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CONCENTRATIONS OF SELECTED TRACE ELEMENTS AND IONS IN SPENT GEOTHERMAL LIQUID AND ASSOCIATED IMPACTS ON GROUNDWATER, SOIL AND VEGETATION IN THE MENENGAI GEOTHERMAL FIELD

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ABSTRACT

To assess the effect of spent geothermal liquids from discharging wells at the Menengai geothermal field on the environment, the concentrations of Na, Cl, K and F ions and the trace elements B, As, Hg, Cd, Cr and Pb in spent geothermal liquid from six geothermal wells and groundwater from four boreholes were analysed. Soils and vegetation in the vicinity of two of the six geothermal wells were also assessed for the concentrations of the trace elements B, As, Hg, Cd, Cr and Pb. Furthermore, the concentrations in spent liquids and groundwater were compared to the local standards for effluent released into the environment and the World Health Organization (WHO) drinking water standards. The soil and vegetation were compared to a reference site 2.5 km away from the discharging wells and further compared to the Food and Agricultural Organization (FAO) standards. The results showed concentrations of the ions Na, Cl and F and the trace elements As, Hg, Cr and Pb in the spent geothermal liquid from some the wells above the requirements of the local effluent standards. In groundwater, the fluoride concentration was double the WHO drinking water standard of 1.5 mg/l, which is typical for groundwater in the Kenyan Rift Valley. All the trace element concentrations were below the WHO drinking water standards except for Pb in two boreholes. In soil and vegetation, all the trace element concentrations were within the reference site levels and the FAO standards. To estimate the effect of the spent geothermal liquid on the groundwater, soils and vegetation, separate linear models were run. The model results indicated no contamination of groundwater, surrounding soils and vegetation by spent geothermal liquid. However, there was limited data for this study and therefore more data is needed to evaluate future impacts. More adequate measures on proper management of the spent geothermal liquid need to be emphasised before reinjection. Measures, such as routine maintenance of High Density Polyethylene (HDPE) liners to avoid seepage of the spent geothermal liquid into the environment, should be considered. Moreover, continuous monitoring of ions and trace elements with more ecosystem components such as other dominant vegetation should also be implemented.

1. INTRODUCTION

1.1 Background

The exploitation of geothermal energy is typically referred to as clean when compared to alternative energy sources such as fossil fuels due to the fact that the potential negative impacts can be mitigated to a larger extent (Kristmannsdóttir and Ármannsson, 2003). The energy is obtained from the earth by drilling into underground geothermal reservoirs. Deep geothermal wells are drilled to a depth of about 1000 m to 3000 m. Hot fluids from the deep geothermal reservoirs are used for electricity generation and other direct uses. During development and utilization of geothermal energy, especially in high temperature liquid dominated systems, dry steam is separated from the fluid for utilization and the remaining product, *spent geothermal liquid* is discharged to the surface. Depending on the geothermal reservoir, the volume of the discharged spent geothermal liquid may vary between wells and fields. In most cases large volumes are reported, for example the Hellisheidi 303 MWe geothermal power plant in Iceland produced 23 million tonnes of spent geothermal liquid in 2014 (Sigurdardóttir and Thorgeirsson, 2014).

The spent geothermal fluids contain several elements and compounds at elevated levels that can pose threats and adverse effects on the environment if not properly contained or discharged, particularly because the fluids are produced during various stages of geothermal development and utilization. The spent geothermal fluids occur in two forms, i.e. either as steam or liquid. Steam plumes are discharged into the atmosphere, especially during well testing, and primarily consist of 95–98% water vapour and uncondensed gases with traces of heavy metals and other elements (Axtmann, 1975). The liquid on the other hand is discharged during drilling, well testing and as separated water from the power plants. During these geothermal development processes, the steam plumes are allowed to disperse into the air while the spent geothermal liquid is directed to ponds which are lined with impervious material for temporary containment awaiting further disposal in either surface water ways or through deep reinjection. In the ponds, the geothermal liquid is contained to cool and reduce its effect on surface water ways during disposal. The containment methods may however be inefficient especially during well testing, which normally lasts a month or longer, resulting in the production of large volumes of spent liquids that may exceed the size of the ponds' carrying capacity and thereby spilling into the nearby environment occurs. The spillages can then get in direct contact with the soil, vegetation and surface water with chances of percolating into sub-surface water and ultimately contaminating the groundwater.

The composition of the spent geothermal fluids primarily consists of dissolved ions and trace elements such as sodium (Na), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), chloride (Cl), molybdenum (Mo), silica (Si), aluminium (Al), arsenic (As), cadmium (Cd), chromium (Cr), mercury (Hg), lead (Pb), selenium (Se) and boron (B) (Ármannsson and Fridriksson, 2009). The concentrations may vary between reservoirs depending on the rock composition, chemical and physical conditions of the weathering solution, the contribution from magmatic gases and adsorption of metal ions on oxide particles (Aiuppa et al., 2000). These ions and elements are well known to have detrimental short or long term effects on organisms if they deposit and bio-accumulate in vegetation, soils and water resources above tolerable levels. Some of these ions and trace elements such as F, and Cr at low concentrations are essential for the normal growth and development of living organisms. However, others like As and Hg in both low and high concentrations have the potential to contaminate the surface and groundwater adversely affecting aquatic ecosystems (Webster and Nordstrom, 2003).

During the early decades of utilization of geothermal energy, the impacts of spent geothermal liquids on the environment had not been widely studied as there were no strict environmental laws and regulations in place. The liquids were discharged onto the surface or into the nearby surface water ways owing to the low awareness on the associated environmental impacts and because these were the least cost methods available for disposal. During the 1960s for example, an 82 km long canal was constructed for disposal of spent geothermal liquid from the Ahuachapán geothermal field in El Salvador to the Pacific Ocean (Goff and Goff, 1997). A decade later, the effects of spent geothermal liquids on the environment became evident as environmental awareness levels advanced with the onset of Environmental Impact Assessment (EIA) studies and the subsequent monitoring and management plans to avoid adverse environmental effects. Today, proper disposal methods of spent geothermal liquids guided by policies that specify their proper handling in order to minimize environmental pollution have been developed and continue to improve based on new research findings. Presently, studies on the impacts of spent geothermal liquids on the environment in most geothermal fields around the world have become important. However, there is very limited information documented on the effects of spent geothermal liquids on soils and vegetation. In line with every geothermal projects' environmental management plan, conservation of biodiversity is important. It is therefore necessary to understand the impacts of spent geothermal liquid on the ecosystem for enhanced mitigation measures to minimise or avoid environmental degradation.

In Kenya, the generation of electricity from geothermal resources began in the early 1980s at the Olkaria geothermal field. Prospecting for the resource and drilling of wells commenced in the 1950s. The Olkaria field is located within the Hell's Gate National Park (HGNP) which is managed by the Kenya Wildlife Service (KWS). The geothermal project co-exists harmoniously with the wild life in accordance to a Memorandum of Understanding (MoU) between the KWS and the Kenya Electricity Generating Company Ltd (KenGen) which stipulates proper management of all environmental concerns. Presently, there are about two hundred geothermal wells and four geothermal power plants, i.e. Olkaria I, II, III, IV with an installed electric capacity of 630 MWe in the Olkaria geothermal area. At Olkaria, one of the main environmental challenges is the large volume of spent geothermal liquids produced at various stages of geothermal development and utilization and the consequent environmental effects. However, stringent measures on proper handling and disposal of these liquids have been enforced following an environmental management plan. Proper containment and re-injection of these liquids is practised at Olkaria and various geothermal fields all over the world today, not only for environmental reasons but because the process is also known to maintain the reservoir pressure. A study by Were (2007) on the speciation of trace elements concentration in spent geothermal liquid and the potential effects on the environment at the Olkaria geothermal field revealed elevated As, Hg, Mo and F concentrations beyond the Kenyan maximum permissible limits for recreational water and effluent discharged to the terrestrial environment. The other elements in the study, i.e. Al, As, Cd, Hg, Cu, Pb and Zn were below permissible limits.

The Menengai geothermal field is the second largest field to be developed in Kenya after the Olkaria geothermal field. Similar to Olkaria and other geothermal fields in the world, large volumes of spent geothermal liquid are produced. Nonetheless, studies on the potential environmental impacts are not fully explored. An Environmental Impact Assessment (EIA) for drilling of geothermal wells at the Menengai geothermal field was carried out in 2008 before drilling commenced. The study provided baseline data on the surface water chemistry of two seasonal streams, i.e. Kanduturi and Wanyororo streams which flow within the caldera, before geothermal activities started. The baseline data on the water quality was therefore important for correlation with future monitoring efforts of the same streams and other environmental components to assess potential contamination with the onset of exploitation activities in the geothermal field for planning of mitigation measures. The physical and chemical parameters that were analysed in the streams include, but are not limited to, pH, Na, SiO_2, Pb, Cu, Cd, B, Cl, F and Li, which were all within the National Drinking water standards except for Pb and F (Wetang'ula et al., 2008). However, in the EIA study, baseline data on the physical and chemical composition for the soil and vegetation at the Menengai geothermal field was not provided.

In this study, the concentrations of selected ions and trace elements in spent geothermal liquid, groundwater, soils and vegetation in the vicinity of geothermal wells at the Menengai geothermal field were assessed and presented. Furthermore, the impact of these element concentrations on soils, vegetation, and groundwater was evaluated to determine patterns that could infer possible contamination. The findings of this study are important to provide baseline information which will strengthen the environmental monitoring programmes and aid in improvement of current mitigation measures.

This study is specifically sought to:

1. Assess the concentrations of Na, Cl, K and F ions and the trace elements B, As, Hg, Cd, Cr and Pb in spent geothermal water from six appraisal wells and to compare the results with the local standards for discharge into the environment (Republic of Kenya, 2006).
2. Assess the concentrations of Na, Cl, K and F ions and the trace elements B, As, Hg, Cd, Cr and Pb in groundwater from four boreholes and to compare the results with the World Health Organization (2008), standards for drinking water.
3. Assess the concentrations of the trace elements B, As, Hg, Cd, Cr and Pb in soils and vegetation in the vicinity of two appraisal wells and compare with the FAO soil and vegetation standards.
4. To assess the potential environmental impacts of spent geothermal liquid on soils, vegetation and groundwater.

2. PREVIOUS STUDIES

Studies on the environmental impacts that arise during development of geothermal resources have been done intensively in various geothermal fields all over the world today. Some studies have been done on the impacts of spent geothermal liquids on the environment in various countries utilizing geothermal energy. For instance in Tuscany, central Italy, Bargagli et al. (1997) studied the environmental effects of trace elements emissions from geothermal power plants in mosses, organs of small mammals, fodder-plants and vegetables for human consumption grown within a 1-2 km radius from the geothermal power plant. A notable increase was detected in the deposition of Hg, B, As, and Sb in the biological samples collected a few hundred meters away from the geothermal power plants. The amounts decreased with increasing distance from the geothermal plant. Due to the trend of the high trace element concentrations in these components decreasing with increasing distance, the implication was that part of these trace elements emanated from the geothermal power plants emission. Concentrations of Hg, B, As and Pb were below permissible levels for vegetables and fodder crops consumption in the vicinity of the power plant and were suitable for human consumption (Bargagli, et al., 1997).

In the Philippines at the Northern Negros geothermal project, a similar study on the effect of spent geothermal fluid during well testing on the surrounding vegetation was done (Tuyor et al., 2005). The results showed significant impacts of elevated concentrations of Na, Cl, and B on the vegetation in the vicinity of the wells. According to the study, the vegetation was subject to long term and higher negative effects during well testing especially when wells blew over a month for adequate measurements and evaluation of the reservoir capacity to generate electricity. The results indicated that salinity and other associated ions of geothermal fluids could be a possible cause of leaf drying which later leads to abnormal defoliation of the exposed vegetation in the vicinity of a well during well testing and that the environmental impacts were widespread during vertical discharge compared to horizontal discharge (Tuyor et al., 2005).

In Iceland, spent geothermal liquids from the Hellisheidi and Nesjavellir geothermal power plants are reinjected back into the reinjection wells and part of the liquid is released to the surface. At Nesjavellir geothermal plant about half of the spent liquid is reinjected and half of it is released on the surface and finds its way into Lake Thingvallavatn. Hellisheidi, on the other side, obtained a permit that allows the release of the spent liquid onto the surface in case of emergencies but most of the liquid is re-injected. Continuous monitoring of the spent geothermal liquid has been on-going at the two power plants in order to assess any potential effects to the nearby surface water resources. The spent geothermal liquids at both power plants showed elevated levels of As, Al and K concentrations which were beyond the Icelandic limits tolerable for groundwater (Sigurdardóttir and Thorgeirsson, 2014). The As concentration of spent liquid from Nesjavellir power plant were pointed out as a major threat of contamination to the nearby and conserved Lake Thingvallavatn, thus posing a high risk of damaging effects to the aquatic life and surrounding terrestrial plants (Wetang'ula, 2004).

In Kenya, a few studies have also been done on the impacts of spent geothermal liquids on the environment, particularly in the Olkaria geothermal field (Simiyu and Tole, 2000; Wetang'ula, 2004 and Were, 1998; 2007). Simiyu and Tole, (2000) studied the concentration of selected trace elements, i.e. Pb, Zn, Cu, Cd, B, As, and Hg in spent geothermal liquid around the Olkaria wells and the potential effects on the food chain through soils and plants in contact with the liquid. The findings of their study revealed higher levels of Pb, Cd, Cu, and B in spent liquid compared to the nearby Lake Naivasha located approximately 12 km SW of Olkaria, which was also used as the reference site. In addition, the soils and vegetation in contact with the spent geothermal liquids also showed concentrations of the elements by factors of between 13 and 6000 compared to concentrations in the overlying spent liquid. In another study, Wetang'ula, (2004) assessed the trace elements concentration in spent geothermal liquids at Olkaria. The findings showed elevated concentrations of As, Mo, Al, and B in spent geothermal liquid compared to the Canadian environmental quality guidelines for plants and livestock. The indication was that these levels posed an eco-toxicological hazard to the environment. All these studies done in Olkaria recommended stringent measures on proper disposal of spent liquids, i.e. containment of spent liquid in lined ponds and continuous reinjection of spent liquid in order to trace elements accumulation in the soils and their uptake by plants and animals, therefore contaminating the food chain.

2.1 Review of selected trace elements and toxicity on the ecosystem

Boron is released into the environment through natural weathering of rocks and from volcanic and other geothermal activities. Boron is found both in geothermal steam and liquid. The addition of B to the environment can also be anthropogenic which include the use of borate containing fertilizers and herbicides and as waste released from borate mining process (Koç, 2007). In trace amounts, it is an essential nutrient for normal growth and development in some plants. However, in high concentration B can be toxic to plants, aquatic and micro-organisms. Plants in general, are far more sensitive than animals to boron toxicity. High levels of boron accumulate in plants and might lead to chlorosis and necrosis eventually burning and scorching the leaves (WHO, 2008). Naturally B is present in surface and underground water primarily as a result of leaching from rocks and soils containing borates and borosilicate, however if excess B is ingested through drinking water for a long period, the immune system can be highly affected (WHO, 2008). An example is given by Guo et al., (2008) where high concentrations of B of up to 3.82 mg/l were measured downstream in the Zangbo River in China, which was due to the discharging of spent geothermal liquid from the geothermal power plant at Yangbajing, which had extremely high B concentration levels of up to 119 mg/l. The geothermal power plant at Yangbajing area in China affected the water quality of the Zangbo river thus causing health problems of the people living in the downstream of Yangbajing area.

Arsenic is also found naturally in the minerals in the earth's crust and in soil, rock, water, and air. There are various sources of arsenic including natural sources such as volcanic activities, geothermal processes, and those caused by human activities which are the main contributors of As concentrations in the environment today. Arsenic was declared a human carcinogen contributing to a high incidence of skin and other cancers in populations exposed to high levels of arsenic leading to As concentration standards in water being lowered from 0.05 mg/l to 0.01 mg/l (Nordstrom, 2002). The element is mostly present in active and fossil geothermal systems and can cause contamination of surface and underground waters and can accumulate in plants and soils. For instance, As released into a river will interact with plants, biota, suspended material, and bed sediments thus potentially contaminating the food chain. Webster and Nordstrom (2003) indicated that the higher As concentrations in suspended sediments of the Waikato river were a function of their proximity to geothermal activity, i.e. where the river passes through the area of geothermal activity and that 7-8% of the As entering the river was adsorbed by the sediments.

High levels of mercury (Hg) in the environment have been recorded in areas where there is discharge and emissions from coal, hydro and geothermal power plants, mining and industrial activities. For instance, Axtmann, (1975) reported elevated Hg concentrations in the Waikato River compared to the spent geothermal liquid from the Wairakei plant in New Zealand which was adversely affecting the aquatic life and quality of the water. Mercury present in the air is deposited into water because of its ability to travel long distances in the air and the bacteria in the surface waters and sediments then converts elemental Hg into organic Hg compounds such as methylmercury. Methylmercury accumulates in fish at levels that may harm the fish and other aquatic life hence leading to mercury accumulation through the food chain.

Cadmium is generally present in the environment at low levels. It is naturally released to the environment through volcanic activities, weathering and erosion. However, human activities have greatly contributed to its increase into the environment through mining, smelting, industrial activities and, utilization of fossil fuels among others. The element has been classified as a human carcinogen by WHO. Moreover, Cd is primarily present in naturally occurring geothermal waters like the hot springs and also in spent geothermal liquid according to the findings by Simiyu and Tole (2000). The study reported Cd concentrations in the naturally occurring hot spring at Olkaria and the spent geothermal liquids from the wells to be in the range of 0.002-0.009 mg/l. The WHO drinking water recommended limit for Cd is 0.003 mg/litre. The Cd concentration in soil and vegetation in contact with the spent geothermal liquid were also reported to be in the range of 18.1–80 mg/l and 0.8–1.0 mg/l, respectively which is below the FAO soil and vegetation standards. High Cd levels in the environment can cause adverse health effects since Cd in soil and water can be taken up by certain crops and aquatic organisms and accumulate in the food-chain, hence affecting human beings especially the kidneys and the skeletal and respiratory system (WHO, 2008).

In the case of chromium, two valence states exist in soil, water and air through natural and anthropogenic sources which are chromium (III) and chromium (VI). Chromium (III) is an important nutrient needed by humans and shortages may cause heart conditions, metabolisms trouble, and even diabetes, but an increased uptake can cause health effects such as skin rashes while chromium (VI) is hazardous to humans and animals and may cause cancer and even death (Zayed and Terry, 2003). Chromium (III) and (VI) occurs mainly in the steel, leather, and textile industries. Most of the chromium present in the air settles in soil or water. Since chromium attaches strongly to soil particles, chromium that settles in soils will not leak into groundwater and chromium settling in water will absorb on sediment and become immobile. Therefore, crop uptake of chromium is generally very low hence there is very little effects on plants. Exposure to chromium can occur through ingestion, inhalation or through skin contact with chromium or chromium compounds. The Cr concentration in spent geothermal liquid from Menengai geothermal wells ranged from 0.01 to 0.1 mg/l and the recommended level of chromium for drinking water is usually as low as 0.05 mg/l.

Lead naturally occurs in the earth's crust usually as lead sulphide (PbS). However, due to human activities, it can also be found in many forms, mainly lead (II) sulphate ($PbSO_4$) and lead carbonates ($PbCO_3$). Lead may leach into the environment from various anthropogenic sources such as mining, steel industries, crop enhancers and improper disposal of batteries among others. When Pb is released into the environment, it makes its way into the air, soils and water sources and has a tendency to accumulate in soils and plants which restricts soil yields and enters the food chain thus affecting the human health. Lead in soil does not biodegrade or decay and absorption by plants is not rapid, therefore contamination of plants by uptake from the soil is rare, although when plants are exposed to lead dust, absorption of the metal dust through their leaves usually occurs, thus accumulating in plants (WHO, 2008). Lead is rarely found in tap water unless as a result of plumbing systems containing lead in the pipes and fittings or the service connections to homes. The amount of lead dissolved from the plumbing system usually depends on the physical and chemical composition of the water including pH, i.e. acidity or alkalinity of the water, temperature and water hardness (WHO, 2008). In geothermal water Pb may occur in high concentrations relative to the WHO drinking water standards depending on the rock mineral composition and water-rock interaction. For examples, Were, (2007) reported two wells in Olkaria with Pb concentrations of 0.247 to 0.373 mg/l, which is an order of a magnitude higher than the WHO recommended limit of 0.01 mg/l.

3. METHODOLOGY

3.1 Study area

The study area is located within the Menengai geothermal field (Figure 1). The Menengai geothermal field is a trachytic central caldera volcano situated in the Kenya Rift within the Eastern sector of the African Rift system and is among 14 geothermal prospects in Kenya. The geothermal field is located on the outskirts of Nakuru Town, about 180 km northwest of Nairobi, few kilometres south of the equator and covers an area of approximately 2,183 km^2 (Mutia and Simboyi, 2015). The geothermal field encompasses the Menengai volcano, the Ol-Rongai volcanoes, Ol-Banita plains and parts of the Solai graben to the northeast bounded by the coordinates 36°01′E and 36° 07′ E and 0° 09′ S and 0° 15′ S. The surface of Menengai geothermal field is covered by volcanic rocks and soils. The visible rocks at the surface of the caldera are mainly the Menengai massif building lava (pre-caldera formations), the pyroclastic (explosive) that accompanied the collapse of the caldera (syn-caldera) and glassy lavas that erupted after the caldera collapse (Njue, 2011). The volcanic soils are usually the dominant soil in young volcanic landscapes areas surrounding Menengai caldera.

The dominant vegetation within the caldera floor includes patches of bushed grassland, mixed bushland and open grasslands. The plant species include *Tarchonanthus camphoratus* (popularly known as leleshwa), *Acacia drepanolobium* and the grass species *Chloris gayana, Digitaria abyssinica* and *Fimbristylis exilis* (geothermal grass) among others (Wetang'ula et al., 2008). *T. camphoratus* is an evergreen shrub that grows to a height of about 9 m. It is favoured by deep soils and it is commonly found on stony soils in grassland, dry forest margins or secondary deciduous bushland. This shrub has been used since time immemorial for various purposes including as fodder for cattle, firewood, construction of the traditional huts, for making of essential oils and it has also been used for various medicinal purposes. Environmentally, it is very important as it controls soil erosion, helps in land reclamation and improves the fertility of the soil.

The local hydrogeology at Menengai is characterised by N-S trending fault/fracture systems which provide underground channels resulting in water disappearing underground in some places (Lagat, 2010). The surface drainage can be observed from the eastern and western rift scarps. On the rift floor, the drainage can mainly be found from Menengai caldera northwards with the exception of drainage from the southern inclines of the caldera into Lake Nakuru. The Menengai geothermal field has no permanent surface waters except for two seasonal streams, i.e. Kanduturi and Wanyororo streams which flow within the caldera. The permanent rivers are Molo and Rongai in the northwest part of the Menengai area, whereas other surface water bodies around include Lakes Nakuru and Lake Solai and the Olbanita swamp.

The rainfall regime in the project area is bimodal with long rains occurring from March to July and short rains from September to November (Wetang'ula et al., 2008). Automatic weather stations installed at the highest and lowest points of the caldera capture data on an hourly basis within the project area. During the period of July 2014 to June 2015 the annual average rainfall recorded ranged from 1000 mm to 316 mm at the highest and lowest points respectively. The rainfall events were concentrated at the centre/peak of the Menengai caldera. The temperature varied with topography with minimum and maximum temperatures of 15.7°C and 21.7°C respectively whereas the average wind speed recorded ranged from 4.53 m/s to 7.53 m/s at the lowest and highest points respectively.

Human settlement within the Menengai field is minimal since it is public land owned by the Kenya Forestry Service (KFS). Settlement is concentrated outside the caldera floor on the southern and western sectors that includes Nakuru municipality and Bahati divisions. The local people occupying the northern and north eastern parts of the prospect area practice small-scale mixed farming that include livestock keeping which mostly graze inside the caldera.

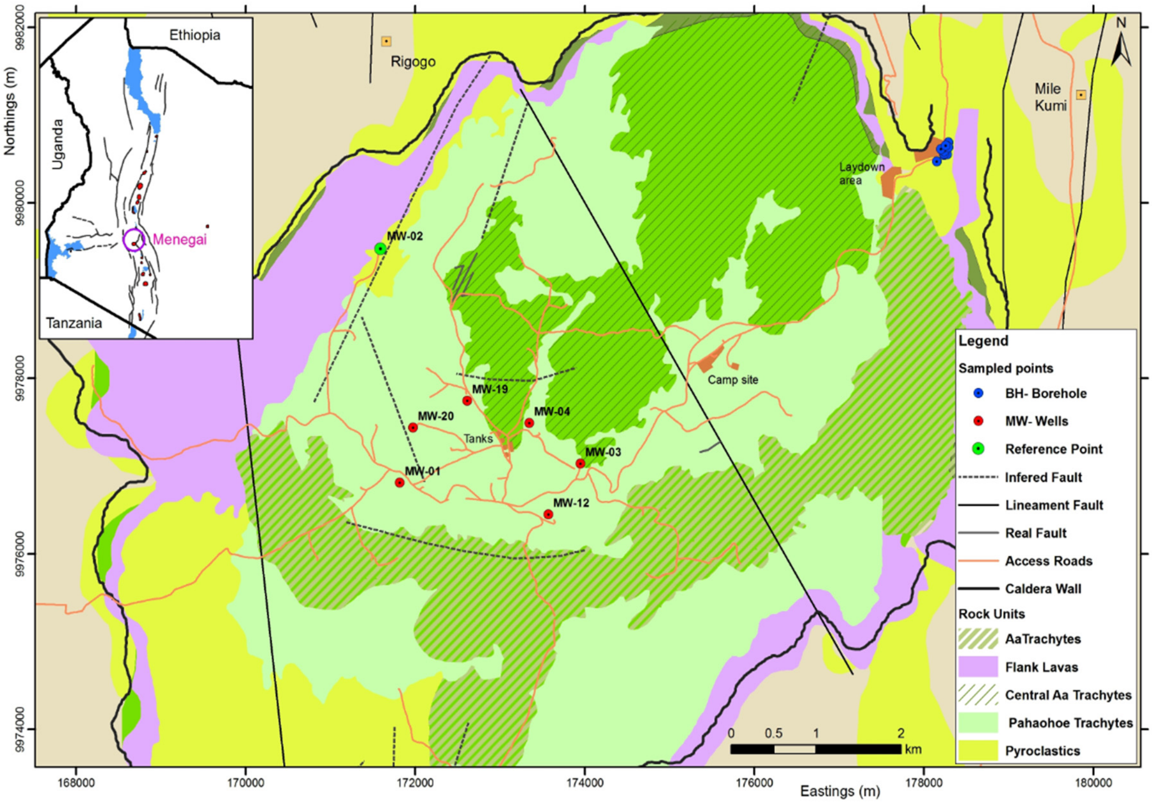

FIGURE 1: Map showing the location of Menengai geothermal field and the sampled points

3.2 Geothermal development at Menengai

Development of geothermal resources in Menengai began in 2004. KenGen undertook surface geoscientific studies to prove the existence of geothermal resources. The results indicated a geothermal potential in excess of 1600 MWe (Republic of Kenya, 2011). To develop the field in bid to meet the country's energy demand, an Environmental Impact Assessment (EIA) study for drilling of geothermal wells was conducted in 2008 by KenGen. The EIA drilling license was then obtained following a laid down Environmental and Social Management Plan (ESMP). However, with the establishment of the Geothermal Development Company (GDC), a state owned parastatal to oversee and develop most geothermal fields in Kenya, the EIA license was transferred from KenGen to GDC.

GDC was established in 2009 to accelerate and deploy geothermal energy in Kenya. This is in line with the country´s policy termed ´Kenya Vision 2030´, which aims at transforming Kenya into a middle income economy by the year 2030 with the provision of affordable and renewable energy as the major driver (Republic of Kenya, 2011). The mandate of GDC includes surface exploration, drilling, resource assessment and promotion of direct utilization of geothermal energy in Kenya. The Menengai geothermal field is the first geothermal field to be fully developed by GDC and the second largest field under development after the Olkaria field in Kenya. To date, geothermal development at this field, since the project was commissioned in 2010, has led to the successful drilling of about 25 deep exploration and production wells with over 2 km depth. GDC is developing the field step-by-step and intends to put up a 105 MWe geothermal power plant. Three Independent Power Producers (IPPs) namely Quantum energy, Sossian Energy and Orpower 22, have been licenced to operate each a 35 MWe modular power plant to achieve the 105 MWe.

As part of the drilling programme in the caldera, ten boreholes within the caldera (Fig 1) were drilled to supply water for drilling, infrastructural works and domestic uses for staff working within the project.

The boreholes were sunk to depths ranging between 100 and 250 m and produce 360 m^3/hr on average (GDC, 2013). The extraction is within the aquifer potential and the recharge is, in general, sufficient. GDC is also linked to the Nakuru Water and Sewerage Company (NAWASCO) to supplement the water resources through piped water services for the project area.

As part of the Environmental Social Monitoring Plan (ESMP) that was adopted in the EIA for drilling of geothermal wells, among the main environmental issues of concern was the containment of spent liquids from discharging wells. According to the plan, the spent liquids were to be contained in HDPE lined ponds with frequent chemical and discharge monitoring. Additionally, to manage the discharge, deep reinjection methods (Wetang'ula et al., 2008) and reuse of the liquids for drilling or other direct uses were proposed for mitigation to avoid contact with the environment.

The spent geothermal liquids from discharging wells in the field are temporarily contained in ponds lined with High Density Polyethylene (HDPE) liners and later on cooled and reused for drilling. Based on the fluid composition, the dissolved solids may potentially contaminate the surrounding surface water, groundwater, soils and vegetation during well testing caused by the steam sprays and overflown liquids. Reinjection of the spent geothermal liquid has not been done although future plans to carry out reinjection after commissioning of the power plants are in place. Routine monitoring of major ions and trace element concentrations in geothermal liquids from the discharging wells is carried out on quarterly basis as well as monitoring of the same elements in the surface and groundwater resources, surrounding soils and vegetation within the vicinity of the wells. However, it is worth noting that the impact of the spent geothermal liquids on the surrounding soils, vegetation and groundwater resources is not addressed in detail in any study.

3.3 Sampling and treatment

Sample collection for this study was done in such a way that all the risks of contamination were minimized and the relevant preservation requirements were met. Proper sample collection was very important in order to acquire data which will reveal the impact of geothermal utilization in Menengai.

3.3.1 Sampling of geothermal spent liquid and groundwater

Six geothermal well sites out of the twenty five drilled wells were selected for sampling of spent geothermal liquid. Four out of the ten groundwater boreholes that have been sunk in Menengai geothermal field by GDC were sampled for this study because they are located in a similar geological area. The ten boreholes have numbers from one to ten. The sampling abbreviations were as follows;

i. Geothermal wells sampled: MW1, MW3, MW4, MW12, MW19, and MW20; and
ii. Groundwater boreholes: BH1, BH2, BH3, and BH4.

Sampling of the geothermal wells was done during the specific time each well was discharging. MW01 discharged at intervals between May 2011 and April 2015 and sampling was done at each interval. Similarly for the other wells, MW3 discharged between September 2012 and June 2013 and was sampled during the same period, MW4 between October 2011 and April 2012, MW12 between February 2013 and May 2014, MW19 discharged from April 2014 to July 2014 whereas MW20 discharged between March 2014 and July 2015 and sampling was done during the same periods with samples collected from the ponds where the spent geothermal liquids were contained.

Samples were collected from all these wells (Figure 1) for the analysis of physical and chemical parameters. The samples for the analysis of the physical parameters, i.e. pH, conductivity and temperature were analysed in the field. The other samples for the chemical parameters were collected in two batches from each sampling point, i.e. one batch for the determination of trace elements which were labelled as Filtered acidified (Fa) and the other batch for the determination of anions and B which were labelled as Filtered untreated (Fu).

These samples were collected in new and pre-washed 500 ml polyethylene sampling bottles. The bottles were rinsed with the sample before samples were collected. During sampling of the spent liquid, the samples were collected from the ponds and the sampling bottles were immersed in the spent water to a depth of approximately 15 cm, wearing plastic hand gloves to prevent contamination. The groundwater was sampled directly from the taps at the borehole site. The bottles were capped immediately after sampling in order to exclude air and wrapped in plastic bags and then transported to the GDC laboratory for immediate treatment.

3.3.2 Treatment and analysis

The samples labelled Fa were for the determination of trace elements, i.e. As, Hg, Pb, Cd, and Cr. In the laboratory, these samples were filtered through a 0.45 μm millipore membrane to remove suspended matter and prevent sample interaction with these materials and immediately acidified using 1.0 ml of Ultrex Supra pure Nitric acid (HNO_3) to prevent the trace elements from adsorbing to the walls of the polyethylene sampling bottles.

The samples labelled Fu were also filtered through a 0.45 μm millipore membrane for the determination of Na, Cl, K, and B. The Fu samples were analysed at the GDC laboratory. The Fa samples were stored in airtight containers sealed with new plastic bags to avoid any kind of contamination and transported to the internationally accredited Kenya Bureau of Standards (KEBS).

The physical parameters, i.e. pH, temperature and conductivity were analysed on-site using a portable pH/conductivity meter. Boron concentration was determined by the Curcumin method using the Perkin Elmer spectrophotometer. The concentrations of Na, K, and Cl were determined using the Mohr titration technique while F was analysed using the Selective Ion Electrode (ISE) sensitive to F. All these analyses were done following the work instructions stipulated in the International Organization for Standardization (ISO) 9001, Quality Management Systems (QMS) procedures (GDC, 2010). Finally, the trace elements As, Cr, Pb, Hg, and Cd were determined with an Atomic Absorption Spectrophotometer (AAS) at KEBS.

3.3.3 Soil and vegetation sampling

To determine if any potential contamination of the environment exists around the discharging wells, sampling of soil and vegetation was done in the immediate vicinity of the discharged wells MW1 and MW3. The sampling sites were chosen along the prevailing wind and steam plume direction adjacent to the wells. This was because there had been no brine spillages on soils and vegetation at the well sites and so it was assumed that the steam's chemical composition would be similar to spent geothermal liquid in the ponds. The most abundant bushed grassland vegetation species, *T. camphoratus,* was chosen for sampling. One site (MW2) was established as a reference point since the well has never discharged and it is located about 2.6 km and 2.5 km from MW1 and MW3, respectively (Figure 1).

Replicate samples of the upper 5.0 cm soil were collected at each sampling site for analysis at each sampling period, similarly two samples of the *T. camphoratus* upper leaves were collected at the same sampling point as the soil samples. Soil was collected using a plastic scoop into polyethylene bags and sealed. The leaves of *T. camphoratus* samples were also randomly collected from *T. camphoratus* shrubs growing at the same position as the soil samples and stored in polyethylene bags. Sampling of soil and vegetation was done while wearing plastic gloves to prevent any kind of contamination. The soil and vegetation samples were immediately transported to the KEBS laboratory for treatment and analysis.

3.3.4 Treatment and analysis

The soil and vegetation samples were transported to KEBS laboratory where treatment and analysis were carried out. At the laboratory, soil samples were sun dried for 96 hours in direct sunlight in a secure area to prevent further contamination and later on sprayed with 0.1 m NaOH and then dried in the oven for two days at a temperature of 45°C. The soil samples were sieved to < 2 mm particles after oven drying and digested with aqua regia to extract the trace elements. The extract obtained was analysed for trace elements using the Atomic Absorption Spectrophotometer.

The leaves of the *T. camphoratus* samples collected were washed with 100 ml of deionized water and sprayed with 0.1 m NaOH and then oven dried for two days at a temperature of 45°C. The vegetation samples were then digested with aqua regia and analysed for the trace elements using AAS.

3.4 Data analysis

All statistical analysis was done using the program R version 3.2.2. All the data was plotted for exploration and presented as boxplots in Appendix I. Furthermore, the data was grouped into five matrices, i.e. spent liquid concentration, groundwater concentration, soil concentration, and vegetation concentration, and the predictor variable (location) and the observations were plotted. Analysis of Variance (Anova) was separately performed for each element in each of the matrices to test for differences in concentrations of the elements across the different sampled locations. The model diagnostics were also performed to ensure normality. In cases where the normality assumptions were not met, mainly because of zero inflation (concentrations with zero values), the data was log transformed with the equation $\mathrm{Log}_e\ (x+v)$, where x is the variable and v the minimum value of the variable. Descriptive statistical analysis was performed to assess the concentration of selected ions and trace elements in spent geothermal liquid, groundwater, soil, and vegetation and the data is presented as mean ± SE.

To assess the effects of spent geothermal liquid on the groundwater, soils, and vegetation, separate linear models were performed. In the models, groundwater, soil, and vegetation were the response variables while the spent geothermal liquid and well discharge locations were the predictors. Because the concentrations of the selected ions and trace elements in the spent geothermal liquid groundwater, soil, and vegetation did not differ significantly with location, they were treated as replicates for further statistical analysis.

4. RESULTS

4.1 Spent geothermal liquids

4.1.1 Physical parameters and selected ions

The temperature of the spent geothermal liquid at all the sampled points ranged from 22 to 31°C while pH values ranged from 8.8-9.6 (Appendix I). The mean temperature and pH values are presented in Table 1. The range of pH of spent geothermal liquid across all sampled wells was above the local limits for effluent discharge into the environment (Republic of Kenya, 2006; Table 1).

The Na, Cl, K and F concentrations in spent geothermal liquid ranged between 1638 and 3468 mg/l, 516 and 806 mg/l, 151 and 240 mg/l and 91 and 161 mg/l, respectively.

The F, Na, and Cl concentrations were above the limits of the local water quality regulations for effluent standards whereas the limits for the concentrations of K are not defined in the standard (Table 1).

There was a significant variation with well discharge locations between MW1 and MW4 for the concentration of Cl and K (Appendix II). The concentration of K was significantly different between all the sampled wells with highest concentrations at MW4. Meanwhile, Cl concentrations were significantly lower at MW4 compared to the rest of the wells. The concentrations of the Na and F ions in spent geothermal liquids did not show a statistically significant difference across the sampled well discharge locations (Appendix II). The major cation and anion present in high concentrations in spent geothermal liquid were Na and Cl respectively.

TABLE 1: Temperature (°C), pH and concentrations (mg/l; mean ±S.E) of Cl, F, Na and K in spent geothermal liquid from Menengai Wells (MW) compared to permissible levels, *n=36.* Bold letters show concentrations which exceeded the local limits for effluent discharge into the environment

Wells	**Temp**	**pH**	**Cl**	**F**	**Na**	**K**
MW1	27.3 ± 0.79	9.1 ± 0.04	**718.50 ± 16.87**	**151.58 ± 1.77**	**2483.16 ± 172.63**	223.72 ± 5.75
MW3	25.2 ± 0.94	9.0 ± 0.14	**703.09 ± 35.10**	**129.01 ± 10.85**	**2594.39 ± 233.40**	189.25 ± 10.30
MW4	27.5 ± 0.87	8.8 ± 0.17	**605.40 ± 28.25**	**133.72 ± 4.23**	**2235.08 ± 107.40**	172.02 ± 5.04
MW12	25.3 ± 0.97	9.6 ± 0.11	**668.16 ± 15.92**	**119.38 ± 4.21**	**2469.07 ± 107.96**	177.65 ± 3.51
MW19	27.2 ± 0.85	9.5 ± 0.09	**682.83 ± 11.15**	**131.23 ± 5.00**	**2545.73 ± 69.23**	179.51 ± 4.79
MW20	24.7 ± 0.82	9.3 ± 0.14	**676.46 ± 15.66**	**135.17 ± 5.95**	**2517.98 ± 184.25**	182.67 ± 8.33
Local standards for effluent discharge into the environment (2006)	NLS*	6.5 - 8.5	250	1,5	200	NLS*

*NLS - No limit specified

4.1.2 Trace elements

The concentration of trace elements in the spent geothermal liquid ranged between 0.020 and 2.070 mg/l of B, 0.001 and 2.000 mg/l of Hg, 0.001 and 7.680 mg/l of As, 0.002 and 0.850 mg/l of Pb, 0.003 and 0.300 mg/l of Cr, and 0.001 to 0.010 mg/l of Cd across all the sampled wells (Appendix I). The mean concentrations are presented in Table 2.

The mean concentrations of B and Cd in spent geothermal liquid were below the recommended local water quality regulations for effluent standards at all the six sampled well discharge locations whereas the concentration of Pb was beyond the permissible limit (Table 2). Elevated Hg concentration in spent

TABLE 2: Mean concentrations (± S.E) of the trace elements concentrations (mg/l) in spent geothermal liquid from Menengai wells (MW) compared to permissible levels, *n=36.* Bold letters show concentrations which exceeded the local standards for effluent discharge into the environment

Wells	**B**	**Hg**	**As**	**Pb**	**Cr**	**Cd**
MW1	0.157 ± 0.050	0.001 ± 0.001	0.001 ± 0.001	**0.013 ± 0.001**	0.009 ± 0.001	0.002 ± 0.001
MW3	0.200 ± 0.130	**0.240 ± 0.210**	**0.112 ± 0.050**	**0.087 ± 0.030**	**0.093 ± 0.030**	0.002 ± 0.001
MW4	0.400 ± 0.340	0.002 ± 0.001	**0.310 ± 0.160**	**0.049 ± 0.020**	0.018 ± 0.020	0.001 ± 0.001
MW12	0.668 ± 0.330	**0.082 ± 0.070**	**3.044 ± 1.610**	**0.570 ± 0.030**	0.051 ± 0.030	0.002 ± 0.001
MW19	0.091 ± 0.030	**0.281 ± 0.250**	**0.172 ± 0.150**	**0.069 ± 0.010**	0.020 ± 0.020	0.001 ± 0.001
MW20	0.274 ± 0.120	**0.400 ± 0.360**	0.020 ± 0.020	**0.227 ± 0.140**	**0.070 ± 0.050**	0.002 ± 0.001
Local standards for effluent discharge into the environment (2006)	1,000	0,010	0,020	0,010	0,050	0,010

geothermal liquid occurred at MW3, MW12, MW19, and MW20 while for As, concentrations were elevated at MW3, MW4, MW12, and MW19. High Cr concentration occurred in the spent geothermal liquid at MW3 and MW20 (Table 2).

Nonetheless, the concentrations of As, Cd, Cr, B, Pb, and Hg in spent geothermal liquid across all the wells did not statistically vary with location except for the concentrations of As at MW12 and Cr at MW3 which were significantly higher compared to the other wells (Appendix II).

4.2 Groundwater

4.2.1 Physical parameters and selected ions

The physical parameters did not vary widely in the four groundwater boreholes. The temperature ranged from 25.6°C to 28.8°C and the pH between 7.1 and 7.8. In comparison with the WHO drinking water standards, the pH was within the recommended level of between 6.5 and 8.5 (Table 3).

The Na, Cl, K and F concentrations ranged from 59.5 to 73.6 mg/l, 14.0 to 19.0 mg/l, 1.0 to 1.4 mg/l and 2.6 to 4.2 mg/l, respectively (Appendix I). The mean concentrations are presented in Table 3. All the measured ions were below the WHO required limits for drinking water except F where the concentrations exceeded the 1.5 mg/l limit (Table 3).

TABLE 3: Temperature (°C), pH and mean concentrations (mg/l; ± S.E) of Na, Cl, K and F in groundwater from Menengai boreholes compared to permissible levels*, n=16.*
Bold letters show concentrations which exceeded the WHO drinking water standards

Boreholes	**Temp**	**pH**	**Na**	**Cl**	**K**	**F**
BH1	27.25 ± 0.50	7.48 ± 0.05	71.93 ± 0.71	17.50 ± 0.80	1.22 ± 0.02	**3.50 ± 0.20**
BH2	26.13 ± 0.20	7.54 ± 0.10	70.63 ± 1.00	17.50 ± 0.50	1.25 ± 0.02	**3.25 ± 0.16**
BH3	26.80 ± 0.08	7.29 ± 0.03	60.00 ± 0.33	14.75 ± 0.37	1.23 ± 0.03	**3.15 ± 0.18**
BH4	26.88 ± 0.22	7.23 ± 0.04	65.29 ± 0.75	14.50 ± 0.22	1.95 ± 0.01	**3.37 ± 0.12**
WHO (2008) Drinking water stds.		6.5 - 8.5	200	250	NLS	1,5

*NLS - No limit specified

Concentrations of Na and Cl appear to be location dependent (Appendix II). The concentration of Na was significantly lower at BH3 whereas Cl concentration was significantly lower at MW4 compared to the rest of the wells. The concentrations of Cl, K, and F in groundwater did not show significant differences across the different boreholes sampled, i.e. BH1, BH2, BH3, and BH4 (Appendix II). The major cation and anion present in high concentrations in groundwater was Na and Cl respectively.

4.2.2 Trace elements

The concentrations of the trace elements in groundwater ranged from 0.001 to 0.060 mg/l B, 0.001 to 0,002 mg/l Hg, 0.001 to 0.021 mg/l As, 0.001 to 0.003 mg/l Cr, 0.001 to 0.003 mg/l Cd and 0.009 to 0.030 mg/l Pb across all the sampled boreholes (Appendix I).

The concentrations of the trace elements, i.e. Hg, Cr, B, As, and Cd in the groundwater were below the recommended WHO drinking water levels expect for Pb at BH1 and BH4 (Table 4).

TABLE 4: Mean concentrations (± S.E) of the trace elements concentration (mg/l) in groundwater from Menengai boreholes compared to permissible levels, *n=16*

Boreholes	**B**	**Hg**	**As**	**Pb**	**Cr**	**Cd**
BH1	0.010 ± 0.001	0.001 ± 0.001	0.010 ± 0.001	**0.020 ± 0.001**	0.001 ± 0.001	0.001 ± 0.001
BH2	0.001 ± 0.001	0.001 ± 0.001	0.001 ± 0.001	0.010 ± 0.001	0.001 ± 0.001	0.001 ± 0.001
BH3	0.001 ± 0.001	0.001 ± 0.001	0.010 ± 0.001	0.001 ± 0.001	0.001 ± 0.001	0.001 ± 0.001
BH4	0.030 ± 0.001	0.001 ± 0.001	0.001 ± 0.001	**0.020 ± 0.001**	0.001 ± 0.001	0.001 ± 0.001
WHO (2008) Drinking water stds.	0,500	0,006	0,010	0,010	0,050	0,003

4.3 Soils and vegetation

4.3.1 Trace elements

The concentrations of trace elements in soils ranged between 0.001 and 3.110 mg/l of B, 0.001 to 0.190 mg/kg of Hg, 0.001 to 3.760 mg/kg of As, 2.370 to 36.20 mg/kg of Pb, 0.015 to 2.620 mg/kg of Cr, and 0.021 to 2.200 mg/kg of Cd at the MW1, MW3, and Reference site (MW2) (Appendix I). In vegetation, the concentration ranged from 0.057 to 3.120 mg/kg of B, 0.001 to 0.190 mg/kg of Hg, 0.001 to 2.380 mg/kg of As, 0.014 to 4.800 mg/kg of Pb, 0.021 to 2.200 mg/kg of Cr, and 0.001 to 0.050 mg/kg of Cd (Appendix I). The mean concentrations are presented in Table 5.

TABLE 5: Mean concentrations (± S.E) of the trace elements concentration (mg/l) in soil and vegetation (mg/kg) from Menengai wells (MW) compared to permissible levels, *n=18*

Sample	**Site**	**B**	**Hg**	**As**	**Pb**	**Cr**	**Cd**
Soil	MW1	0.548 ± 0.470	0.056 ± 0.032	1.026 ± 0.590	15.955 ± 3.660	0.500 ± 0.390	0.247 ± 0.220
	MW3	0.131 ± 0.120	0.001 ± 0.001	0.070 ± 0.060	21.364 ± 6.210	0.416 ± 0.140	0.001 ± 0.010
	Ref*	0.144 ± 0.071	0.004 ± 0.001	0.080 ± 0.040	14.198 ± 3.530	0.330 ± 0.130	0.042 ± 0.030
FAO soil standards		5,00	15,00	50,00	300,00	400,00	3,00
T.camphoratus	MW1	1.239 ± 0.452	0.001 ± 0.001	0.960 ± 0.410	1.030 ± 0.700	0.287 ± 0.260	0.008 ± 0.001
	MW3	0.233 ± 0.150	0.057 ± 0.050	0.137 ± 0.120	0.210 ± 0.100	0.424 ± 0.330	0.001 ± 0.001
	Ref*	0.097 ± 0.040	0.001 ± 0.001	0.072 ± 0.060	0.226 ± 0.090	0.281 ± 0.170	0.040 ± 0.021
FAO vegetation standards		2,00	15,00	50,00	300,00	400,00	3,00

*Ref - Reference site

The concentrations of B, As, Hg, Pb, Cr, and Cd in soil and vegetation were below the recommended FAO standards in both soil and vegetation across the three sites. The trace elements concentrations in soil across the three sites did not show a wide variation, even though statistically higher concentrations of Hg and As were measured in the soils at MW1 compared to MW3 and the reference site MW2 (Appendix II). The average trace element concentrations in soil at MW3 were in the same range or lower compared to the reference site except for Pb which was high at MW3. The concentration of the trace elements in vegetation showed a wide variation in the concentration of B and As being significantly higher in vegetation at MW1 (Appendix II).

4.4 Potential effect of spent geothermal liquid on groundwater, soils and vegetation

The effect of the trace elements B, As, Hg, Cd, Cr, and Pb in spent geothermal liquid on soil was not significant. Nonetheless, the model estimates that the concentration of Cr in spent geothermal liquid around the wells shows a positive association with Cr in surrounding soils, although the relationship is not significant (Appendix III).

The concentrations of B, As, Hg, Cd, Cr, and Pb in spent geothermal liquid showed no significant effects on the surrounding vegetation, however model estimates showed that B concentration in the spent geothermal liquid was correlated with the B concentration in vegetation although the association was not significant (Appendix III).

The effect of B, As, Hg, Cr, and Pb concentrations in spent geothermal liquid on the groundwater within Menengai was not significant, although elevated Cd concentrations were observed. The model estimates also showed the concentration of Cd and Cr in spent geothermal liquid and groundwater was positively associated.

5. DISCUSSION

5.1 Spent geothermal liquid

Spent geothermal fluids are well known to contain some trace elements and ions which in high concentration have the potential to contaminate the environment. The spent geothermal liquids from the sampled wells at the Menengai geothermal field were alkaline in nature with elevated pH levels beyond the recommended local water quality regulations for effluent standards of 6.5–8.5 due to the high concentrations of total dissolved carbonates in the spent geothermal waters. These findings are similar to the spent geothermal liquid at Olkaria from discharging geothermal wells (Were, 2007).

The average concentrations of the ions analysed, i.e. Na, F, K, and Cl in the spent geothermal liquid were found to be in concentrations over 30 times higher compared to the groundwater. This is quite common for spent geothermal liquids especially in high temperature geothermal areas where chemical constituents like Na and Cl ions occur in abundance, with Cl concentrations ranging from 1000 to 10,000 mg/kg (Barbier, 2002). The geothermal liquid that ascends up contains variable solute concentrations which depend on various factors such as the fluid source or mixing, rock type or temperature of the fluids (Arnórsson et al., 2007). As a result of these processes, elevated concentrations of dissolved solids in spent geothermal liquids might cause vegetation damage such as drying of the leaves and abnormal defoliation (Tuyor et al., 2005) if not properly disposed. This is in line with a study on the fluid chemistry, feed zones and boiling in the first exploration well at Menengai (MW1) in Kipng'ok, (2011) classified the aquifer water for MW1 as Na-HCO_3 type with relatively high Cl values of greater than 500 ppm. In comparison to the thermal groundwaters of Vulcano Island in Sicily, similar results of elevated Na, Cl, K, and F were reported (Aiuppa et al., 2000). The variations observed in the K and Cl concentration between MW1 and MW4 could not be established due to limited data.

From an environmental perspective, it is important to monitor the trace element concentrations in the spent geothermal liquid in Menengai geothermal field, considering it is a forest reserve. Elevated levels of trace element concentrations such as Pb, As, Hg, and Cr in the spent geothermal liquid were measured in some of the wells. These trace elements are considered toxic to the environment due to their ability to bio accumulate in terrestrial and aquatic living organisms through the food chain thus causing adverse environmental and health effects. For this reason, proper disposal of spent geothermal liquid needs to be highly emphasised. However, comparing this finding to other geothermal waters, i.e. spent geothermal liquid or naturally occurring geothermal water such as hot springs, the trace elements concentrations in the spent geothermal liquids from Menengai are in the same range or lower in concentration. For example, the trace element concentration in hot springs at Olkaria reported in Simiyu and Tole (2000) occurred in similar range as the spent geothermal liquids of Menengai except for As and Cr which were high in the hot springs. In comparison to other fields such as the Yangbajing geothermal field in China, the concentration of As and B in spent geothermal liquids in Menengai were very low compared to the spent geothermal liquid collected from the production wells of the Yangbajing geothermal power plants in Guo et al. (2008).

The concentrations of As at MW12 and Cr at MW 3 showed a wide variation in concentrations compared to the other wells which is not expected considering they have a similar reservoir composition and the trace elements' occurrence in geothermal waters including spent geothermal liquid is generally depending on factors such as rocks chemical composition, physical conditions of the weathering solution (temperature, acidity and redox conditions) and the contribution of magmatic gases (Aiuppa et al., 2000). This can be attributed to the different sampling seasons or the variation in As concentration could also be explained partly by the adsorption to silica polymers in the ponds.

5.2 Groundwater

The water quality for the groundwater in Menengai geothermal field from four boreholes was determined. F concentrations were more than double the permissible limit of 1.5 mg/l in all the boreholes measured which is typical in the Kenyan rift due to the underlying geological formation. Similar findings were reported in the pre-drilling EIA for Menengai where two seasonal streams that flow within the caldera showed elevated concentrations of Pb and F levels (Wetang'ula et al., 2008). Human consumption of water with high levels of F concentration can lead to mottling of teeth and in severe cases it might cause crippling skeletal fluorosis (WHO, 2008).

The trace elements concentrations in the groundwater were also below the recommended drinking water limit (WHO, 2008) except for Pb at BH1 and BH4. The elevated Pb concentration in the groundwater may be attributed to the rock composition of Menengai area and not from geothermal activities considering Pb was still high in the pre-drilling report. In the Menengai field, being a volcanic area, Pb is naturally present in the underground rock and soil. Another source of Pb could be from the metallic piping material where the boreholes water is channelled since Pb can easily react with water depending on the physical and chemical composition of the water. Risks from elements such as Pb are intensified by their high ability to increase in concentration as they move up the food chain and children are more susceptible to the most damaging effects of Pb toxicity as they absorb 4-5 times higher Pb concentration than adults after exposure (WHO, 2008).

The variation in the concentration of Na and Cl in the groundwater at BH1 and BH4 could be due to sampling and analytical errors. The model estimates showed that the trace elements concentrations (B, Hg, Pb, Cr, As, and Cd) in the spent geothermal liquid does not have an effect on the groundwater. Although detailed studies on the potential effects of the spent geothermal liquid on the groundwater within Menengai need to be carried out due to insufficient data for this study.

5.3 Soil and vegetation

The trace elements concentrations, i.e. B, As, Hg, Cd, Cr, and Pb in the soil and vegetation in the vicinity of MW1 and MW3 were not different compared to the reference site MW2. All three sites had very low trace elements concentrations that originate from the crust with no potential effects coming from the spent geothermal liquid. The trace elements did not show any accumulation in the soil and vegetation and seems unlikely to pose any risk for the livestock that graze within the project area. Therefore, geothermal activities in Menengai have not had any impact on the concentration of the soils and vegetation at these sites. However, detailed studies are highly recommended for the other well sites within the project area. Although these findings are not similar to the study by Simiyu and Tole, (2000) on the trace elements concentrations in waters, soil and plants in the Olkaria geothermal field. In the study, higher concentration of B, As, and Hg in soils in contact with the spent geothermal liquid were reported at Olkaria compared to the soil concentration in Menengai. Vegetation samples in contact with the spent geothermal liquid at Olkaria also showed higher B concentrations compared to the vegetation in Menengai.

6. CONCLUSIONS AND RECOMMENDATIONS

The spent geothermal liquid at the Menengai geothermal field showed elevated levels of ions and trace elements, i.e. Cl, Na, Hg, As, Pb, and Cr in spent geothermal liquid in all wells relative to local water quality regulations for effluent discharge into the environment.

The concentrations in the groundwater were within the WHO drinking water levels except for F which is typical in the Kenyan rift. The elevated levels of Pb are caused by the natural geothermal processes and the rocks and soils composition of Menengai area or the piping material for channelling the groundwater. Since this groundwater is mainly used for drilling and civil activities there is no cause for alarm, but before this water is used for human consumption it should undergo proper treatment.

The trace element concentration in soils and vegetation in the vicinity of the three wells, i.e. MW1, MW2, and MW3 were within the recommended FAO levels for soil and vegetation and there is no evidence of trace elements accumulation. There were no differences in trace element concentration at MW1 and MW3 in comparison with the reference site, however more investigation is required since statistically higher concentrations of Hg and As in soil and B and As in vegetation were observed at MW1.

The geothermal activities in Menengai field and specifically the discharge of spent geothermal liquid has not had any effect so far on the surrounding soil, vegetation and groundwater, however further studies are necessary since data for this study was quite limited.

The Menengai geothermal field being a forest reserve, it is important from an environmental perspective to properly contain these spent geothermal liquids to avoid direct contact with the environment. Therefore, this study recommends:

I. Reinjection of spent geothermal fluids to be adopted since the output for these spent liquids is projected to increase with further development.
II. Routine maintenance of the HDPE liners should also be carried out to avoid seepage into the ground and ponds should not be filled beyond their maximum capacity.
III. Frequency in the monitoring of the trace elements concentrations in the spent geothermal liquid, groundwater, soil, and vegetation in the vicinity of all the wells in Menengai should be increased from quarterly to monthly to establish a good database for modelling effects.
IV. Detailed study on the different types of the dominant vegetation species in Menengai which need to be sampled and analysed for the saline ions and trace elements since only one species type was assessed and as part of baseline, other dominant species should be included in the routine monitoring.
V. Assessment of the trace elements mobility, speciation and distribution in the spent geothermal liquid from the different wells.

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APPENDIX I: Selected ions and trace elements concentration (mg/l) in spent geothermal liquid, groundwater, soil, and vegetation

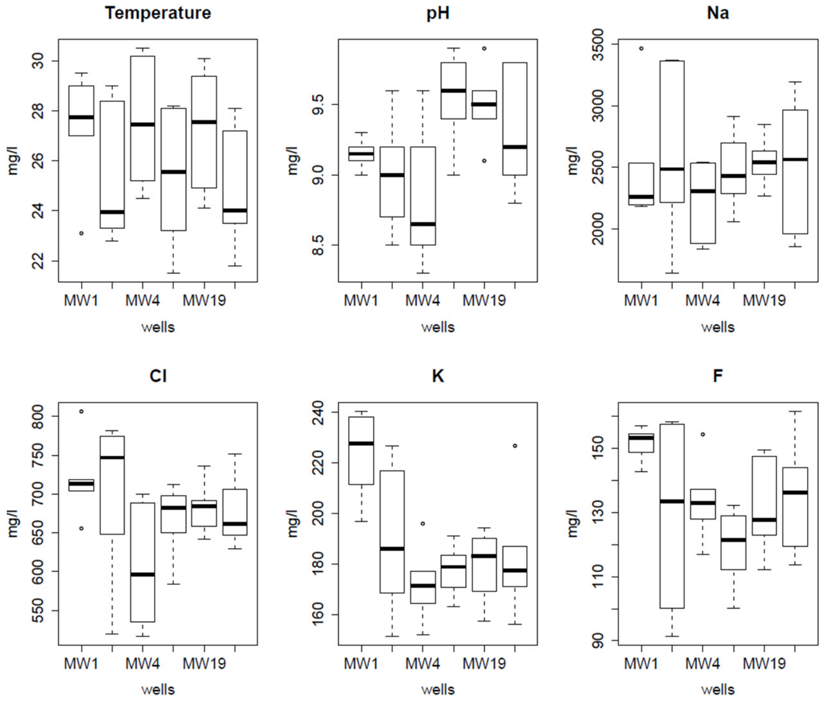

FIGURE 1: Physical parameters and ion concentrations (mg/l) in spent geothermal liquid at Menengai wells. The x-axis represents the sampled wells in the following order, MW1, MW3, MW4, MW12, MW19, and MW20

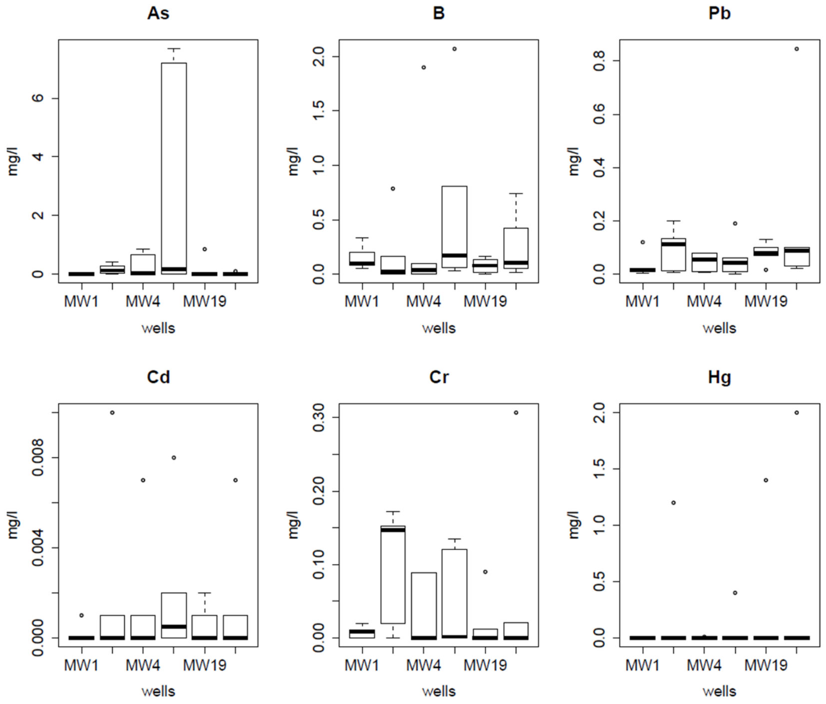

FIGURE 2: Trace elements concentrations (mg/l) in spent geothermal liquid at Menengai wells. The x-axis represents the sampled wells in the following order, MW1, MW3, MW4, MW12, MW19, and MW20

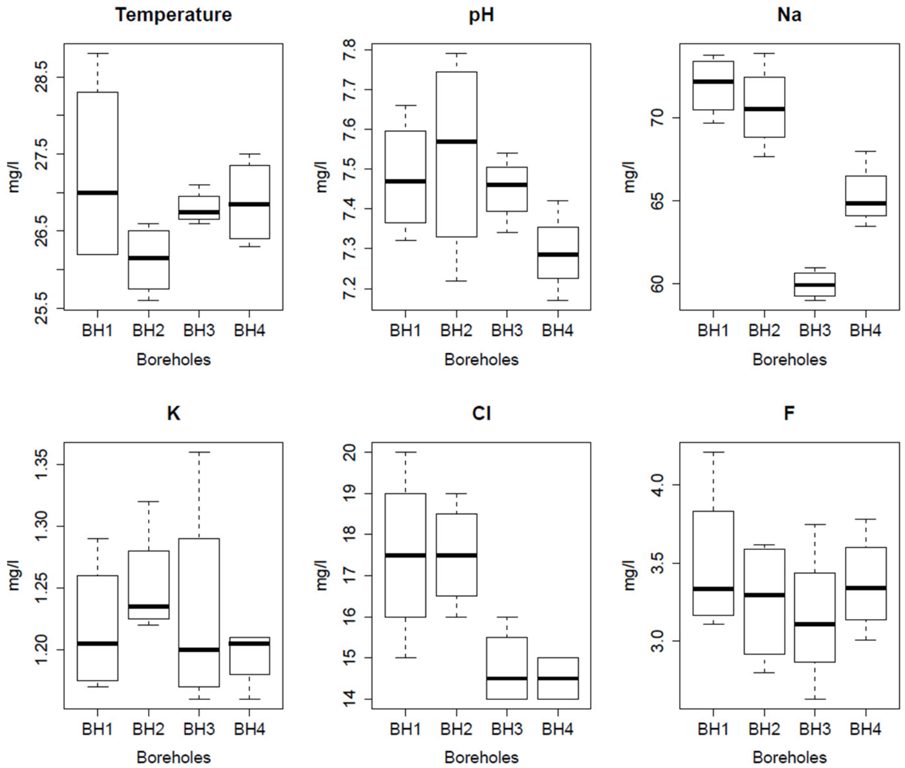

FIGURE 3: Physical parameters and ion concentrations (mg/l) in groundwater from Menengai boreholes - BH1, BH2, BH3, and BH4

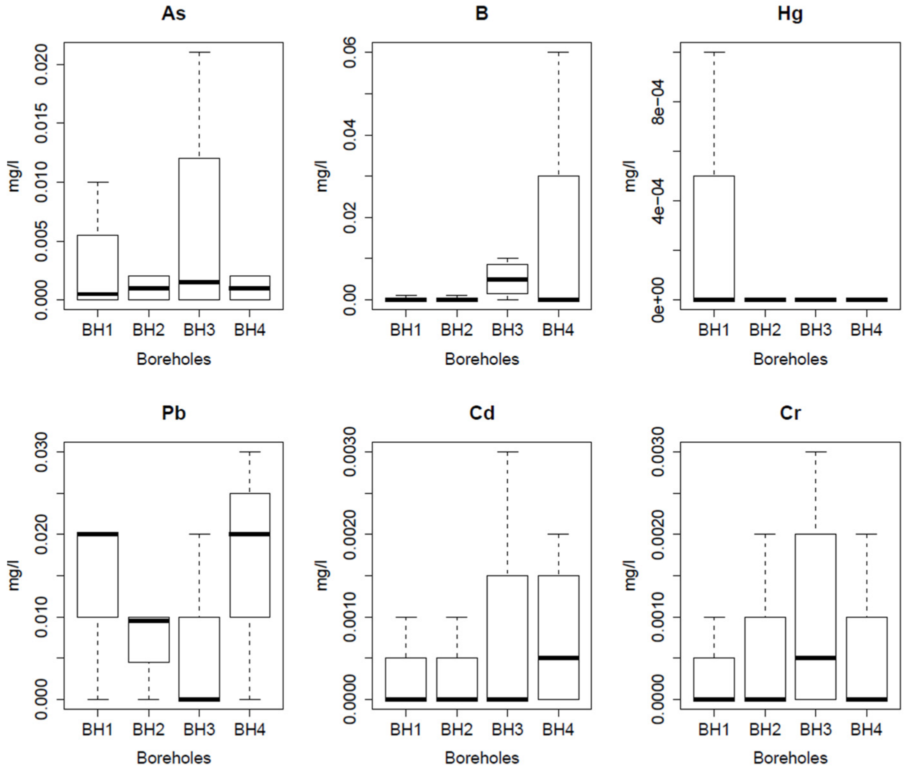

FIGURE 4: Trace elements concentrations (mg/l) in groundwater from Menengai boreholes - BH1, BH2, BH3, and BH4

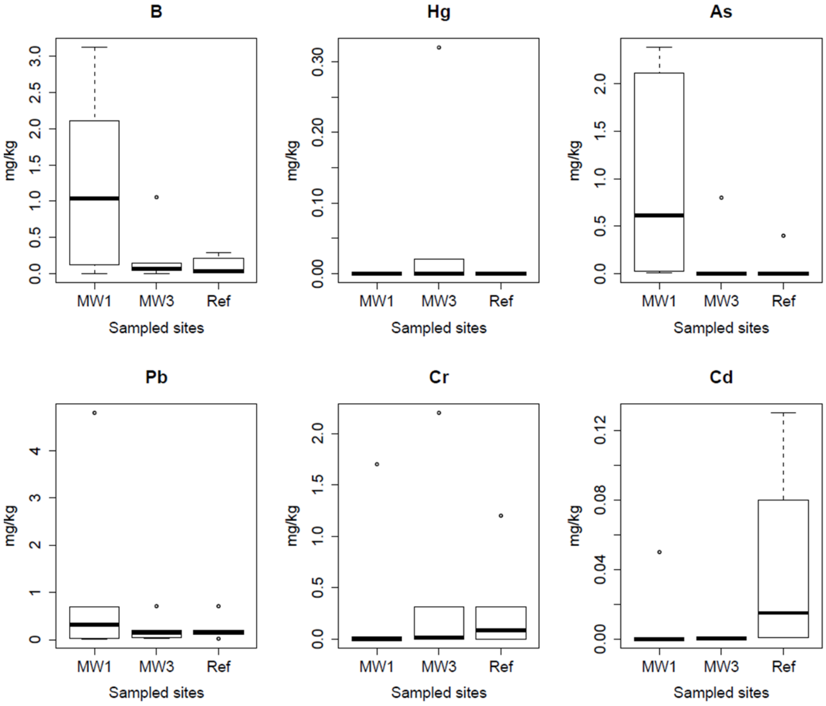

FIGURE 5: Trace elements concentrations (mg/kg) in vegetation samples in the vicinity of Menengai wells - MW1, MW3, and Reference site (MW2)

APPENDIX II: Analysis of Variance (Anova) results for spent geothermal liquid and groundwater across the different sampled locations

TABLE 1: Analysis of Variance (Anova) results for the concentrations of Na, Cl, K, and F in spent geothermal liquid across the different sampled locations from Menengai wells

Response	Predictor	Estimate	Std Error	t-value	P-value
Na concentration in spent geothermal liquid	Intercept-Location MW1	2483,16	184,70	13,444	**0,000**
	Location MW12	-14,09	261,21	-0,054	0,957
	Location MW19	62,57	261,21	0,240	0,812
	Location MW20	34,81	261,21	0,1333	0,895
	Location MW3	111,23	261,21	0,426	0,673
	Location MW4	-248,07	261,21	-0,950	0,350
Residual standard error: 452.4, DF: 30					
Cl concentration in spent geothermal liquid	Intercept-Location MW1	718,15	26,18	27,441	**0,000**
	Location MW12	-50,35	37,03	-1,360	0,184
	Location MW19	-35,67	37,03	-0,963	0,343
	Location MW20	-42,04	37,03	-1,135	0,265
	Location MW3	-15,41	37,03	-0,416	0,680
	Location MW4	-113,1	37,03	-3,054	**0,005**
Residual standard error: 64.13, DF: 30					
K concentration in spent geothermal liquid	Intercept-Location MW1	223,71	7,93	28,22	**0,000**
	Location MW12	-46,06	11,21	-4,109	**0,000**
	Location MW19	-44,21	11,21	-3,943	**0,000**
	Location MW20	-41,05	11,21	-3,661	**0,001**
	Location MW3	-34,47	11,21	-3,074	**0,001**
	Location MW4	-51,70	11,21	-4,611	**0,000**
Residual standard error: 19.42, DF: 30					
F concentration in spent geothermal liquid	Intercept-Location MW1	151,58	7,12	21,304	**0,000**
	Location MW12	-32,2	10,06	-3,200	0,050
	Location MW19	-20,34	10,06	-2,022	0,050
	Location MW20	-16,41	10,06	-1,631	0,113
	Location MW3	-22,57	10,06	-2,243	0,060
	Location MW4	-17,86	10,06	-1,775	0,086
Residual standard error: 17.43, DF: 30					

*Estimates indicate the effects of the predictors compared to the intercept and followed by a test statistic

TABLE 2: Analysis of Variance (Anova) results for the concentrations of B, Hg, As, Cd, Cr, and Pb in spent geothermal liquid across the different sampled locations from Menengai wells

Response	**Predictor**	**Estimate**	**Std Error**	**t-value**	**P-value**
log B concentration in spent geothermal liquid	Intercept-Location MW1	0,171	0,960	0,178	0,860
	Location MW12	0,400	1,357	0,300	0,766
	Location MW19	-0,068	1,357	-0,050	0,961
	Location MW20	0,094	1,357	0,069	0,945
	Location MW3	0,021	1,357	0,015	0,988
	Location MW4	2,570	1,357	1,894	0,068
Residual standard error: 2.35, DF: 30					
log Hg concentration in spent geothermal liquid	Intercept-Location MW1	0,001	0,221	0,005	0,996
	Location MW12	0,068	0,313	0,217	0,830
	Location MW19	0,235	0,313	0,752	0,458
	Location MW20	0,333	0,313	1,065	0,296
	Location MW3	0,535	0,313	1,708	0,098
	Location MW4	0,001	0,313	0,004	0,997
Residual standard error: 0.542, DF: 30					
log As concentration in spent geothermal liquid	Intercept-Location MW1	0,020	0,064	0,032	0,975
	Location MW12	2,530	0,905	2,795	**0,001**
	Location MW19	0,134	0,905	0,149	0,883
	Location MW20	0,010	0,905	0,010	0,991
	Location MW3	0,155	0,905	0,171	0,865
	Location MW4	0,255	0,905	0,281	0,781
Residual standard error: 1.568, DF: 30					
log Cd concentration in spent geothermal liquid	Intercept-Location MW1	0,001	0,001	0,613	0,544
	Location MW12	0,001	0,001	1,084	0,287
	Location MW19	0,000	0,001	0,217	0,830
	Location MW20	0,001	0,001	0,759	0,454
	Location MW3	0,001	0,001	1,084	0,287
	Location MW4	0,001	0,001	0,759	0,540
Residual standard error: 0.003, DF: 30					
log Cr concentration in spent geothermal liquid	Intercept-Location MW1	0,013	0,028	0,454	0,653
	Location MW12	0,035	0,040	0,879	0,386
	Location MW19	0,009	0,040	0,229	0,820
	Location MW20	0,047	0,040	1,17	0,251
	Location MW3	0,098	0,040	2,458	0,020
	Location MW4	0,021	0,040	0,546	0,589
Residual standard error: 0.069, DF: 30					
log Pb concentration in spent geothermal liquid	Intercept-Location MW1	0,004	0,057	0,632	0,532
	Location MW12	0,027	0,081	0,330	0,742
	Location MW19	0,049	0,081	0,602	0,552
	Location MW20	0,164	0,081	2,030	0,051
	Location MW3	0,065	0,081	0,799	0,430
	Location MW4	0,017	0,081	0,208	0,837
Residual standard error: 0.140, DF: 30					

* Estimates indicate the effects of the predictors compared to the intercept and followed by a test statistic

TABLE 3: Analysis of Variance (Anova) results for the concentrations of the ions Na, Cl, K , F, and trace elements, B, As, Hg, Cd, Cr, and Pb in groundwater boreholes across the different sampled locations

Response	**Predictor**	**Estimate**	**Std Error**	**t-value**	**P-value**
Na concentration in ground water	Intercept Location-BH1	71,930	0,948	75,915	**0,000**
	Location BH2	-1,298	1,340	-0,968	0,352
	Location BH3	-11,975	1,340	-8,937	**0,000**
	Location BH4	-6,643	1,340	-4,957	**0,000**
Residual standard error: 1.895, DF: 12					
K concentration in ground water	Intercept Location-BH1	1,218	0,029	41,431	**0,000**
	Location BH2	0,035	0,042	0,842	0,416
	Location BH3	0,013	0,042	0,301	0,769
	Location BH4	-0,023	0,042	-0,541	0,598
Residual standard error: 0.059, DF: 12					
Cl concentration in ground water	Intercept Location-BH1	1,750	6,731	25,997	**0,000**
	Location BH2	1,538	9,520	0,000	1,000
	Location BH3	-2,750	9,520	-2,889	**0,014**
	Location BH4	-3,000	9,520	-3,151	**0,009**
Residual standard error: 1.346, DF: 12					
F concentration in ground water	Intercept Location-BH1	3,498	0,212	16,461	**0,000**
	Location BH2	-0,245	0,301	-0,815	0,431
	Location BH3	-0,348	0,301	-1,156	0,270
	Location BH4	-0,13	0,301	-0,433	0,673
Residual standard error: 0.425, DF: 12					
log B concentration in ground water	Intercept Location-BH1	7,500	7,582	0,099	0,923
	Location BH2	7,512	1,072	0,000	1,000
	Location BH3	4,750	1,072	0,443	0,666
	Location BH4	1,450	1,072	1,376	0,194
Residual standard error: 0.015, DF: 12					
log Hg concentration in ground water	Intercept Location-BH1	0,000	0,000	6,000	**0,000**
	Location BH2	0,000	0,000	-1,414	0,183
	Location BH3	0,000	0,000	-1,414	0,183
	Location BH4	0,000	0,000	-1,414	0,183
Residual standard error: 0.0002, DF: 12					
log As concentration in ground water	Intercept Location-BH1	0,008	0,003	2,737	**0,018**
	Location BH2	-0,002	0,004	-0,437	0,670
	Location BH3	0,003	0,004	0,812	0,433
	Location BH4	-0,002	0,004	-0,437	0,670
Residual standard error: 0.005, DF: 12					
log Cd concentration in ground water	Intercept Location-BH1	7,500	4,787	1,567	0,143
	Location BH2	-3,130	6,770	0,000	1,000
	Location BH3	5,000	6,770	0,739	0,474
	Location BH4	5,000	6,770	0,739	0,474
Residual standard error: 0.009, DF: 12					
log Cr concentration in ground water	Intercept Location-BH1	0,000	0,001	1,455	0,171
	Location BH2	0,000	0,001	0,343	0,738
	Location BH3	0,000	0,001	1,029	0,324
	Location BH4	0,000	0,001	0,343	0,738
Residual standard error: 0.001, DF: 12					
log Pb concentration in ground water	Intercept Location-BH1	0,025	0,005	5,117	**0,000**
	Location BH2	-0,007	0,007	-1,122	0,284
	Location BH3	-0,010	0,007	-1,447	0,173
	Location BH4	0,003	0,007	0,362	0,723
Residual standard error: 0.010, DF: 12					

*Estimates indicate the effects of the predictors compared to the intercept and followed by a test statistic

TABLE 4: Analysis of Variance (Anova) for the concentrations of B, As, Hg, Cd, Cr, and Pb in soil and vegetation in the vicinity of Menengai wells

Response	**Predictor**	**Estimate**	**Std Error**	**t-value**	**P-value**
log B concentration in soil	Intercept-Location MW1	0,5478	0,305	1,794	0,0929
	Location MW3	-0,417	0,4317	-0,967	0,3491
	Location MW2 (Reference site)	-0,4702	0,4317	-1,089	0,293
Residual standard error: 0.73, DF: 15					
log Hg concentration in soil	Intercept-Location MW1	0,056	0,019	2,861	**0,012**
	Location MW3	-0,055	0,028	-1,987	0,066
	Location MW2 (Reference site)	-0,052	0,028	-1,867	0,082
Residual standard error: 0.037, DF: 15					
log As concentration in soil	Intercept-Location MW1	1,0258	0,3719	2,758	**0,0146**
	Location MW3	-0,9557	0,526	-1,817	0,0089
	Location MW2 (Reference site)	-0,997	0,526	-1,896	0,078
Residual standard error: 0.911, DF: 15					
log Cd concentration in soil	Intercept-Location MW1	0,2467	0,1439	1,714	0,107
	Location MW3	-0,246	0,2035	-1,209	0,245
	Location MW2 (Reference site)	-0,2048	0,2035	-1,006	0,33
Residual standard error: 0.37, DF: 15					
log Cr concentration in soil	Intercept-Location MW1	0,5	0,275	1,822	0,0885
	Location MW3	-0,083	0,388	-0,216	0,8322
	Location MW2 (Reference site)	-0,1705	0,388	-0,439	0,667
Residual standard error: 0.637, DF: 15					
log Pb concentration in soil	Intercept-Location MW1	15,995	5,077	3,143	**0,007**
	Location MW3	5,409	7,179	0,753	0,4628
	Location MW2 (Reference site)	-1,757	7,179	-0,245	0,8099
Residual standard error: 12.937, DF: 15					
log B concentration in vegetation	Intercept-Location MW1	1,234	0,2994	4,139	0,000
	Location MW3	-1,006	0,4235	-2,376	0,030
	Location MW2 (Reference site)	-1,0143	0,4235	-2,698	0,017
Residual standard error: 0.07, DF: 15					
log Hg concentration in vegetation	Intercept-Location MW1	0,008	0,003	0,016	0,987
	Location MW3	0,05	0,004	1,313	0,209
	Location MW2 (Reference site)	0	0,004	0,004	0,997
Residual standard error: 0.66, DF: 15					
log As concentration in vegetation	Intercept-Location MW1	0,96	0,2716	3,534	**0,003**
	Location MW3	-0,055	0,3842	-2,142	0,05
	Location MW2 (Reference site)	-0,8894	0,3842	-2,316	0,035
Residual standard error: 0.73, DF: 15					
log Cd concentration in vegetation	Intercept-Location MW1	0,008	0,013	0,623	0,54
	Location MW3	-0,007	0,018	-0,414	0,685
	Location MW2 (Reference site)	0,032	0,018	1,69	0,112
Residual standard error: 0.037, DF: 15					
log Cr concentration in vegetation	Intercept-Location MW1	0,286	0,285	1,004	0,331
	Location MW3	0,1368	0,404	0,339	0,74
	Location MW2 (Reference site)	-0,006	0,404	-0,016	0,988
Residual standard error: 0.698, DF: 15					
log Pb concentration in vegetation	Intercept-Location MW1	1,0297	0,448	2,299	**0,036**
	Location MW3	-0,82	0,6335	-1,294	0,215
	Location MW2 (Reference site)	-0,8033	0,6335	-1,268	0,2241
Residual standard error: 1.937, DF: 15					

* Estimates indicate the effects of the predictors compared to the intercept and followed by a test statistic

APPENDIX II: Linear models for the trace element concentrations of B, As, Hg, Cd, Cr, and Pb in groundwater, soil, and vegetation

TABLE 1: Linear models for the trace element concentrations of B, As, Hg, Cd, Cr, and Pb in groundwater, soil, and vegetation

Response	**Predictor**	**Estimate**	**Std Error**	**t-value**	**P-value**
log B concentration in soil	Intercept	0,376	0,307	1,224	0,249
	B in spent geothermal liquid	-0,079	0,315	-0,251	0,807
Residual standard error: 0.937, DF: 10					
log Hg concentration in soil	Intercept	0,0313	0,020	1,584	0,144
	Hg in spent geothermal liquid	-0,026	0,057	-0,456	0,658
Residual standard error: 0.065, DF: 10					
log As concentration in soil	Intercept	0,677	0,402	1,685	0,123
	As in spent geothermal liquid	-2,475	3,837	-0,645	0,533
Residual standard error: 1.207, DF: 10					
log Cd concentration in soil	Intercept	0,150	0,141	1,063	0,313
	Cd in spent geothermal liquid	-21,020	47,222	-0,445	0,666
Residual standard error: 0.443, DF: 10					
log Cr concentration in soil	Intercept	0,438	0,276	1,586	0,144
	Cr in spent geothermal liquid	0,471	3,693	0,127	0,901
Residual standard error: 0.786, DF: 10					
log Pb concentration in soil	Intercept	22,890	4,070	5,624	**0,000**
	Pb in spent geothermal liquid	-41,850	21,520	-1,945	0,080
Residual standard error: 11.92, DF: 10					
log B concentration in Vegetation	Intercept	0,517	0,311	1,663	0,127
	B in spent geothermal liquid	0,476	0,319	1,493	0,166
Residual standard error: 0.950, DF: 10					
log Hg concentration in Vegetation	Intercept	0,030	0,030	1,015	0,334
	Hg in spent geothermal liquid	-0,008	0,084	-0,095	0,926
Residual standard error: 0.096, DF: 10					
log As concentration in Vegetation	Intercept	0,697	0,293	2,381	**0,039**
	As in spent geothermal liquid	-2,85	2,800	-1,020	0,332
Residual standard error: 0.880, DF: 10					
log Cd concentration in Vegetation	Intercept	0,005	0,005	1,124	0,287
	Cd in spent geothermal liquid	-0,728	1,587	-0,459	0,656
Residual standard error: 0.015, DF: 10					
log Cr concentration in Vegetation	Intercept	0,424	0,277	1,533	0,156
	Cr in spent geothermal liquid	-1,612	3,699	-0,436	0,672
Residual standard error: 0.787, DF: 10					
log Pb concentration in Vegetation	Intercept	0,067	0,479	1,405	0,190
	Pb in spent geothermal liquid	-0,531	2,533	-0,210	0,838
Residual standard error: 1.403, DF: 10					
log B concentration in ground water	Intercept	0,006	0,004	10367	0,193
	B in spent geothermal liquid	-0,003	0,008	-0,395	0,699
Residual standard error: 0.015, DF: 14					
log Hg concentration in ground water	Intercept	0,000	0,000	1,001	0,334
	Hg in spent geothermal liquid	0,000	0,000	-0,252	0,805
Residual standard error: 0.0003, DF: 14					
log As concentration in ground water	Intercept	0,003	0,002	2,101	0,054
	As in spent geothermal liquid	-0,005	0,005	-0,859	0,405
log Residual standard error: 0.005, DF: 14					
log Cd concentration in ground water	Intercept	0,000	0,000	1,511	0,153
	Cd in spent geothermal liquid	0,267	0,039	6,89	**0,000**
Residual standard error: 0.0004, DF: 14					
log Cr concentration in ground water	Intercept	0,000	0,000	0,998	0,335
	Cr in spent geothermal liquid	0,006	0,003	1,632	0,125
Residual standard error: 0.0009, DF: 14					
log Pb concentration in ground water	Intercept	0,013	0,004	3,538	**0,003**
	Pb in spent geothermal liquid	-0,036	0,044	-0,803	0,436
Residual standard error: 0.010, DF: 14					

* Estimates indicate the effects of the predictors compared to the intercept and followed by a test statistic