ChemSearch Journal 15(1): 20 – 26, June, 2024
Publication of Chemical Society of Nigeria, Kano Chapter

Received: 25/01/2024 Accepted: 19/02/2024
http://www.ajol.info/index.php/csj

Hydrochemical and Geothermometric study of thermal waters of Kaswa/Mahagi in Ituri Province, Democratic Republic of the Congo

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ABSTRACT

The thermal waters of Kaswa/Mahagi, located in the Albertine Rift (North-East of the Democratic Republic of the Congo) constitute a hydrogeochemical and geothermal potential that the country needs for its development. This study aimed to determine the lithological nature and the temperature of the reservoir of these waters. The combination of Hydrogeochemical and statistical methods made it possible to achieve these objectives. The thermal waters of Kaswa/Mahagi, volcanic waters of origin are essentially evaporitic in its lithological nature, the bedrock calcium chloride sulfate. The identified metallic trace elements and their distribution in the thermal waters of Kaswa/Mahagi were: Fe^{2+}(4.36mg/L) > Pb^{2+}(3.84mg/L) > Zn^{2+}(1.03mg/L) > Cu^{2+}(0.48mg/L) > Mn^{2+}(0.18mg/L) > Cr^{3+}(0.09mg/L). The concentrations of Cd^{2+}, Ni^{2+}, Hg^{2+}, Bi^{3+} and Sn^{2+} were less than 0.02 mg/L. Certain metallic trace elements were in significant concentrations, thus reflecting their circulation in depths. The application of SiO_2 geothermometers showed that their temperature in the deep reservoir oscillates between 70 and 75°C, while the geothermometers of Na-K-Ca displayed an average temperature of 89°C; the thermal loss being important considering the temperature measured at emergence and attributed to many factors. These results are useful for integrated management of water resources and the exploitation of geothermal potential for the benefit of the population.

Keywords: Evaporitic, Geothermometers, Kaswa, Lithology, Thermal water

INTRODUCTION

Man has been interested in thermal waters for more than 2000 years, mainly because of their therapeutic virtue (Duriez, 2006). Thermal waters are underground waters with a higher emergence temperature than waters from the region aquifers. They generally come from originally cold waters which heat up at depths under the influence of the geothermal gradient or magmatic heat, only a tiny part of thermal waters reaches the surface via geological accidents (Castany, 1982).

In the Democratic Republic of the Congo, numerous thermal springs are located especially in the eastern part of the country, forming the West African Rift and characterized by volcanic activities. They constitute a geothermal potential that is unfortunately unexploited to this day (Bagalwa *et al.*, 2015; UNDP, 2016). The thermal waters of Kaswa/Mahagi are located in the Albertine Rift and flow from the rocks of the Monts-bleu, near Lake Albert and are located near the fracture lines which border the escarpment, at the places of dislocation of the earth's crust (Luse and Makonga 2019; Omasombo *et al.*, 2021). Their average temperature taken at the point of emergence varying between 42°C and 59°C, rich in mineral ions and sulfur (Budju *et al.*, 2023a). Theses hot springs attract the curiosity of many visitors and serve as a natural hot bath for the indigenous who also carry out hygienic and sanitary practices associated with beliefs in divinity and ancestral power (Budju *et al.*, 2023b).

The geochemical signature of the waters depends generally on the nature of the rocks reservoir, but also on their contact time with the rocks and the temperature is generally higher in the reservoir rocks than at their points of emergence (Duriez, 2006). The hydrogeochemical study of the Kaswa/Mahagi thermal waters carried out previously by our research team made it possible to describe the origin and the mineralisation process of these thermal waters. Currently, there is still a gap regarding the identification of the reservoir rock of the thermal water of Kaswa/Mahagi. Thus, the information about the aquifers of these waters needs to be deepened for a better identification of the reservoir of the thermal waters of Kaswa/Mahagi.

The objective of the present study is to determine the lithological nature and the temperature of the Kaswa/Mahagi thermal waters in the reservoir rock. Hydrochemical data collected using standard water analysis methods will help to obtain the complementary information on the thermal reservoir for a better understanding of the underground process.

MATERIALS AND METHODS

Site of the study

This study took place in Kaswa in the Mokambo Chiefdom in Mahagi territory, located in Ituri Province, North-East of the Democratic Republic of the Congo. The large part of the Mokambo chiefdom is made up of the Blue Mountains range whose highest peak reaches 1900 m. The Albertine Rift region forms the Nile basin. There are numerous rivers leading into Lake Albert, developed water wells and springs of waters used for drinking. In the region, humid tropical climates, with two distinct seasons are noted: the dry season and the rainy season. The minimum ambient temperature is 22ºC and the maximum temperature is 32ºC with an annual average of 26ºC. The average annual rainfall of Mokambo is 600.8 mm (Lepersonne, 1974; Mbuluyo and Faidance 2018; Omasombo *et al.*, 2021). The study site is represented by Figure 1.

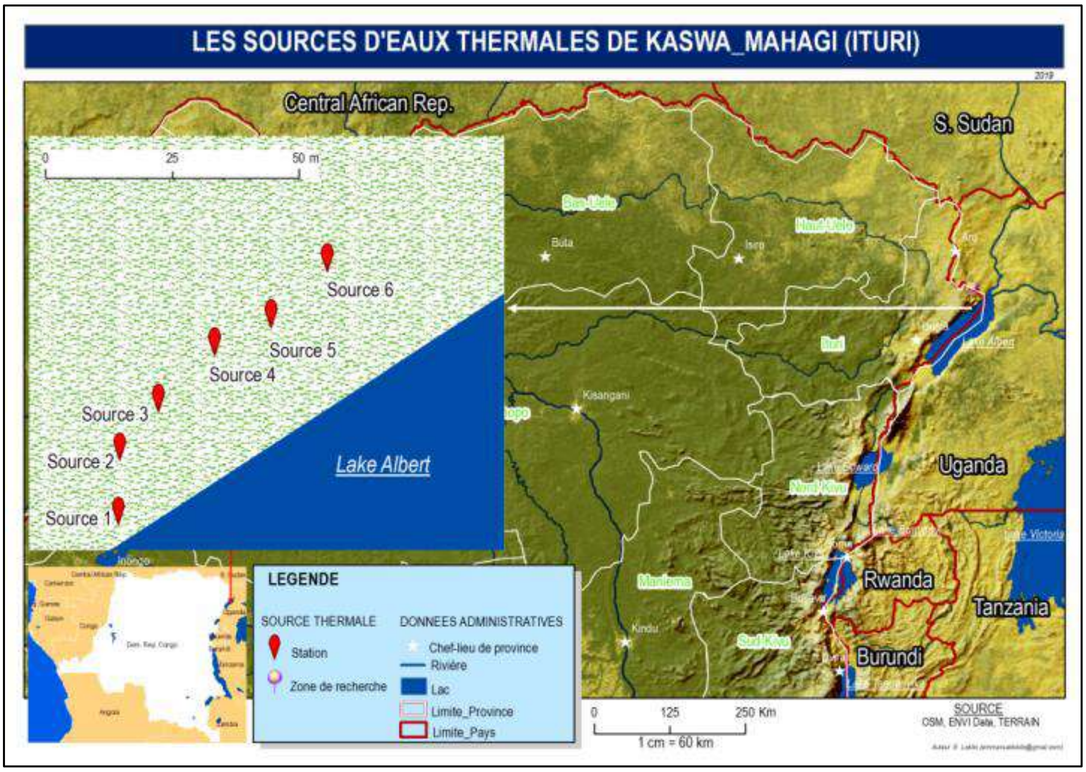

Figure 1: Kaswa/Mahagi thermal water sample collection sites

Legend: Thermal spring 1, 2, 3, 4, 5 and 6 are noted by Kα, Kβ, Kγ, Kδ, Kε and Kλ (K=Kaswa)

Sampling

Six hot springs in the Mokambo chiefdom, Ramogi locality, precisely at the fishermen's camp called Kaswa, have been analysed. Kaswa is located at 2º00'46.678 North and 31º04'57.829 East, at an altitude of 735 m. The coordinates of the different sites were taken using the GARMIN "eTrex®10" GPS device, with a characteristic 2.2" monochrome screen.

The samples were taken at the emergence points, during eight campaigns carried out from 2014 to 2019 and updated in 2021 and 2022, in the months of January and April corresponding respectively to the dry and wet seasons. The analyses were carried out in steps of 5 days for a campaign with three tests per selected parameter.

Hydrochemical data collection

In order to highlight the lithological nature and the temperature of the reservoir, the hydrochemical parameters were determined. Three parameters, namely temperature, electrical conductivity and pH of the thermal water, were taken in situ. The temperature was taken using a 0-100°C scaling thermometer while the electrical conductivity and pH were measured using the Water Proof PCST Tespr-35 multi-parameter probe.

The concentration of major and minor ions were measured in the laboratory, conditioning being carried out according to the NF EN ISO 5667-3 standards (June 2004) and the recommendations of Rodier *et al.* (1984), Rodier *et al.* (2009) and FUNASA (2013). Thus, chlorides (Cl^-) were measured by the Mohr method, sulphates (SO_4^{2-}) and total silica (SiO_2) by gravimetry, calcium (Ca^{2+}) by complexometry and total sulfur (S^{2-}, HS^- , $S_2O_4^{2-}$) by iodometry. Magnesium (Mg^{2+}) was measured using the HANNA HI 83200 Photometer while the concentration of hydrogen carbonate ions (HCO_3^-) was obtained by the Palintest 5000, Labo photometer. The concentration of sodium (Na^+), potassium (K^+) and metallic trace elements including iron (Fe^{2+}), lead (Pb^{2+}), copper (Cu^{2+}), zinc (Zn^{2+}), Manganese (Mn^{2+}), chromium (Cr^{3+}), cadmium (Cd^{2+}),nickel (Ni^{2+}), bismuth (Bi^{3+}), mercury (Hg^{2+}) and tin (Sn^{2+}) was obtained using a flame atomic absorption spectrometer (FAAS) brand Perkin Elmer brand, Model Analyst 400.

The hydrogeochemical profile and the origin of the thermal waters of Kaswa/Mahagi were highlighted by the hydrochemical diagram of Stabler and Giggenbach, using the hydrochemistry software "Diagrams". In order to determine the lithological nature of the thermal water reservoir, the model developed by D'Amore *et al.*, 1983), that of the International Geothermal Research Institute (IGRI) was used, as describe also by Bouchareb-Houchine *et al.* (2012). Indeed, the method resorts to the use of the ratios of the concentrations of the major elements and the sum of cations (+) and anions (-) expressed in meq/L: A = 100 x ((HCO_3-SO_4)/Σ (-)),B = 100 x ((SO_4/Σ(-)) - (Na/Σ(+)), C = 100 x (Na/Σ(+) + Mg/Σ(-)), D = 100 x ((Na - Mg)/Σ(+)), E = 100 x ((Ca + Mg)/Σ(+) - HCO_3/Σ(-)), F = 100 x (Ca - Na - K)/ Σ(+). The six levels of parameters (A, B, C, D, E and F) thus obtained were defined and normalized between -100 and +100 according to which the diagrams were established then compared to the reference diagrams α, β, γ and δ.

The temperature of the reservoir was obtained using silica geothermometers considering the predominance of one or other of its three allotropic varieties, namely quartz (>160 °C), chalcedony (120-160 °C) and amorphous silica (ordinary temperature). We noted that the silica concentration at the emergencies was ultimately that corresponding to the temperature of the water in the mixing zone and can be calculated using one of the three formulas proposed by Arnorsson *et al.* (1983), thus giving the temperatures T1, T2 and T3. The Na-K-Ca geothermometer was also used, asthe corrected Na-K geothermometer (Fournier and Truesdell, 1973;Serra and Sanjuan, 2004), the temperature obtained is symbolised by T4.

RESULTS AND DISCUSSION

Hydrochemical data

The average results of the analysis carried out are shown in Table 1.

Table 1: Physical parameters, ion balance and SiO_2 concentration of Kaswa/Mahagi thermal waters

ST	T (°C)	CE (µS/cm)	Na^+ (mg/L)	K^+ (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	SO_4^{2-} (mg/L)	HCO_3^- (mg/L)	Cl^- (mg/L)	$S_{tot.}$ (mg/L)	SiO_2 (mg/L)
Kα	45.7	981	4.06	3.15	49.63	28.83	420.10	2.39	178.18	55.68	29.23
Kβ	56.7	1202	3.83	2.49	75.33	47.55	445.2	2.40	147.20	46.8	25.12
Kγ	42.9	1085	4.27	3.8	31.3	22.95	423.05	2.42	203.65	59.43	26.62
Kδ	59.9	1230	5.12	3.27	112.20	55.70	489.55	24.4	190.10	60.58	28.11
Kε	57.4	1033	4.21	2.57	190.23	66.25	433.98	2.41	172.80	51.83	29.29
Kλ	45.5	932	4.65	2.91	52.55	52.55	469.13	3.47	144.72	50.1	31.27

Legend: ST: thermal spring; K: Kaswa; S_{tot}: total sulfur

Hydrogeochemical study

Hydrogeochemical profile

The Stabler diagram revealed that the thermal waters of Kaswa/Mahagi have high calcium, magnesium, sulphates and chloride concentration and form the main salts of these waters, hence their high electrical conductivities. Thus their hardness is high, evaluated from calcium and magnesium ions. However, the concentrations of sodium, potassium and bicarbonates remain low (Figure 2).

The ternary diagram shows that all six thermal springs of Kaswa/Mahagi are concentrated in the volcanic water zone considering the classification suggested by Giggenbach (1991) (Figure 3). The magmatic origin of the thermal waters of Kaswa/Mahagi can be justified by the fact that these waters are located in the Albertine Rift region, the East of the Democratic Republic of the Congo forming the West African Rift and characterized by volcanic activities (Esseqqat, 2011). The abundant presence of sulfur and chloride (Table 1), also suggests the magmatic origin of these thermal waters.

Lithological nature of the reservoir

The method developed by D'Amore *et al.* (1983) takes into account the ionic balance of the water in order to highlight the lithology of the reservoir. Applied to the thermal waters of Kaswa/Mahagi, we note that all six thermal springs correspond to the α model, relating to the evaporitic series. Indeed, the International Geothermal Research Institute diagram shows an intermediate rectangular configuration relating to circulation in an anhydritic series (Figure 4). The abundance of the elements Ca, Mg, Cl, SO_4 but also Na-K testify to the leaching of evaporitic levels. This result is similar to that of the thermal waters of North-East Tunisia, studied by Trabelsi *et al.* (2007), which shows also the evaporitic aspects of these thermal waters.

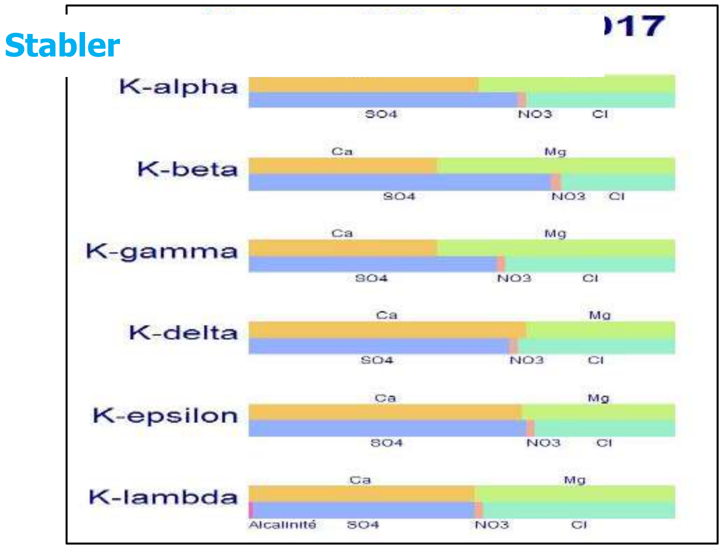

Figure 2: Hydrochemical profile of Kaswa/Mahagi thermal waters according to Stabler

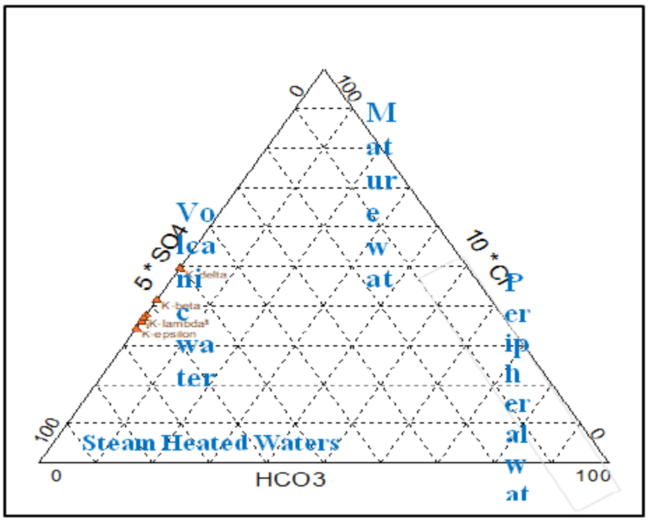

Figure 3: Ternary diagram of Kaswa/Mahagi thermal waters (Giggenbach model)

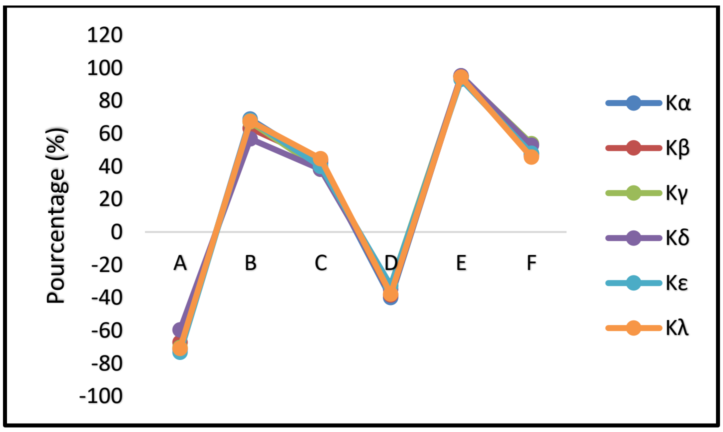

Figure 4: Diagram of the International Institute for Geochemical Research (IIRG) applied to the thermal waters of Kaswa/Mahagi

Metallic trace elements

Table 2: Concentration of metallic trace elements (in mg/L) of Kaswa/Mahagi thermal waters

Thermal springs	Pb^{2+}	Cu^{2+}	Fe^{2+}	Zn^{2+}	Mn^{2+}	Cr^{3+}	Cd^{2+}, Ni^{2+}, Hg^{2+}, Bi^{3+}, Sn^{2+}
Kaswa α	2.82	0.58	4.48	1.41	0.17	0.11	<0.02
Kaswa β	1.77	0.33	4.08	0.92	0.17	0.094	<0.02
Kaswa γ	6.16	0.41	4.22	0.95	0.23	0.088	<0.02
Kaswa δ	5.14	0.62	4.97	1.11	0.093	0.076	<0.02
Kaswa ε	5.16	0.47	4.22	0.89	0.22	0.079	<0.02
Kaswa λ	1.89	0.44	4.19	0.91	0.19	0.091	<0.02

The concentration of trace elements in the thermal waters of Kaswa/Mahagi varies from one source to another. In general, for the metals studied, the concentrations range is as follows: 2.82 < Pb^{2+} < 6.16 mg/L, 0.33 < Cu^{2+} < 0.62 mg/L, 4.08 < Fe^{2+} < 4.97 mg/L, 0.89 < Zn^{2+} < 1.41 mg/L, 0.093 < Mn^{2+} < 0.23 mg/L, 0.076 < Cr^{3+} < 0.11 mg/L. The concentration of Cd^{2+},Ni^{2+}, Hg^{2+}, Bi^{3+} and Sn^{2+} were less than 0.02 mg/L (Table 2). Considering average concentrations, the succession in descending order is as follows: Fe^{2+} > Pb^{2+} > Zn^{2+} > Cu^{2+} > Mn^{2+} > Cr^{3+} > Cd^{2+}, Ni^{2+}, Hg^{2+}, Bi^{2+},Sn^{2+}.

We noticed a significant concentration of metallic trace elements including lead, iron, zinc, manganese and chromium in these thermal waters. According to Lakdar *et al.* (2007), the richness in trace elements shows that the waters also circulated at depths. The thermal waters of Kaswa/Mahagi were thus enriched in various metallic trace elements during their underground and ascending journey towards the surface of the earth.

Geothermometric study

There are several geothermometers allowing the estimation of the temperature of the last thermodynamic equilibrium, including those with silica and Na-K-Ca having been applied as part of this study.

Table 3: Equilibrium temperature in the reservoir obtained using some chemical geothermometers

Thermal springs	T_1 (°C) SiO_2	T_2(°C) SiO_2	T_3(°C) SiO_2	T_4(°C) Na-K-Ca	M±σ (a,b,c)
Kaswa α	64.99	82.24	78.48	114.21	75.23±9.07
Kaswa β	60.14	76.74	72.24	81.92	69.71±8.58
Kaswa γ	61.91	78.75	74.55	104.98	71.75±8.77
Kaswa δ	63.62	80.71	76.74	77.48	73.69±8.94
Kaswa ε	61.53	78.34	74.05	67.66	71.30±8.73
Kaswa λ	55.34	84.56	81.13	89.77	73.68±7.98

The application of the silica geothermometers reveals an average temperature between 69.71±8.58°C observed at the Kaswa-β thermal spring and 75.23±9.07°C at the Kaswa-α spring. The temperatures obtained using the Na-K-Ca geothermometer oscillates between 67.66°C recorded at the Kaswa-ε source and 114.21°C recorded at Kaswa-α (Table 3).

We noted that the results obtained using silica better estimate the temperature of the deep reservoir because it was closer to those displayed at emergence. The values obtained showed that the thermal waters were of low enthalpy (T° < 100°C). In all cases, there was significant heat dissipation during the/ underground movement of these thermal waters. Thus, the Kaswa α source, the most affected, lost about half of its heat, from the deep reservoir until its emergence (42-75°C). The thermal loss can be justified by the length of the path travelled and the mixing or dilution phenomena experienced with water of meteoric origin until their emergence, as also noted by Bouchareb-Houchine *et al.* (2012) about the thermal springs of Hammam Righa in Algeria.

CONCLUSION

This study determined the lithological nature and temperature in the reservoir rock of the thermal waters of Kaswa/Mahagi. The study revealed that the six thermal springs are located in the volcanic water zone. Their nature is essentially evaporitic and is enriched in sulfur. The main evaporates identified were calcium chloride, magnesium chloride, calcium sulphate and magnesium sulphate and release the different chemical elements from water. The high concentration of some metallic trace elements in the thermal waters reflects their circulation at depths. The temperature at the reservoir level fluctuates between 70 and 75°C, higher than the temperature at emergences. These thermal waters experienced considerable thermal loss up to about half of their original heat. These thermal losses can be justified by many factors. This information is essential for integrated management of water resources and geothermal exploitation in the region. However, other studies need to be carried out in this process, notably the dilution rate determination, influence of seasonal variation on the mineralisation process and temperature estimation with other geothermometers is suggested for the future.

ACKNOWLEDGEMENTS

Our gratitude goes to the Chemistry Laboratory Managers of ISP/Bunia, the Hydrochemistry Laboratory of the Department of Chemistry and Industry/Faculty of Science and Technology of the University of Kinshasa and Uganda Industrial Research Institute for their availability of the necessary materials, chemicals products and data processing tools.

AUTHOR CONTRIBUTION

The corresponding author RB was responsible for the conception of this work and the writing of the main manuscript, YI and TT contributed to the supervision of the work and the correction of the manuscript. The author CS provided the guidelines, the supervision of the work as a whole and the correction of the manuscript.

CONFLICT OF INTEREST

The authors declare the absence of any conflict of interest.

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