, reduction in leaf size, necrosis of tips and distortion of foliage. Aluminium reduces productivity on acid soils; several crops show aluminium toxicity at very low concentrations. Iron is an essential micronutrient; deficiency of iron in plants produces chlorosis. Deficiency of iron occurs in alkaline soils while the deposition of iron on plants produces foliage damage and blemishes (ANZECC, 2000).

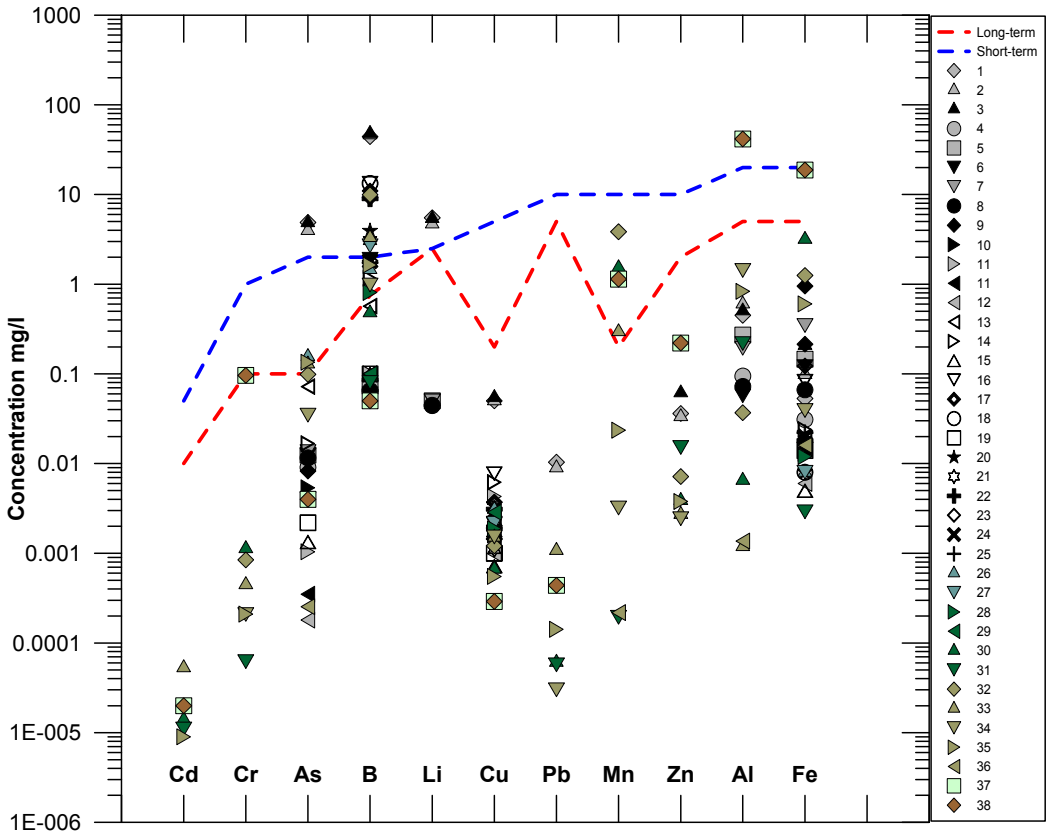

FIGURE 18: Minor and trace elements in all the samples (recommended limits, Texas A&M University, 2003)

10. CHEMICAL ASSESSMENT OF PROSPECTS FOR INDUSTRIAL WATER UTILISATION

Industrial applications are very diverse and the quality of the water required is very different, depending on the type of processes for each application. Many industries use the domestic water supply while others are using waters from streams, lakes, underground water and estuaries (WAWQG, 1993). Geothermal resources can contribute to these industrial needs, not only as a heat resource but also as a water resource for different industrial applications. Potential industrial applications include process heating, evaporation, drying, distillation, refrigeration, sterilisation, washing, salt and chemical extraction. Industrial processes require temperatures up to 150°C; however, lower temperatures can be used in some cases, especially for drying of various agricultural products (Lund, 1996).

For the purposes of this study, we consider geothermal resources only as a water supply for industrial applications. Although it is an important heat source for many industries, as mentioned above, temperature has not been taken into consideration in this case.

In order to minimise problems such as corrosion, scaling, and problems concerned with the product quality, the water used as an industrial supply must satisfy specific guidelines for different industrial applications such as: Industrial water requirements for heating and steam generation, for cooling towers (recirculation systems), for hydro-electricity power generation supplies, for the textile industry, for pulp and paper industry, for some food and beverage industries, for the iron and steel industry, for tanning and leather industry, for petroleum industry, etc (WAWQG, 1993). Here, as an example, we are going to study the possible use of the prospect water for the pulp and paper industry.

10.1 Pulp and paper industry

Water is used in the pulp and paper industry during all processes. Water is used for washing the pulp to remove the cooking liquors, after cooking (168-175°C) wood with sodium sulphate and caustic soda in a digester (Kraft, or sulphate method). Hot water is used for washing (≈ 100°C) which can be heated using geothermal fluids or by direct use. During the bleaching process, chlorine dioxide is used followed by neutralization with calcium hypochlorite. Finally, a dilute water suspension of pulp is deposited on a fine screen, which permits the water to drain through while retaining the fibrous layer. This layer is then removed from the screen, pressed, and dried, which can be done by heating the air with geothermal fluids (Lienau and Lund, 1998).

TABLE 26: Water quality guidelines for pulp and paper industry (Adapted from US EPA, 2004)

Parameter	Pulp and paper Kraft, bleached
Fe	0.1
Mn	0.05
Ca	20
Mg	12
Cl	200*
SiO_2	50
Alkalinity	75*
Hardness	100
TDS	300*
pH	6 - 10

All values are in mg/l except pH. *Source: WAWQG (1993)

Table 26 shows the water quality requirements for the pulp and paper industry, for the bleaching processes. Most parameters were taken from US EPA (2004) and some from WAWQG (1993).

Corrosive problems in the pulp and paper industries are present in different steps of the process. Corrosive problems are associated with changes in temperature, pH, sulphur compounds, total dissolved solids (TDS), and chlorides. Corrosion can be controlled by monitoring and maintaining these parameters in proper quantities and conditions (temperature and pH). For mitigating corrosion, inhibitors can be applied to the process and also weight loss coupons can be used for regular inspections as a preventive corrosion strategy (Koch et al., 2001). In Figures 19 and 20, a graphical representation of the water quality for all the samples is shown.

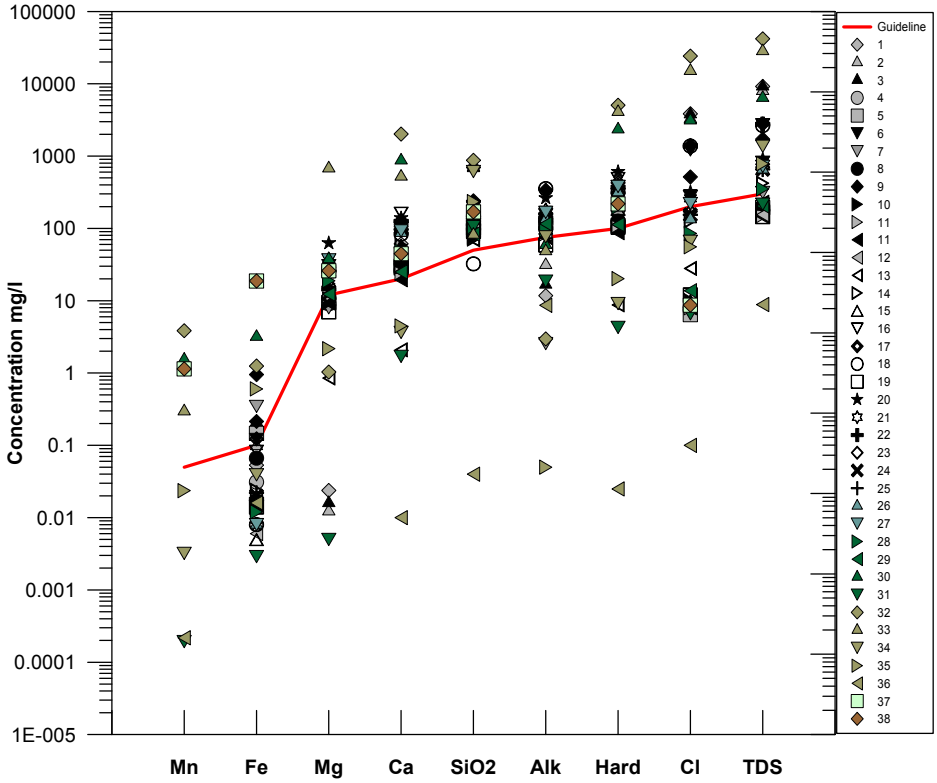

FIGURE 19: Water quality guideline for pulp and paper industry compared with water quality of all the samples

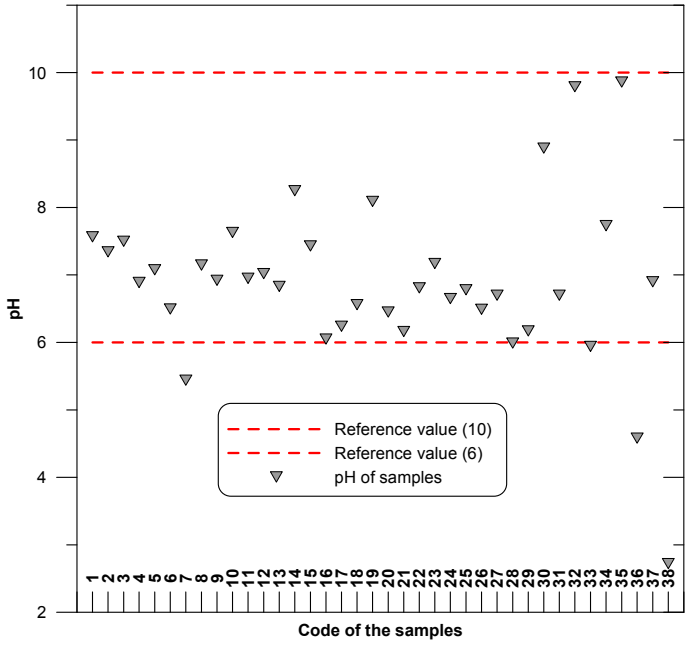

FIGURE 20: Recommended pH for pulp and paper industry compared with pH of all the samples

The interaction between the surface of materials and the aqueous environment, acidic or alkaline, leads to corrosive problems, many times under conditions of thermal stress. The solubility of corrosive products are proportional to the temperature and pH and, therefore, to small scale formation. The deposit formations are oxides, hydroxides, and hydrous oxides of metals such as Cr, Mn, Fe, Co, Ni, and Cu, depending on the material composition. The presence of Mn and Fe in the water supply increases the formation of its deposits. A decrease in pressure and temperature leads to the deposition of electrolytes and neutral compounds such as NaCl and SiO_2. Alkalinity is the buffer capacity of water or the ability of water to resist changes in pH. Materials such as mild steel and carbon steel exhibit a minimum rate of corrosion at 25°C in the pH range of 8 to 10. Thus, it is important to maintain the appropriate value of alkalinity in the water supply. Dissolved salts (TDS) and high hardness values (Ca^{+2}, Mg^{+2}, Na^{+1}, HCO_3^{-1}, Cl^{-1}, CO_3^{-2}, and SO_4^{-2}) tend to precipitate when saturation is reached due to local changes in temperature and concentrations. The presence of soluble salts (e.g. $CaCO_3$ and $CaSO_4$) having inverse solubility results in scaling (Venkateswarlu, 1996). Table 27 illustrates the water quality of all the samples compared with the water quality guideline for the pulp and paper industry.

TABLE 27: Water quality for pulp and paper industry

| Parameter | Code of the samples | | |

11. SUMMARY AND CONCLUSIONS

Geothermal water represents an important water resource for different applications, in which the water quality plays an important role in defining possible cascading uses. Of a total of 38 samples taken in this study, 37% of the samples classified according to the dominant anions were chloride water type, 39% were bicarbonate water type, and 24% were sulphate water type. The chemical composition of these samples is variable. The water quality in these samples is controlled by several factors such as mineral-water interaction related to volcanic activity associated with subduction zones, mixing processes with natural saline waters and seawater (in some cases from Iceland), and geothermal alteration which is the predominant factor.

All study areas were related to geothermal alteration, in either low- or high-enthalpy geothermal fields; different water types were found in various environments such as springs, groundwater, a river, and a lagoon (Apoyo caldera). Chloride waters indicate deep geothermal discharge, sulphate waters indicate geothermal steam-heated water, and bicarbonate waters are common on the margin of the field with high CO_2 reactivity.

Many samples exhibited high levels in major elements such as Na and Cl, and trace elements such as Al, As, and B; some samples presented high concentrations in parameters such as TDS, EC, Fe, and Mn, which measured above the (WHO, 2008) guidelines for drinking water. The water quality deficiency was highlighted in chloride water types, followed by sulphate water. Bicarbonate water types were deemed most suitable for drinking water.

According to the EU mineral water classification (2009), the chloride water type presents the best balneological properties; most of these water samples were rich in mineral salts. However, they had variable ion compositions. Water samples from The San Jacinto – Tizate geothermal field contained more than 200 mg/l Na. Waters from Apoyo caldera and Mombacho volcano contained more than 150 mg/l Ca, more than 250 mg/l CO_2, and more than 200 mg/l Na. Finally, the water from selected Icelandic geothermal fields contained more than 150 mg/l Ca, more than 1 mg/l Fe, and more than 200 mg/l Na. Sulphate waters ranged from low to intermediate mineral contents containing CO_2 and less than 20 mg/l Na. Bicarbonate waters were classified as having low mineral content and very low mineral content for Nicaragua and Iceland, respectively, and contained less than 20 mg/l Na. All the samples were also classified on the basis of pH and temperature; the samples ranged from weakly acidic to weakly alkaline, except in a few cases. Highly thermal and superheated effects on the water were notable in the chloride water type. In order to determine if these waters were suitable for recreational purposes, they were compared with ten times the WHO guidelines for drinking water; almost all the samples were below these guidelines, except in a few cases where water samples of chloride water types exceeded the limits for TDS, EC, As, Cd, and B.

Physicochemical parameters and inorganic species were used to evaluate the possible water uses for fish culture. A strict relationship between the water type and recommended limit values for physicochemical parameters such as pH, temperature, alkalinity and hardness was not observed. Due to the high sensibility of many fish suitable for aquaculture, very low limit values for inorganic toxicants are required. According to these limit values, many of the samples were not suitable for fish culture, showing higher quantities in H_2S, Zn, Fe, Mn, Cr, Al, and As than the general guidelines for aquaculture. In many cases, samples from Nicaragua had no inorganic data available; it is recommended to take that into consideration for future projects.

Salinity and boron toxicity are important parameters to take into account, as well as minor and trace elements, for irrigation water. A classification of water done according to salinity indicated that chloride water types were unsuitable for irrigation; sulphate water type samples exhibited a water quality permissible for irrigation and the bicarbonate water type samples had good quality for irrigation. According to the boron toxicity classification, the chloride water type samples generally were unsuitable for irrigation; sulphate water types showed variable behaviour depending on the

sensitivity of the plants to boron. The high boron content was the main problem in the water both for long term use as well as short term use. Some water samples exceeded the recommended guidelines for irrigation water, showing concentrations of Fe, Al, Li, and As above the reference values for short term use. The same pattern was observed for long terms use, with the addition of that high content of Mn exceeded this guideline.

The main problems in industry are corrosion and scaling, dependent on physicochemical factors such as pH, temperature, and pressure. These problems are controlled by material-water interaction processes which release inorganic species depending on the material's chemical compositions. The presence of salts with reverse solubility forms scaling due to pressure and temperature changes during industrial processes. According to the chemical water quality, most of the study samples were not suitable for the pulp and paper industry because they exhibited higher concentrations in various parameters (Mn, Fe, Mg, Ca, SiO_2, Cl, alkalinity, hardness, and TDS) than the pulp and paper industry guidelines recommended by the US EPA (2004). One exception was the condensate sample from Reykjanes (geothermal power plant, sample 37).

ACKNOWLEDGEMENTS

First of all I would like to especially express my gratitude to Dr. Ingvar B. Fridleifsson, Director of UNU-GTP and Mr. Lúdvík S. Georgsson, Deputy Director of the UNU-GTP for allowing me to attend this specialist training where I have improved my geothermal knowledge. I also want to thank Dr. Thráinn Fridriksson for recommending and encouraging me to write this report and providing me with the geochemical data from the ISOR database. Also my thanks go to my advisor Gestur Gíslason for his wise advice during the development of this research project. I want to extend my gratitude to all the professional staff of the UNU-GTP, especially to Ms. Thórhildur Ísberg, Ms. Dorthe H. Holm, Mr. Markús A.G. Wilde and Mr. Ingimar Haraldsson for all the help that they gave to me throughout these six months. I also want to express my gratitude to Mr. Mario González, Director of the Geothermal Department of the Ministry of Energy and Mines of Nicaragua for providing me with most of the data which allowed me to develop this project. Finally, I want to thank my wife, Eveling Rodriguez, and my children, Annie Michelle and Kevin Alexandre, for their patience and support during this training.

REFERENCES

Aligan M.E., 2010: Opportunities for direct use of geothermal resources in the Bicol region, Philippines. *Proceedings of the World Geothermal Congress 2010, Bali, Indonesia,* 8 pp.

ANZECC, 2000: *Australian and New Zealand Environment and Conservation Council guidelines for fresh and marine water quality. Primary industries – rationale and background information (irrigation and general water uses, stock drinking water, aquaculture and human consumers of aquatic food).* ANZEEC, paper no. 4, vol. 3, Chapter 9, 51 pp.

Ármannsson, H., Benjamínsson, J., and Jeffrey, A.W.A., 1989: Gas changes in the Krafla geothermal system, Iceland. *Chemical Geology, 76,* 175-196.

Ármannsson, H., and Fridriksson, Th., 2009: Application of geochemical methods in geothermal exploration. Presented at "Short Course on Surface Exploration for Geothermal Resources", organized by UNU-GTP and LaGeo, in Ahuachapan and Santa Tecla, El Salvador, 17-30 October, 2009.

Árnadóttir, S., Gunnarsson, H.S., Gautason, B., Axelsson, G., Flóvenz, Ó.G., Hjartarson, Á., Árnason,

Á. and Árnason F., 2010: The Reykir geothermal area in Fnjóskadalur, North-Iceland: District heating in rural Iceland. *Proceedings of the World Geothermal Congress 2010, Bali, Indonesia,* 5 pp.

Arnórsson, S., 1995: Geothermal systems in Iceland; structures and conceptual models; I, high-temperature areas. *Geothermics, 24,* 561-602.

Arnórsson, S., Björnsson, A., Björnsson, S., Einarsson, P., Gíslason, G., Gudmundsson, G., Gunnlaugsson, E., Jónsson, J., and Sigurmundsson, S.G, 1975: *The Krísuvík area. A complete report on geothermal exploration*. Orkustofnun, Reykjavík, report OS JHD-7554 (in Icelandic), 71 pp + figures.

Bertani R., 2010: Geothermal power generation in the world 2005-2010: Update report. *Proceedings of the World Geothermal Congress 2010, Bali, Indonesia,* 41 pp.

Clifton, A., and Kattenhorn, S., 2006: Structural architecture of a highly oblique divergent plate boundary segment. *Tectonophysics, 419*, 27-40.

CNE, 2001: *Nicaragua geothermal master plan.* National Energy Commission of Nicaragua (CNE) and Geothermex.

Dall´Aglio, M., 1991: Biogeochemical cycles of elements. In: D'Amore, F. (coordinator), *Application of geochemistry in geothermal reservoir development*. UNITAR/UNDP publication, Rome, 1-35.

Edmunds, W.M., and Shand, P. (eds.), 2008: *Natural ground water quality.* Blackwell Publishing, USA, 488 pp.

El-Manharawy, S., and Hafez, A., 2003: A new chemical classification system of natural waters for desalination and other industrial uses. *Salination*, *156*, 163-180.

European Commission, 2007: *Standards for drinking water quality, section 2*. European communities regulations 2007 (drinking water, no. 2), S.I. 278 of 2007, issue no. 1, 12 pp.

European Union, 2009: Directive 2009/54/EC of the European parliament and the council, of 18 June 2009, on the exploitation and marketing of natural mineral waters. *Official Journal of the European Union, OJ L 164,* 58 pp.

Freeston, D.H., 1996: Direct uses of geothermal energy 1995. *Geothermics 25-2*, 189-214.

Fridleifsson, I.B., Bertrani, R., Huenges, E., Lund, J.W., Ragnarsson, Á., and Rybach, L., 2008: The possible role and contribution of geothermal energy to the mitigation of the climate change. In: Hohmeyer, O. and Trittin, T. (eds.): *IPCC Scoping Meeting on Renewable Energy Sources, Proceedings, Lubeck, Germany,* 59-80.

Gandouzi, M.A., 1999: Geothermal waters in greenhouses in Tunisia: use of computers to control climate and fertigation (fertilisation?) with cooled geothermal water. Report 3 in: *Geothermal Training in Iceland 1999.* UNU-GTP, Iceland, 71-95.

Giroud N., 2008: *A chemical study of arsenic, boron and gases in high-temperature geothermal fluids in Iceland*. University of Iceland, PhD thesis, 110 pp.

Gudmundsson, B.T., and Arnórsson, S., 2002: Geochemical monitoring of the Krafla and Námafjall geothermal areas, N-Iceland. *Geothermics, 31,* 195-243.

Jakobsson, S.P., Jónsson, J., and Shido, F., 1978: Petrology of the western Reykjanes Peninsula, Iceland. *J. Petrology, 19-4,* 669-705.

Johnson, G., and Zhang H., 1990: *Classification of irrigation water quality*. Oklahoma State University, Division of Agricultural Sciences and Natural Resources, 4 pp.

Jónasson, K., 1994: Rhyolite volcanism in the Krafla central volcano, north-east Iceland. *Bulletin of Volcanology, 56*, 516-528.

Komatina, M.M., 2004: *Medical geology. Vol. 2: Effects of geological environments on human health.* Elsevier Science, 502 pp.

Koch, G.H., Brongers, M., Thompson, N., Virmani Y.P., and Payer, J.H., 2001: *Corrosion cost and preventive strategies in the United States.* FHWA, Washington D.C.

Kristmannsdóttir, H., 2010: Prospects in balneology to boost the economy and employment of rural NE Iceland. *Proceedings of the World Geothermal Congress 2010, Bali, Indonesia*, 10 pp.

Kühn, M., 2004: *Reactive flow modelling of hydrothermal systems.* Springer Verlag, Heidelberg, 332 pp.

Lagat, J., 2010: Direct utilization of geothermal resources in Kenya. *Proceedings of the World Geothermal Congress 2010, Bali, Indonesia,* 7 pp.

Langmuir, D. 1997: *Aqueous environmental geochemistry*. Prentice-Hall Internat., NJ, 600 pp.

Lienau, P.J., and Lund, J.W., 1998: *Industrial applications*. Chapter 16 in: Lund, J.W.; Lienau, P.J. and Lunis B.C., (eds.), *Geothermal direct-use engineering and design guidebook*. Geo-Heat Center, Klamath Falls, OR, 333-357.

Líndal, B., 1973: Industrial and other applications of geothermal energy, except poser production and district heating. In: Armstead, H.C.H. (eds.) *Geothermal energy.* Paris, UNESCO, LC 7297*,* 135-148.

Lund, J.W., 1996: *Lectures on direct utilization of geothermal energy*. UNU-GTP, Iceland, 123 pp.

Lund, J.W., 2009: Development of direct use projects. *Proceedings of International Course & EGEC Business Seminar on: Organization of a Successful Development of a Geothermal Project,* 13 pp.

Lund, J.W., Freeston, D.H.., and Boyd, T.L., 2010: Direct utilization of geothermal energy 2010, worldwide review. *Proceedings of the World Geothermal Congress 2010, Bali, Indonesia,* 23 pp.

Mance, G., Musselwhite, C., and Brown, V.M., 1984: *Proposed environmental quality standards for List II substances in water. Arsenic*. Medmenham Water Research Centre, Technical Report TR 212.

Markússon, S.H., 2009: *Acid sulphate alteration of basalts in active geothermal systems, Krísuvík, Iceland*. University of Iceland, MSc thesis, 60 pp.

Óskarsson, N., and Sigvaldason, G.E., 1982: A dynamic model of the rift zone petrogenesis and the regional petrology of Iceland. *J. Petrology, 23*, 28-74.

Parello, F., Aiuppa, A., Calderon, H., Calvi, F., Cellura, D., Martinez, V., Militello, M., Vammem, K., and Vinti, D., 2008: Geochemical characterization of surface waters and groundwater resources in the Managua area (Nicaragua, Central America). *Applied Geochemistry, 23*, 914-931.

Phocaides, A., 2007: *Handbook on pressurized irrigation techniques* (2nd ed.). Food and Agriculture Organization (FAO) of the United Nations, Rome.

Rafferty, K., 2003: Industrial processes and the potential for geothermal applications. *Geo-Heat Centre (GHC), Bulletin*, 7-11.

Roberts, P.A., 1975: *Fish culture utilization of geothermal energy*. Energy Research and Development Administration, Idaho National Engineering Laboratory, 50 pp.

Saman, J., 2000: The properties of the curative water and its uses for therapeutical treatment in Jordan. *Proceedings Geomedicine Seminar, Vienna,* 29-37.

Smith, R.A., 2002: Basic geology and chemistry of borate. *American Ceramic Societ, Bulletin, 81*, 1-64.

Strelbitskaya, S., 2005: Interpretation of the chemical composition of geothermal fluid from the geothermal field of Baransky volcano, Iturup Island, Russia. Report 17 in: *Geothermal Training in Iceland 2005.* UNU-GTP, Iceland, 333-351.

Svobodova, Z., Lloy, R., Machova, J., and Vykusova, B., 1993: *Water quality and fish health*. EIFAC, technical paper 54, FAO, Rome, 71 pp.

Texas A&M University, 2003: *Irrigation water quality standards and salinity management strategies*. Produced by Agriculture Communication, 8 pp.

Todd, D.K., and Mays, L.W., 2004: *Groundwater hydrology* (3rd ed.). John Wiley & Sons Int., 656 pp.

Tylor, R., 2005: *Identifying new opportunities for direct uses geothermal development*. California Energy Commission, Geothermal Program, San Diego, 137 pp.

US EPA, 2004: *Guidelines for water reuse.* US Environmental Protection Agency. Municipal support division office of wastewater management office of water, Washington, DC. EPA/625/R-04-108, Chapter 2. 7-27.

Venkateswarlu, K.S., 1996: *Water chemistry. Industrial and power station water treatment*. Bhabha Atomic Research Centre, Bombay, Water Chemistry Division, New Age International Ltd., 463 pp.

WAWQG, 1993: *Western Australian water quality guidelines for fresh and marine waters (Australian guidelines, 1992)*. Report of the Environmental Protection Authority, draft, Perth, Western Australia, Bulletin 711, 41-47.

WHO, 2003: *Guidelines for safe recreational-water environments. Vol. 1, coastal and fresh-waters.* World Health Organization, Geneva.

WHO, 2008*: Guidelines for drinking-water quality. Vol. 1, recommendations* (3rd ed.). World Health Organisation, Geneva.

Wright, P.M., 1991: Geochemistry. Chapter 4 in: *Direct use engineering and design guidebook.* University of Utah Research Institute, Salt Lake City, UT. GHC Bulletin, 8-12.

Zweig, R.D., Morton, J.D., and Stewart, M.M., 1999: *Source water quality for aquaculture, a guide for assessment. Environmentally and socially sustainable development.* The World Bank, Washington DC, 62 pp.