

# **The Effect of Spent Geothermal Liquid on Ground Water Quality at the Menengai Geothermal Field, Kenya**

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## **Keywords**

*Trace elements, Dissolved Ions, Spent geothermal liquid*

## **ABSTRACT**

To assess the effect of spent geothermal liquids from discharging wells at the Menengai geothermal field to the environment, the concentrations of the Sodium (Na), Chloride (Cl), Potassium (K) and Fluoride (F) ions and the trace elements, Boron (B), Arsenic (As), Mercury (Hg), Cadmium (Cd), Chromium (Cr) and Lead (Pb) in spent geothermal liquid from six geothermal wells and ground water from four water boreholes were assessed. Further, the concentrations in spent geothermal liquid and groundwater were compared to the Kenya local standards for effluent discharge into the environment and the World Health Organization (WHO) drinking water standards. The results showed elevated concentrations of ions Na, Cl and F, and the trace elements As, Hg, Cr and Pb in the spent geothermal liquid from some wells relative to the local effluent standards. In ground water, the F ion concentration was two times higher than the WHO drinking water standard of 1.5 mg/l; this is typical of ground water in the East African Rift Valley (EARV). All the trace element concentrations were below the WHO drinking water standards except for Pb in two boreholes. To estimate the effect of the spent geothermal liquid on the ground water, separate linear models were run using the program R version 3.2.2. The model results indicated no evidence of contamination of the ground water by the spent geothermal liquid at the Menengai geothermal field, a pertinent finding to the continuous environmental monitoring and management of the Menengai geothermal project. We recommend continuous management of the spent geothermal liquid to ensure sustainable geothermal development.

## 1. Introduction

The exploitation of geothermal energy is typically referred to as clean when compared to alternative energy sources, such as fossil fuels, owing to the fact that the potential negative impacts can be mitigated to a large extent (Kristmannsdóttir and Ármannsson, 2003). The energy is obtained from the earth by tapping into underground reservoirs of heat. Deep geothermal wells are drilled to a depth of about 2000 m to 3000 m to tap into hot fluids that lie deep in the earth; these fluids ascend and 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 either re-injected into a geothermal well or discharged into a well lined surface pond for disposal. 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 (Sigurdardottir et al., 2014).

The spent geothermal fluids contain several elements and compounds at elevated levels that can pose threats and adverse effects into 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 mostly 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 condensed 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 into either surface water ways or through deep re-injection. In the ponds, the geothermal liquid is contained to cool and reduce its high silica content which normally may block the re-injection wells or affect 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 ponds' carrying capacity and thereby spilling into the nearby environment. The spillages can get in direct contact with the soils and surface water with chances of percolating into sub-surface water and ultimately contaminating the underground water.

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). These 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). The ions and trace elements are well known to have detrimental short or long term effects on organisms if they deposit and bio-accumulate in soils and water resources above tolerable levels; however some components such as F and Cr at low concentration may be essential for the normal growth and development of living organisms. Other components: As and Hg, in both low and high concentrations have the potential to contaminate the surface and underground water adversely affecting aquatic ecosystems (Webster and Nordstrom, 2003).

Elevated concentrations of these components in spent geothermal liquids and ground water have the potential to affect plants and animals through interaction. For example, Boron (B) in trace amounts is an essential nutrient for normal growth and development in some plants; however in high concentration, B can be toxic to terrestrial 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). On the other hand, Arsenic and Mercury is mostly present in active and fossil geothermal systems and can cause contamination of surface and underground waters and 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).

In Kenya, the generation of electricity from geothermal resources began in the early 1980's at the Olkaria geothermal field although prospecting for the resource and drilling of wells commenced in the 1950s. The Olkaria field is located within the border of the Hell's Gate National Park (HGNP) which is managed by the Kenya Wildlife Service (KWS). The Menengai geothermal field on the other hand is the second largest field to be developed in Kenya after Olkaria. Similarly as Olkaria and other geothermal fields in the world, large volumes of spent geothermal liquid are produced at Menengai. 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, and to-date over 30 geothermal wells have been drilled. In this study, the concentrations of selected ions i.e. Na, Cl, K and F and trace elements B, As, Hg, Cd, Cr and Pb in spent geothermal liquid and ground water are assessed and presented. Further the effect of these element concentrations in spent geothermal liquid on the ground water is evaluated to determine patterns that could infer possible contamination. The findings of this study are important in providing baseline information which will strengthen the environmental monitoring programmes and aid in improvement of current mitigation measures.

## **2. Background Information and Methodology**

### **2.1 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 the 14 geothermal prospects in Kenya. The project is located on the outskirts of Nakuru Town, about 180 Km Northwest of Nairobi and a few kilometers south of the equator; it covers an area of approximately 2,183 km<sup>2</sup> (Mutia et al., 2015).

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 post-caldera collapse (Njue, 2011). The volcanic soils are usually the dominant soil in young volcanic landscapes areas surrounding Menengai caldera.

The local hydrogeology at Menengai is characterized by N-S trending fault/fracture systems which provide underground channels resulting in stream water disappearing underground in some places. The surface drainage is from the eastern and western rift scarps. On the rift floor, the drainage is mainly from Menengai Caldera northwards with the exception of drainage from the southern inclines of the caldera into Lake Nakuru (Lagat et al., 2010). The Menengai geothermal field has no permanent surface waters except for two (2) seasonal streams, the Kanduturi and Wanyororo streams which flow within the caldera.

The rainfall regime in the project area is bimodal with the long rains occurring from March to July and the short rains from September to November. At the project site, there are automatic weather stations installed at the highest and lowest points of the caldera to capture data on an hourly basis. During the period 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 minimum and maximum temperature was 15.7°C and 21.7°C and the average wind speed ranged from 4.53 m/s to 7.53 m/s.

Human activities within the Menengai field are minimal as the area is public land owned by the Kenya Forestry Service (KFS). Settlement is concentrated outside the caldera and on the southern and western sectors in the Nakuru municipality and Bahati divisions. The local people occupying the northern and northeastern parts outside the project practice small-scale mixed farming that includes livestock keeping; with grazing licenses from KFS, the communities are allowed to graze in zoned areas within the Caldera.

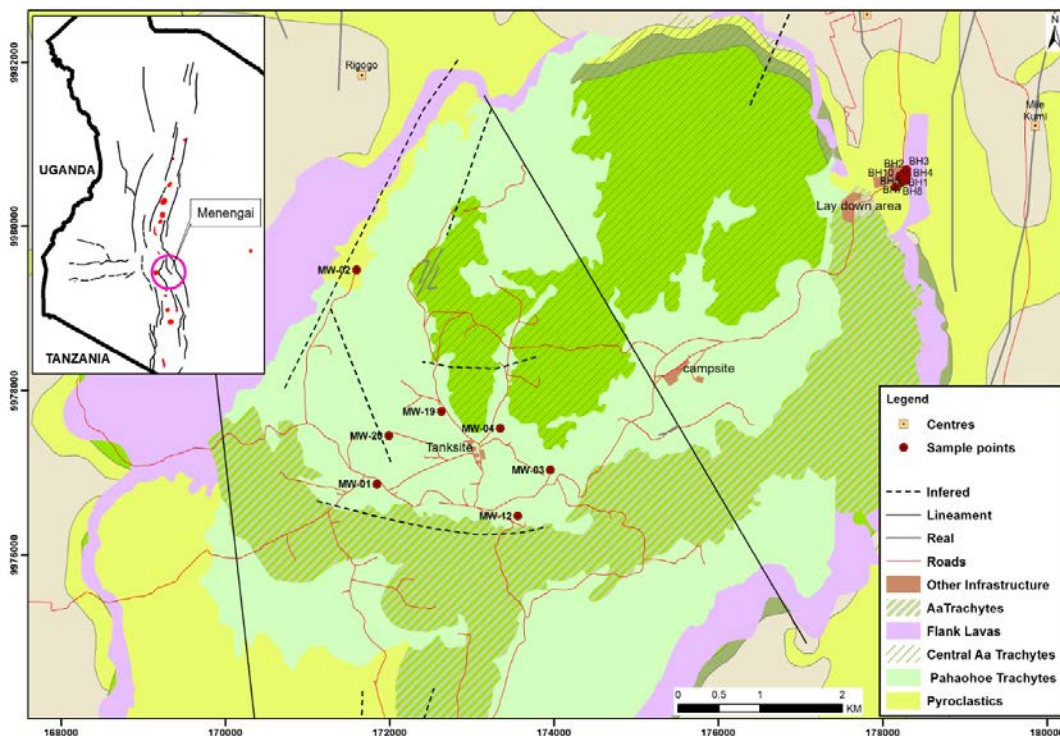


**FIGURE 1: Map showing the location of Menengai geothermal project and the study area (indicated by the sample points).**

## ***2.2. Geothermal Development at the Menengai Project***

Development of geothermal resources in Menengai began in 2004. The Kenya Electricity Generating Company (KenGen) undertook surface geo-scientific studies to prove 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 creation 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.

The 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 entirely developed by the GDC and the second largest field under development after Olkaria field in Kenya. To-date, geothermal development activities at this field since the project commissioned in 2010 have entailed successful drilling of about thirty-five (35) deep exploration and production wells at over 2 km depth. The corporation is developing the field over a step wise process and intends to put up a 105 Mwe geothermal power plant. Three (3) Independent Power Producers (IPPs) namely Quantum energy, Sossian Energy and Orpower 22 have been licensed to operate each 35 MWe modular power plants 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 and infrastructural works within the project. The boreholes were sunk to depths ranging between 100 and 250 m and produce an average total yield of 360m<sup>3</sup>/hr (GDC, 2013) although they have varying pumps depending on the yield, depth and pump chamber level. The abstraction levels are within the aquifer potential and the recharge is in general sufficient. GDC has also linked with the Nakuru Water and Sewerage Company (NAWASCO) to supplement the water resources through piped water services for the project area.

The Environmental Social Monitoring Plan (ESMP) that was adopted in the EIA for drilling of geothermal wells is in place and among the main environmental issues of concern is the containment of spent liquids from discharging wells. According to the plan, the spent liquids were to be contained in High Density Polyethylene (HDPE) lined ponds with frequent chemical and discharge monitoring. Although to manage the discharge, deep re-injection methods (Wetang'ula et al., 2008) and re-use 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 HDPE liners for cooling and re-use for drilling. Based on the fluid composition, the ions and elements present in the spent geothermal fluids (steam plumes and liquid) may potentially contaminate the surface and ground water during well testing, this is caused by the steam sprays and overflowed liquids. Re-injection of the spent geothermal liquid has not yet been done, although there are future plans

to carry out re-injection after commissioning of the power plants. Routine monitoring of major ions and trace elements present in spent geothermal liquids from the discharging wells is carried out by GDC on quarterly basis as well as monitoring of the same elements in the surface and underground water resources. However, it is worth noting that the impact of the spent geothermal liquids on the surface and ground water resources in Menengai is not detailed in any study.

## ***2.3 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 for drawing accurate and meaningful conclusions on what was actually happening in the environment around Menengai.

### ***2.3.1 Sampling of Spent Geothermal Liquid and Ground water***

Six geothermal well sites out of the twenty five drilled wells as at 2014 were selected for sampling of spent geothermal liquid. Four out of the ten ground water boreholes that have been sunk in Menengai geothermal field by GDC were sampled for this study because they are located in a similar geological setting. The sampling abbreviations were as follows;

- I. Geothermal wells sampled: MW1, MW3, MW4, MW12, MW19 and MW20
- II. Ground water 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 from April 2014 to July 2014 and MW20 between March 2014 and July 2015. Sampling was conducted during the discharging periods with samples collected from the ponds where the spent geothermal liquids were contained.

Samples were collected from all the wells (Figure 1) for the analysis of physical and chemical parameters. The samples for the analysis of the physical parameters (i.e., pH, and temperature) were collected and analysed on site. 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 ions 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 sample collection. During sampling of the spent geothermal liquid, the samples were collected from the ponds and the sampling bottles immersed in the spent water to a depth of approximately 15 cm while wearing plastic hand gloves to prevent contamination. Ground water 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.

### 2.3.2 Treatment and Analysis

The samples labeled Fa were for the determination of trace elements i.e. As, Hg, Pb, Cd and Cr. At the laboratory, these samples were acidified using 1.0 ml of Ultrex Supra pure Nitric acid (HNO<sub>3</sub>) to prevent the trace elements from adsorbing to the walls of the polyethylene sampling bottles and filtered through a 0.45 µm millipore membrane to remove suspended matter and prevent sample interaction with these materials.

The samples labeled Fu were also filtered through a 0.45 µm millipore membrane for the determination of Na, Cl, K and B. The Fu samples were analyzed at the GDC laboratory. The Fa samples were stored in air tight containers to avoid any kind of contamination and transported to the internationally accredited Kenya Bureau of Standards (KEBS) laboratories for analysis.

The physical parameters were analysed on site using a potable Hanna HI 255 pH/Conductivity Meter. Boron concentration was determined by the Curcumin method using the Perkin Elmer Model 551-S spectrophotometer. The concentrations of Na, K and Cl concentrations were determined using the Mohr titration technique while F was analyzed using the ORION Ion Selective Electrode ISE sensitive to F. All these analyses were done as per the work instructions stipulated in the International Organization for Standardization (ISO) 9001, Quality Management Systems (QMS) procedures (GDC quality manual, 2010) at the GDC laboratory. Finally, the trace elements As, Hg, Cd, Cr and Pb were determined using the Agilent 4100 Microwave Plasma Atomic Emission spectrometer (MP-AES) at KEBS.

### **2.4 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 (Appendix 1). Further, the data was grouped into three matrices with the results plotted, (1) spent liquid concentration, (2) ground water concentration and (3) the predictor variable (location). 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;  $\text{Loge}(x+v)$ , 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 and ground water and the data presented as mean  $\pm$  SE.

To assess the effects of spent geothermal liquid on the ground water, separate linear models were performed. In the models, ground water was the response variables while the spent geothermal liquid and the sampled locations were the predictors. Because the concentrations of the trace elements in the spent geothermal liquid and ground water did not differ significantly with location, they were treated as replicates for further statistical analysis.

### 3. RESULTS

#### 3.1 Spent Geothermal Liquid

##### 3.1.1 Physical parameters and selected ions

The temperature of the spent geothermal liquids at all the sampled points ranged from 22 to 31 °C while pH values ranged from 8 to 10. 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 standards for effluent discharge into the environment (Republic of Kenya, 2006), (Table 1).

The concentration of the selected ions in spent geothermal liquid ranged between 1638 and 3468 mg/l Na, 516 and 806 mg/l Cl, 151 and 240 mg/l K and 91 and 161 mg/l F.

The F, Na and Cl concentrations were beyond 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. The concentration of K was significantly different between all the sampled wells with higher concentration levels at MW4. Meanwhile, Cl concentration was 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 all the sampled well discharge locations. The major cation and anion present in high concentrations in spent geothermal liquid were Na and Cl respectively.

**TABLE 1: Mean concentrations ( $\pm$  S.E) of the physical parameters (°C) and selected ions (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                                                              | Temp            | pH             | Cl                                   | F                                    | Na                                     | K                  |
|--------------------------------------------------------------------|-----------------|----------------|--------------------------------------|--------------------------------------|----------------------------------------|--------------------|
| MW1                                                                | 27.3 $\pm$ 0.79 | 9.1 $\pm$ 0.04 | <b>718.50 <math>\pm</math> 16.87</b> | <b>151.58 <math>\pm</math> 1.77</b>  | <b>2483.16 <math>\pm</math> 172.63</b> | 223.72 $\pm$ 5.75  |
| MW3                                                                | 25.2 $\pm$ 0.94 | 9.0 $\pm$ 0.14 | <b>703.09 <math>\pm</math> 35.10</b> | <b>129.01 <math>\pm</math> 10.85</b> | <b>2594.39 <math>\pm</math> 233.40</b> | 189.25 $\pm$ 10.30 |
| MW4                                                                | 27.5 $\pm$ 0.87 | 8.8 $\pm$ 0.17 | <b>605.40 <math>\pm</math> 28.25</b> | <b>133.72 <math>\pm</math> 4.23</b>  | <b>2235.08 <math>\pm</math> 107.40</b> | 172.02 $\pm$ 5.04  |
| MW12                                                               | 25.3 $\pm$ 0.97 | 9.6 $\pm$ 0.11 | <b>668.16 <math>\pm</math> 15.92</b> | <b>119.38 <math>\pm</math> 4.21</b>  | <b>2469.07 <math>\pm</math> 107.96</b> | 177.65 $\pm$ 3.51  |
| MW19                                                               | 27.2 $\pm$ 0.85 | 9.5 $\pm$ 0.09 | <b>682.83 <math>\pm</math> 11.15</b> | <b>131.23 <math>\pm</math> 5.00</b>  | <b>2545.73 <math>\pm</math> 69.23</b>  | 179.51 $\pm$ 4.79  |
| MW20                                                               | 24.7 $\pm$ 0.82 | 9.3 $\pm$ 0.14 | <b>676.46 <math>\pm</math> 15.66</b> | <b>135.17 <math>\pm</math> 5.95</b>  | <b>2517.98 <math>\pm</math> 184.25</b> | 182.67 $\pm$ 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

### 3.1.2 Trace Elements

The concentration of trace elements in spent geothermal liquid ranged between 0.020 and 2.070 mg/l B, 0.001 and 7.680 mg/l As, 0.001 and 2.000 mg/l Hg, 0.001 to 0.010 mg/l Cd, 0.003 and 0.300 mg/l Cr and 0.002 and 0.850 mg/l Pb across all the sampled wells. 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 geothermal liquid occurred at MW3, MW12, MW19 and MW20, while for As, concentrations was 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 B, As, Cd, Cr, Hg and Pb 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.

**TABLE 2: Mean concentrations ( $\pm$  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 $\pm$ 0.050 | 0.001 $\pm$ 0.001                   | 0.001 $\pm$ 0.001                   | <b>0.013 <math>\pm</math> 0.001</b> | 0.009 $\pm$ 0.001                   | 0.002 $\pm$ 0.001 |
| MW3                                                                | 0.200 $\pm$ 0.130 | <b>0.240 <math>\pm</math> 0.210</b> | <b>0.112 <math>\pm</math> 0.050</b> | <b>0.087 <math>\pm</math> 0.030</b> | <b>0.093 <math>\pm</math> 0.030</b> | 0.002 $\pm$ 0.001 |
| MW4                                                                | 0.400 $\pm$ 0.340 | 0.002 $\pm$ 0.001                   | <b>0.310 <math>\pm</math> 0.160</b> | <b>0.049 <math>\pm</math> 0.020</b> | 0.018 $\pm$ 0.020                   | 0.001 $\pm$ 0.001 |
| MW12                                                               | 0.668 $\pm$ 0.330 | <b>0.082 <math>\pm</math> 0.070</b> | <b>3.044 <math>\pm</math> 1.610</b> | <b>0.570 <math>\pm</math> 0.030</b> | 0.051 $\pm$ 0.030                   | 0.002 $\pm$ 0.001 |
| MW19                                                               | 0.091 $\pm$ 0.030 | <b>0.281 <math>\pm</math> 0.250</b> | <b>0.172 <math>\pm</math> 0.150</b> | <b>0.069 <math>\pm</math> 0.010</b> | 0.020 $\pm$ 0.020                   | 0.001 $\pm$ 0.001 |
| MW20                                                               | 0.274 $\pm$ 0.120 | <b>0.400 <math>\pm</math> 0.360</b> | 0.020 $\pm$ 0.020                   | <b>0.227 <math>\pm</math> 0.140</b> | <b>0.070 <math>\pm</math> 0.050</b> | 0.002 $\pm$ 0.001 |
| Local standards for effluent discharge into the environment (2006) | 1.000             | 0.010                               | 0.020                               | 0.010                               | 0.050                               | 0.010             |

## 3.2 Ground Water

### 3.2.1 Physical Parameters and Selected Ions

The physical parameters did not vary widely in the four ground water 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 concentrations recorded for the cations and anions ranged from 59.5 to 73.6 mg/l Na, 14.0 to 19.0 mg/l Cl, 1.0 to 1.4 mg/l K and 2.6 to 4.2 mg/l F. The mean concentrations are presented in

Table 3. All the measured ions were below the WHO drinking water standards except for F where the concentrations exceeded the 1.5 mg/l limit (Table 3).

There was a significant variation with the borehole locations between BH1, BH3 and BH4 for the concentration of Na and Cl ions. 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 K, and F in ground water did not show significant differences across the different boreholes sampled i.e. BH1, BH2, BH3 and BH4. The major cations and anions present in high concentrations in ground water were Na and Cl respectively.

**TABLE 3: Mean concentrations ( $\pm$  S.E) of the physical parameters ( $^{\circ}$ C) and selected ions (mg/l) in ground water, 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 $\pm$ 0.50 | 7.48 $\pm$ 0.05 | 71.93 $\pm$ 0.71 | 17.50 $\pm$ 0.80 | 1.22 $\pm$ 0.02 | <b>3.50 <math>\pm</math> 0.20</b> |
| BH2                  | 26.13 $\pm$ 0.20 | 7.54 $\pm$ 0.10 | 70.63 $\pm$ 1.00 | 17.50 $\pm$ 0.50 | 1.25 $\pm$ 0.02 | <b>3.25 <math>\pm</math> 0.16</b> |
| BH3                  | 26.80 $\pm$ 0.08 | 7.29 $\pm$ 0.03 | 60.00 $\pm$ 0.33 | 14.75 $\pm$ 0.37 | 1.23 $\pm$ 0.03 | <b>3.15 <math>\pm</math> 0.18</b> |
| BH4                  | 26.88 $\pm$ 0.22 | 7.23 $\pm$ 0.04 | 65.29 $\pm$ 0.75 | 14.50 $\pm$ 0.22 | 1.95 $\pm$ 0.01 | <b>3.37 <math>\pm</math> 0.12</b> |
| WHO (2008)           |                  |                 |                  |                  |                 |                                   |
| Drinking water stds. |                  | 6.5 - 8.5       | 200              | 250              | NLS             | 1.5                               |

\*NLS-No Limit Specified

### 3.2.2 Trace Elements

The concentration of the trace elements in ground water 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.

The concentration for the trace elements (B, As, Cd, Cr and Hg) in the ground water were below the recommended WHO drinking water standards except for Pb at BH1 and BH4 (Table 4).

## 4.0 DISCUSSION, CONCLUSION AND RECOMMENDATION

### 4.1 Spent Geothermal Fluids

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).

**TABLE 4: Mean concentrations ( $\pm$  S.E) of the trace elements concentration (mg/l) in ground water, from Menengai boreholes compared to permissible levels,  $n = 16$ . Bold letters show concentrations which exceeded the WHO drinking water standards**

| Boreholes            | B                 | Hg                | As                | Pb                                  | Cr                | Cd                |
|----------------------|-------------------|-------------------|-------------------|-------------------------------------|-------------------|-------------------|
| BH1                  | 0.010 $\pm$ 0.001 | 0.001 $\pm$ 0.001 | 0.010 $\pm$ 0.001 | <b>0.020 <math>\pm</math> 0.001</b> | 0.001 $\pm$ 0.001 | 0.001 $\pm$ 0.001 |
| BH2                  | 0.001 $\pm$ 0.001 | 0.001 $\pm$ 0.001 | 0.001 $\pm$ 0.001 | 0.010 $\pm$ 0.001                   | 0.001 $\pm$ 0.001 | 0.001 $\pm$ 0.001 |
| BH3                  | 0.001 $\pm$ 0.001 | 0.001 $\pm$ 0.001 | 0.010 $\pm$ 0.001 | 0.001 $\pm$ 0.001                   | 0.001 $\pm$ 0.001 | 0.001 $\pm$ 0.001 |
| BH4                  | 0.030 $\pm$ 0.001 | 0.001 $\pm$ 0.001 | 0.001 $\pm$ 0.001 | <b>0.020 <math>\pm</math> 0.001</b> | 0.001 $\pm$ 0.001 | 0.001 $\pm$ 0.001 |
| WHO (2008)           |                   |                   |                   |                                     |                   |                   |
| Drinking water stds. | 0.500             | 0.006             | 0.010             | 0.010                               | 0.050             | 0.003             |

The average concentrations of the ions analyzed 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 ground water. 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/l (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, the high elevated ions 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) that classified the aquifer water for MW1 as Na-HCO<sub>3</sub> type with relatively high Cl values of greater than 500 ppm. When compared to the thermal ground waters of Vulcano Island in Sicily, similar results of elevated Na, Cl, K and F were reported (Aiuppa, 2000). The variations observed in the K and Cl concentration between MW1 and MW4 could not be established due to the limited number of data sets.

Elevated levels of trace elements concentrations such as Cr, As, Hg and Pb 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 liquids needs to be over emphasized. However, on comparison of this finding to other geothermal waters (e.g., 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 spring 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 spring. 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, an unfamiliar phenomenon considering the fact that the wells have a similar reservoir composition. However, we do understand that trace element occurrence in geothermal waters including spent geothermal liquid generally depend on factors such as rock chemical composition, physical conditions of the weathering solution (temperature, acidity and redox conditions) and the contribution of magmatic gases (Aiuppa, 2000). These variations can also be attributed to the different sampling seasons; the variation of As concentration could also be explained partly by the adsorption of silica polymers to the ponds.

#### **4.2 Ground water**

The water quality for the ground water in Menengai geothermal field from four boreholes were determined and F concentration was more than double the permissible limit of 1.5 mg/l in all the boreholes measured which is typical in the East African Rift Valley (EARV) due to the underlying geological formation (i.e., the volcanic rocks particularly the young basaltic rocks which contain high concentrations of fluoride and fluorapatite) (Tekle-Haimanot et al., 1995). 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). In a different study in Ethiopia, where the EARV also cuts through, high F concentration in the ground water level from several boreholes was reported. The F concentration ranged from 1.5 to 36 mg/l with a mean concentration of 10.0 mg/l (Tekle-Haimanot et al., 1995). The consumption of water with high levels of F concentration can lead to adverse health problems especially in children, such as mottling of teeth and in severe cases high F concentration in water might cause crippling skeletal fluorosis (WHO, 2008).

The trace element concentrations in the ground water were below the recommended WHO (2008) drinking water limit except for Pb at BH1 and BH4. The elevated Pb concentration in the ground water may be attributed to the rock composition of Menengai area and not geothermal activities considering Pb was still high in the pre drilling report. The Menengai field being a volcanic area, Pb is naturally present in the underground rocks and soil considering ground water interacts with the rocks and soils thus acquiring a chemical composition similar to the rocks. Another source of Pb could be from the metallic piping material where the borehole water is channeled; therefore 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. Children are highly susceptible to the most damaging effects of Pb toxicity as they absorb 4-5 times Pb concentration more than adults after exposure (WHO, 2008).

#### **4.3 Conclusion and Recommendation**

Our results indicate that the discharge of spent geothermal liquid from drilling activities at the Menengai geothermal field has so far not had any significant effect on the ground water,

however continuous monitoring and studies are recommended to assure environmental sustainability.

The Menengai geothermal field is an important national forest reserve, it is thus important from an environmental perspective to properly contain all spent geothermal liquids to avoid direct contact of the spent geothermal liquid with the environment. This study therefore recommends:

1. Re-injection of all spent geothermal liquid. This is critical as the output of spent geothermal liquids is projected to increase with further development.
2. Routine maintenance of the HDPE liners to avoid seepage and contact of the liquids with the ground, in addition the ponds should not be filled beyond the maximum carrying capacity.
3. Increased frequency in monitoring of trace elements concentrations in spent geothermal liquid and ground water at Menengai. Monitoring should advance from quarterly to monthly to establish a comprehensive database for the modeling environmental effects.
4. Assessment of the trace elements mobility, speciation and distribution in the spent geothermal liquid from the wells and potential environmental effects.

## REFERENCES

- Aiuppa, A., Dongarra, G., Capasso, G., and Allard, P., 2000: Trace elements in the thermal ground waters of Vulcano Island (Sicily). *J. Volcanol. Geotherm. Res.*, 98-1, 189-207.
- Arnórsson, S., Stefánsson, A., and Bjarnason, J.Ö., 2007: Fluid-fluid interaction in geothermal systems. *Reviews in Mineralogy and Geochemistry*, 65, 229-312.
- Axtmann, R.C., 1975: Environmental impact of a geothermal power plant. *J. Scientific Research*, 187, 795-803.
- Ármansson, 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, Ahuachapán and Santa Tecla, El Salvador, 12 pp.
- Barbier, E., 2002: Geothermal energy technology and current status: an overview. *Renewable and Sustainable Energy Reviews*, 6-1/2, 3-65.
- GDC, 2013: *Water resources management plan*. Geothermal Development Company (GDC), Nakuru, Kenya, internal report, 29 pp.
- Guo, Q., Wang, Y., and Liu, W., 2008: B, As, and F contamination of river water due to wastewater discharge of the Yangbajing geothermal power plant, Tibet, China. *Environmental Geology*, 56-1, 197-205.
- Kipng'ok, J.K., 2011: Fluid chemistry, feed zones and boiling in the first geothermal exploration well at Menengai, Kenya. Report 15 in: *Geothermal training in Iceland 2011*. UNU-GTP, Iceland, 281-302.

- Kristmannsdóttir, H., and Ármannsson, H., 2003: Environmental aspects of geothermal energy utilization. *Geothermics*, 32, 451-461.
- Lagat, J., 2010: Direct utilization of geothermal resources in Kenya. *Proceedings of the World Geothermal Congress 2010, Bali, Indonesia*, 7 pp.
- Mutia, T.M., and Simboyi, H., 2015: Environmental audit score-card for Menengai geothermal project, Kenya. *Proceedings of the World Geothermal Congress 2015, Melbourne, Australia*, 9 pp.
- Njue, L.M., 2011: The Menengai caldera structure and its relevance to geothermal potential. *Geothermal Resources Council Transactions*, 35, 1201-1208.
- R Core Team. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. 2013. ISBN 3-900051-07-0.
- Republic of Kenya, 2006: *Environmental Management and Co-ordination (Water Quality) Regulations, Legal Notice No. 121*, Republic of Kenya, Government Printers, Kenya, 30 pp
- Sigurdardóttir, H., and Thorgeirsson, A.T. (ed), 2014: *Environmental report*. Reykjavik Energy, Reykjavik, Iceland, 83 pp.
- Simiyu, G., and Tole, M., 2000: Concentrations of trace elements in waters, soils and plants of Olkaria geothermal field, Kenya. *Proceedings of World Geothermal Congress 2000, Kyushu-Tohoku, Japan*, 681-688.
- Tekle-Haimanot, R., Fekadu, A., Bushera, B., and Mekonnen, Y, (1995): Fluoride levels in water and endemic fluorosis in Ethiopian Rift Valley. *Proceedings of the 1<sup>st</sup> International Workshop on Fluorosis Prevention and Defluorination of water 1995, Ngurdoto, Tanzania*, pp 16.
- Tuyor, J.B., de Jesus, A.C., Medrano, R.S., Garcia, J.R.D., Salinio, S.M., and Santos, L.S., 2005: Impact of geothermal well testing on exposed vegetation in the Northern Negros geothermal project, Philippines. *Geothermics*, 34, 252-265.
- Webster, J.G., and Nordstrom, D.K., 2003: Geothermal arsenic. In: Welch, A.H., Stollenwerk, K.G., (eds.), *Arsenic in groundwater: Geochemistry and occurrence*. Kluwer Academic Publishers, Boston, Massachusetts, 101-126.
- Were, J.O., 1998: Aspects of waste management and pollution control in Olkaria geothermal field, Kenya. Report 16 in: *Geothermal training in Iceland 1998*. UNU-GTP, Iceland, 423-460.
- Were, J.O., 2007: *The speciation of trace elements in spent geothermal fluids and implications for environmental health around Olkaria, Kenya*. University of Iceland, MSc thesis, UNU-GTP, Iceland, report 1, 73 pp.
- Wetang'ula, G.N., 2004: *Assessment of geothermal waste water disposal effects, case studies: Nesjavellir (Iceland) and Olkaria (Kenya) fields*. University of Iceland, MSc thesis, UNU-GTP, Iceland, report 2, 76 pp.

- Wetang'ula G.N., Were, J.O., Kubo, B., Omenda, P., Onacha, S., 2008: *Menengai geothermal drilling project, Nakuru. Environmental impact assessment study report*. Kenya Electricity Generating Company Ltd., Kenya, 138 pp.
- WHO, 2008: *Guidelines for drinking water quality* (3<sup>rd</sup> ed.). World Health Organization (WHO), Geneva, Switzerland.

**APPENDIX 1:** Selected ions and trace elements concentration (mg/l) in spent geothermal liquid and ground water at the Menengai geothermal field in Kenya.

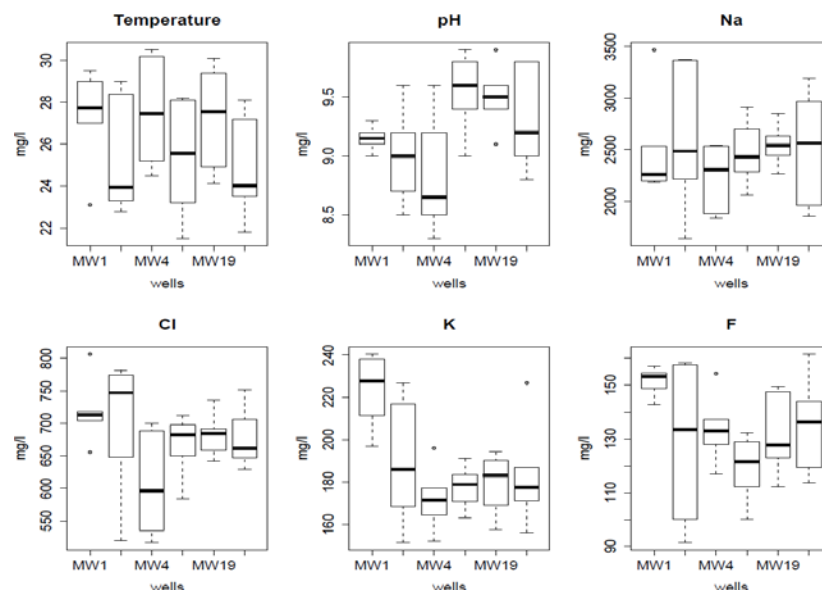


**FIGURE 1:** Physical parameters and ion concentrations (mg/l) in spent geothermal liquid at Menengai wells. The x-axis represents the sampled wells in the following order, MW1, MW3, MW4, MW12,

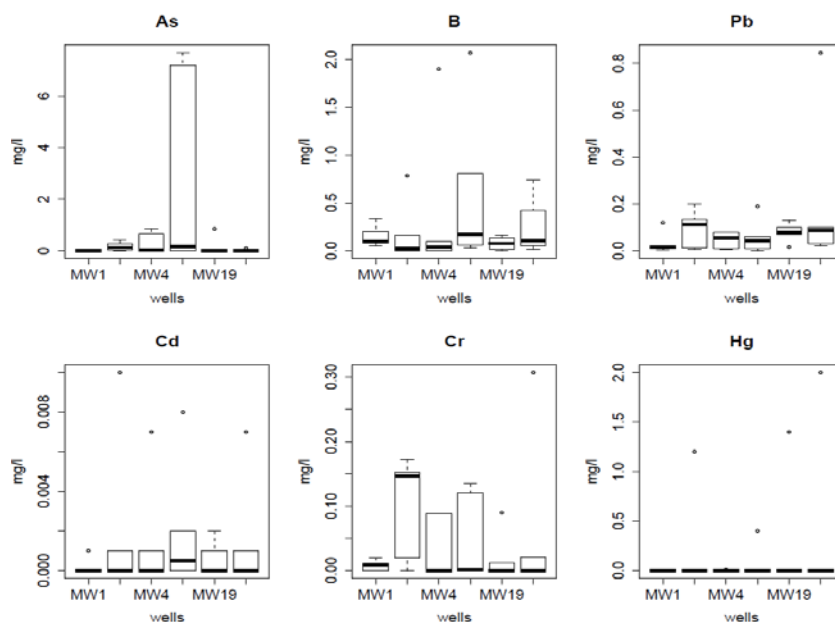


**FIGURE 2:** Trace elements concentrations (mg/l) in spent geothermal liquid at Menengai wells. The x-axis represents the sampled wells in the following order, MW1, MW3, MW4, MW12, MW19 and MW20.

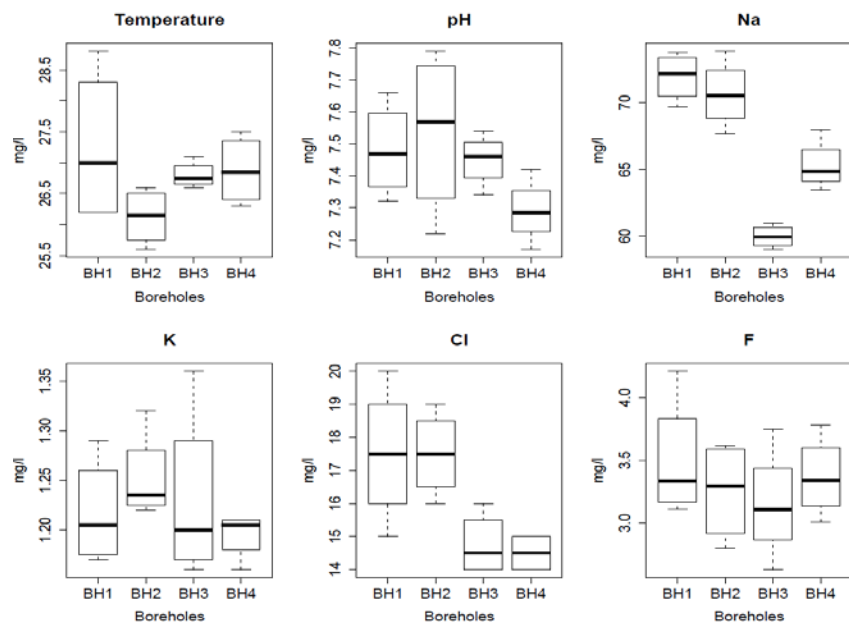


**FIGURE 3: Physical parameters and ion concentrations (mg/l) in ground water from Menengai boreholes - BH1, BH2, BH3 and BH4**

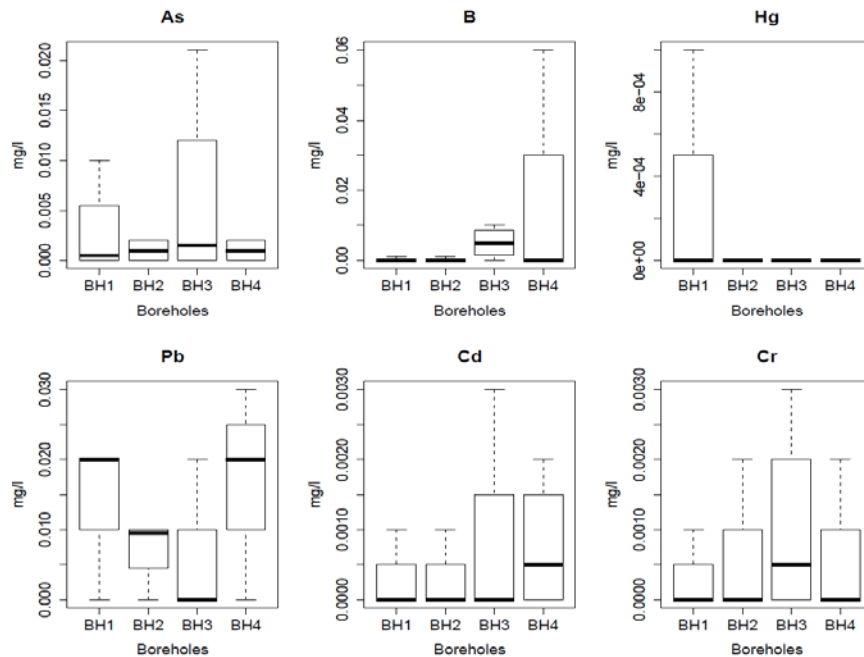


**FIGURE 4: Trace elements concentrations (mg/l) in ground water from Menengai boreholes - BH1, BH2, BH3 and BH4**