

Research Article

Trace Metal Elements (TMEs) in Groundwater Around the Former Industrial Gold Mine of Poura in Burkina Faso – West Africa

Adama Yameogo^{1, 2, *} , Nicolas Kagambega^{1, 2} , Isso Felix Bado² ,
Abdoul-Azize Barry² 

¹Mining Engineering Department, Higher School of Engineering, Yembila Abdoulaye Toguyeni University, Fada N’Gourma, Burkina Faso

²Geosciences and Environment Laboratory, Department of Earth Sciences, Joseph Ki-Zerbo University, Ouagadougou, Burkina Faso

Abstract

The objective of this study is to assess the quality of groundwater around the first industrial mine in Burkina Faso, whose activities have been closed since 1999. The diagnosis of pollution by trace metal elements of groundwater around the old Poura gold mine was carried out through the determination of the contents of Trace Metal Elements (TME) at MP-AES and the measurements of the physicochemical parameters in situ on 38 samples of borehole water. These data made it possible to calculate the pollution risk index, to establish correlations between the different physicochemical parameters on the one hand and with the trace metal elements on the other hand, from the Pearson matrix and to carry out a multivariate statistical analysis, in particular that in principal components (PCA), with a view to determining the origin of the polluting elements. The results obtained made it possible to identify four samples of groundwater with an acidic pH (GWF18 (6.44), GWF19 (6.39), GWF23 (6.1) and GWP01 (5.99)) and 34 samples of groundwater whose Cd, Al, Fe, As, Pb, or Hg contents are higher than the standards in force in Burkina Faso. The Pollution risk Index (PI) indicates that 35 groundwater samples are slightly polluted and 3 groundwater samples are very heavily polluted (GWP01 (PI = 456%), GWF06 (PI = 132.5%), GWF03 (PI = 105.1%)). The Pearson correlation matrix and the principal component analysis (PCA) show that the origin and mobilization of the trace metal elements involved (Al, As, Cd, Cr, Fe, Hg and Pb) are linked to natural mineralization and anthropogenic activities such as mining and agricultural activities, favored by the infiltration of water into the subsoil through geological structures such as fractures and faults.

Keywords

Groundwater, Pollution, Trace Metal Elements, Poura, Burkina Faso

*Corresponding author: yameogoadama42@yahoo.fr (Adama Yameogo)

Received: 10 September 2024; **Accepted:** 27 September 2024; **Published:** 29 October 2024



1. Introduction

Integrated water resources management is a major challenge worldwide [1] and particularly in Burkina Faso. This problem is related to two major facts. First of all, there is an increase in demand for water due to strong population growth and a rise in living standards. Added to this is the reduction in water resources linked to the reduction in surface runoff and the deficit in groundwater recharge. Finally, in addition to this limitation of water, it is also necessary to note the degradation of its quality through pollution linked to human activities [2-4]. The fact that surface water contributes to the recharge of the water table, the quality of groundwater also depends on it. These problems reinforce each other to lead to situations that are detrimental to human development: water shortages and water-borne diseases [5-9]. Extractive activities, linked to the mining boom in recent decades and intensive agriculture, appear to contribute significantly to the deterioration of the quality of water resources. Although the exploitation of mineral resources contributes significantly to the socio-economic development of countries, the bad practices sometimes observed are sources of environmental problems.

Currently, more than half of the world's drinking water comes from groundwater [10]. However, extractive activities, such as gold mining and panning, frequently lead to pollution of soil and groundwater resources [11-13]. In Burkina Faso, [14] studied the factors that control groundwater quality and arsenic mobility in waters around the Bomboré gold zone. [15] showed a strong enrichment of arsenic in the waters and soils of the Poura mine watershed. To date, the environmental impacts of mining discharges in Burkina Faso have been widely studied, unlike issues relating to trace metal pollution in groundwater. For the specific case of the Poura site, the subject of this study, the work of [16] highlighted the acidogenic nature of mining discharges likely to pollute water resources.

These environmental problems may appear or become more pronounced in the short, medium or long term depending on climatic variations in the area where these types of activities take place. Water is the most sensitive environmental media due to its high mobility.

The objective of this study is to diagnose and assess the risks of groundwater pollution by trace metal elements, particularly those potentially toxic around the Poura gold district, a former and first industrial mine in Burkina Faso, where gold panning and agriculture coexist. This work focuses on the one hand on an analysis of water quality through a normative assessment of concentrations and the determination of the pollution index of the physicochemical parameters and the TMEs selected, which are respectively single-element or multi-element pollution approaches and on the other hand on a multi-variate statistical analysis (principal component

analysis).

2. Material and Method

2.1. Study Area

The study area is located between latitudes 11°30' and 11°40' North and longitudes 2°40' and 2°50' West, approximately 180 km from Ouagadougou, the capital of Burkina Faso (Figure 1). It is located in the Sudano-Sahelian climatic zone, marked by two seasons: a dry season (from mid-October to mid-May) and a rainy season (from mid-May to mid-October).

The average annual rainfall and temperature recorded over the last three decades vary between 683 and 1135 mm and between 28.2 and 29.5 °C respectively. Daily temperatures are very variable and can reach a minimum of 23 °C in December and a maximum of 34 °C in April.

The study area belongs to the Mouhoun watershed, one of the largest of the four main watersheds in the country. The hydrographic network is meshed by the Mouhoun River and its tributaries, the main ones being the two "Balé" ("Grand Balé" and "Petit Balé") and the Sambayourou [15]. The Mouhoun is a permanent watercourse that flows from north to south with an interannual flow of 64.5 m³/s, according to a report from the Volta Basin Authority [17]. To overcome the lack of water, a water supply connected to the Mouhoun River was set up by the National Office of Water and Sanitation ("ONEA") of Burkina Faso which serves the two rural communes (Poura and Fara) in addition to the installation of several boreholes throughout the villages and communes of the locality. These water resources are intended for drinking, domestic use, irrigation and watering animals.

The geology of the study area is essentially composed of Birimian formations composed mainly of andesites, basalts, migmatitic and anatectic gneisses, TTG (tonalites, trondhjemites, granodiorites), arkosic sandstones, felsic to intermediate intrusions, mafic and ultramafic intrusions, siltstones, argillites, pelites, cherts, epiclastites, quartzites and felsic volcanic rocks [18].

The study area is home to the first industrial gold mine in Burkina Faso, which was operated from 1984 to 1999 by the "Société de Recherche et d'Exploitation Minière du Burkina (SOREMIB)", which constituted a key area from which countless artisanal mining sites have proliferated in the area. Poura is also a region with strong agricultural activities due to the favorable climate and the fertility of the soil.

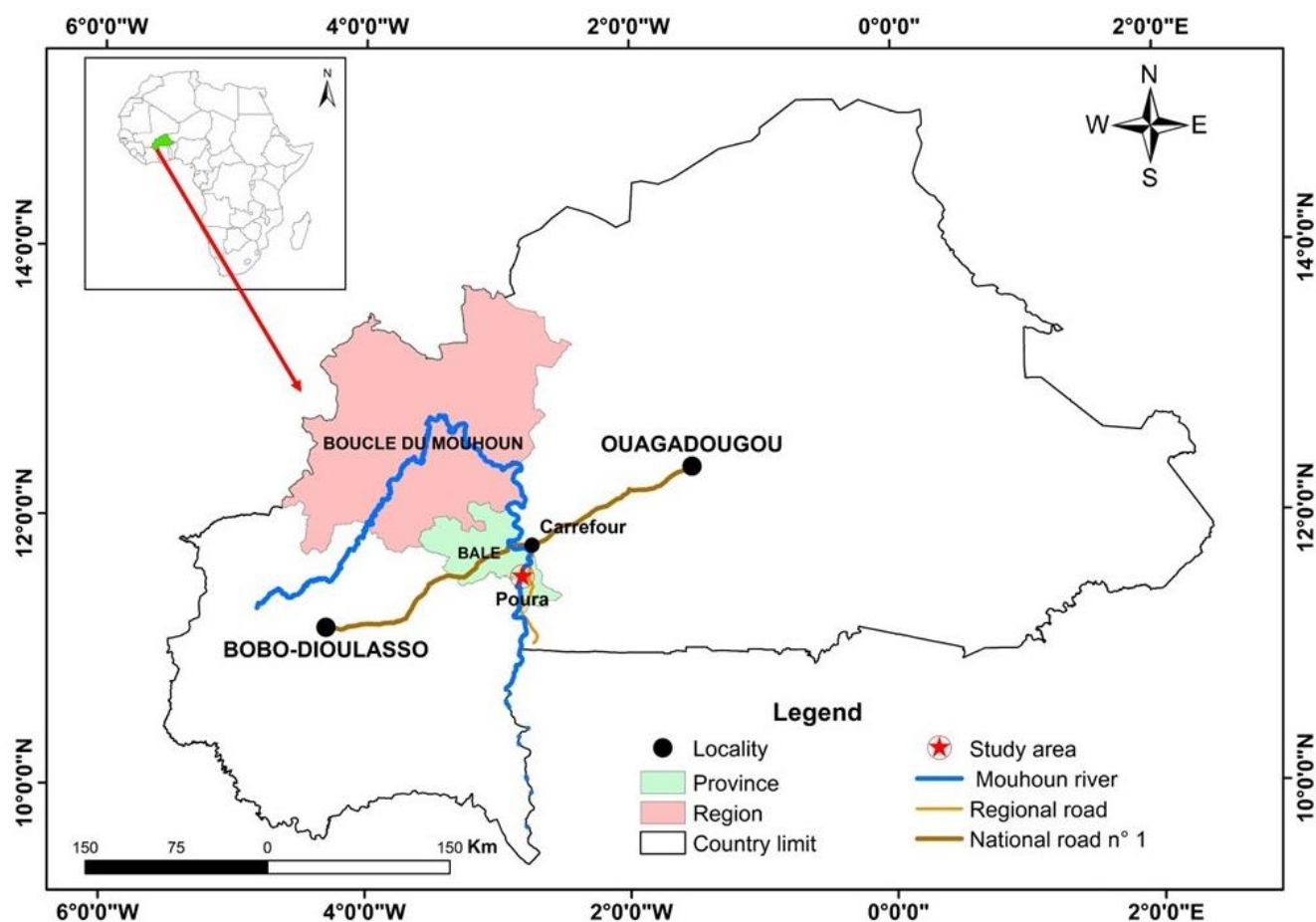


Figure 1. Location of the study area.

2.2. Methodology

The methodology adopted consisted of random sampling of groundwater based on accessibility to the study area, during the high water period in Burkina Faso, that is to say during the month of August 2021.

The samples collected were packaged in sterile 500 ml polyethylene bottles. To avoid any contamination, the bottles are rinsed three times with water from the site before any packaging. At each groundwater sampling site, two samples are taken, one of which is acidified by adding 1.0 ml of nitric acid (HNO_3) and the other non-acidified. All samples are packed in a cooler and sent to the analysis laboratory for determination of physicochemical parameters and trace metal elements contents.

The analyses were carried out at the environmental analysis laboratory, Senexel in Burkina Faso using a microwave plasma atomic emission spectrometer (MP-AES). The methods used are those of Method 200.7 [19] and MA. 200 – Met 1.2, Rev.5 [20]. The samples are mixed by vortex then left to stand. The total volume of the final solution obtained is 55 ml. Thus, we move on to direct analysis and/or with sub-

sequent dilutions if necessary.

The physicochemical parameters of each sample were measured in situ using a multifunction device that gives a direct reading.

A multivariate statistical analysis was also performed. The interpretation of pollution data is carried out on the basis of a comparative study with local standards [21], as recommended by WHO (World Health Organization), on the quality of drinking water [22] and the determination of the pollution index introduced by [23] and resumed by [24].

3. Results and Discussions

3.1. Sampling

Thirty-eight (38) groundwater samples were collected from active borewells within fractured crystalline aquifers in the Poura and Fara districts. All samples were taken from hand-pumped wells at depths ranging from 30 to 75.30 m, with a gradient of between 6 and 36 m and flow rates varying from 0.8 to 10.50 m^3/h . (Figure 2).

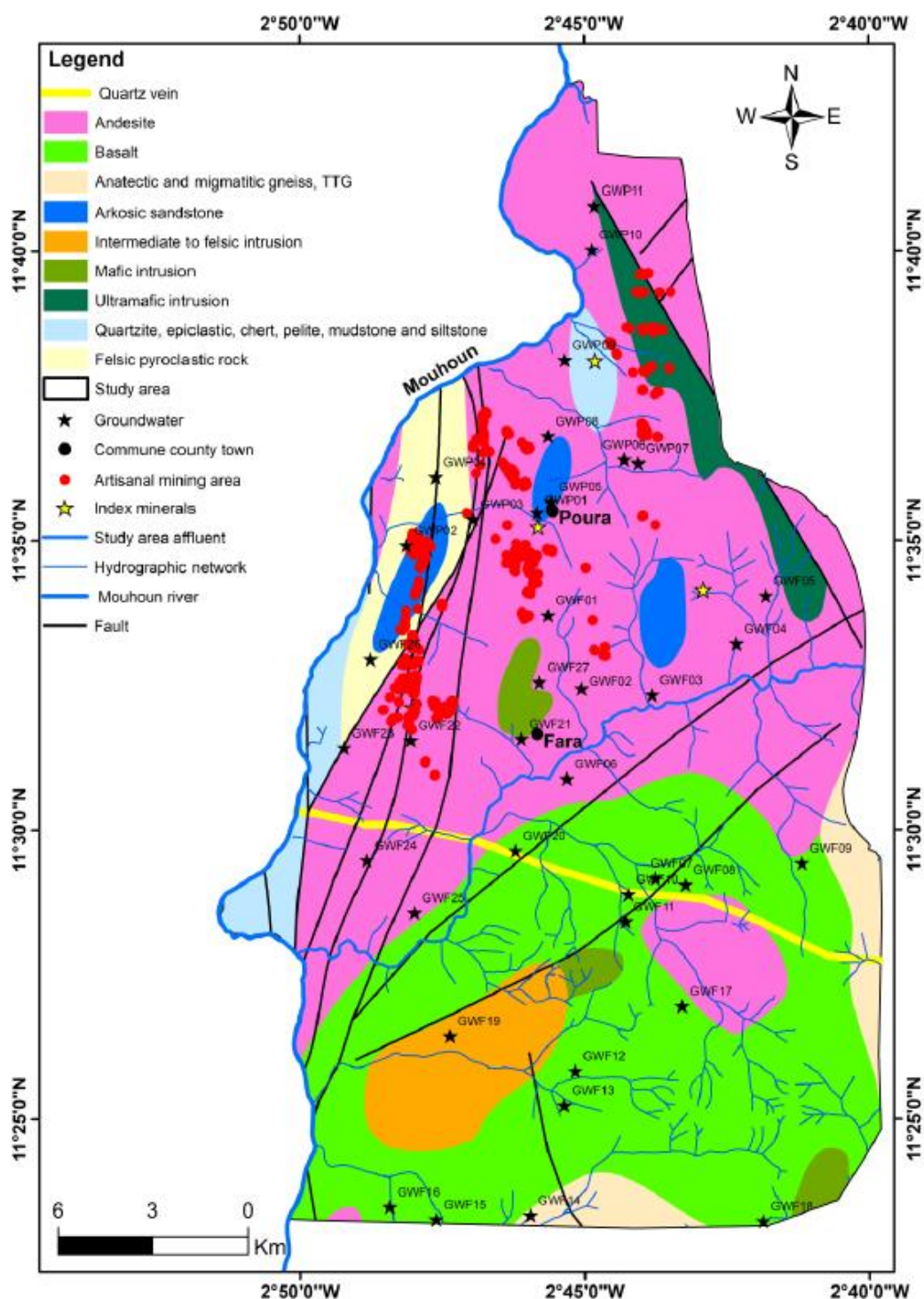


Figure 2. Sampling map.

3.2. Physicochemical Parameters

3.2.1. Hydrogen Potential (pH)

The results obtained show that the pH values vary between 5.99 and 7.63 with an average of 7.02 (Table 1). These values indicate that the pH of the groundwater is moderately acidic (5.99 and 6.44) to slightly alkaline (7.63). Similar results were

obtained in the North, centre and west of Burkina Faso [15, 25-28].

In accordance with the standards in force in Burkina Faso concerning the pH values of groundwater (pH between 6.5 and 8.5), four samples have pH values lower than 6.5 and are therefore acidic. These are samples GWF18 (6.44), GWF19 (6.39), GWF23 (6.1) and GWP01 (5.99). These waters could therefore be considered unfit for human consumption and domestic use given their acidity [3, 27]. This acidity may be

linked to anthropogenic pollution by infiltration or linked to the geological nature of the land crossed [6, 29, 30].

Table 1. Physicochemical parameters.

Sample	GWF 01	GWF 02	GWF 03	GWF 04	GWF 05	GWF 06	GWF 07	GWF 08	GWF 09	GWF 10	GWF 11	GWF 12	GWF 13	GWF 14	Standards-BF (2005)
pH	7.22	7.63	6.66	7.10	7	6.58	7.16	6.99	6.96	7.38	6.93	6.86	7.32	6.58	6.5-8.5
T (°C)	29.60	26.40	31.70	31.50	31	33.80	33	32.50	34.90	31.50	30.90	31	26.80	29.60	10-40
EC (µs/cm)	454	356	267	460	671	262	421	465	410	324	337	273	213	286	1000
TDS (ppm)	322	248	188.70	324	476	185.40	299	331	286	229	238	193.2	151.90	194.40	1000

Sample	GWF 15	GWF 16	GWF 17	GWF 18	GWF 19	GWF 20	GWF 21	GWF 22	GWF 23	GWF 24	GWF 25	GWF 26	GWF 27	GWP 01	Standards-BF (2005)
pH	6.58	7.36	6.92	6.44	6.39	6.88	7.27	7.17	6.10	7.18	7.33	7.44	7.46	5.99	6.5-8.5
T (°C)	30.40	31	32	31.30	32.10	31.40	32.90	31.60	33.70	33.60	32.50	32.90	29.80	31	10-40
EC (µs/cm)	328	461	992	263	210	489	506	540	166.10	548	417	599	530	247	1000
TDS (ppm)	231	327	705	185.80	148	352	360	384	116.10	388	296	425	375	175.10	1000

Sample	GWP0 2	GWP0 3	GWP0 4	GWP0 5	GWP0 6	GWP0 7	GWP0 8	GWP0 9	GWP1 0	GWP1 1	Mim.	Max.	Average	Standards-BF (2005)
pH	7.48	7.32	6.74	6.75	7.11	7.40	7.32	7.18	7.10	7.40	5.99	7.63	7.02	6.5-8.5
T (°C)	32.40	32.50	32.20	32.30	33	32.50	32.50	32.30	30.4	31.60	26.4	34.9	31.63	10-40
EC (µs/cm)	668	350	337	277	457	610	522	410	432	397	166.1	992	419.87	1000
TDS (ppm)	476	269	239	197.10	323	433	379	292	310	280	116.1	705	298.23	1000

3.2.2. Temperature (T)

The temperatures (T) measured are between 26.4 and 33.8 °C, with an average of 31.6 °C. The temperature standards in Burkina Faso are between 18 and 40 °C. The values obtained are therefore in accordance with the standards in force and generally correspond to the temperatures of tropical zones and therefore the climatic context [27, 31, 32]. The same applies to the difference between the maximum and minimum temperature, which is 8.5 °C.

Also, it should be noted that the infiltration of surface wa-

ters can influence a considerable decrease or increase in temperature during their mixing at depth [33]. The temperatures measured in two very close sampling sites (GWF02 borehole and Fara dam), indicate almost similar values, respectively 26.4 °C and 26 °C, confirming this observation. In view of the standards in force in Burkina Faso, the temperature is not a parameter which compromises the potability of groundwater in the study area.

3.2.3. Electrical Conductivity (EC)

Electrical conductivity is a parameter used to assess the

degree of mineralization of water, given that each ion acts through its concentration and specific conductivity. The measured electrical conductivity ranges from 166.1 to 992 $\mu\text{S}/\text{cm}$, with an average of 419.9 $\mu\text{S}/\text{cm}$. The values obtained comply with the potability standards in force in Burkina Faso. However, in places, highly mineralized borehole water samples (GWP02: 668 $\mu\text{S}/\text{cm}$; GWF05: 671 $\mu\text{S}/\text{cm}$ and GWF17: 992 $\mu\text{S}/\text{cm}$) were observed, tending towards the pollution threshold, although sampling took place during periods of high water. This mineralization could be linked to human activities including gold panning which has exposed the mineral elements resulting from the dismantling (weathering) of the source rock loaded with minerals which, through leaching, infiltrates the water table with a high pollutant load [6, 33, 34].

3.2.4. Total Dissolved Solids (TDS)

Total Dissolved Solid (TDS) represents the total amount of substances dissolved in water [6, 35, 36]. It is the total amount of mobile charged ions, including minerals, salts and metals dissolved in a given volume of water, expressed in mg/l or parts per million (ppm). TDS values range from 116.1 to 705 ppm, with an average of 298.2 ppm. Borehole water samples with TDS above average represent 47.37% of all groundwater samples. However, the recorded TDS values remain below the threshold value of 1000 ppm in accordance with the standards in force in Burkina Faso.

In summary, the results of the physicochemical parameters indicate a pollution of groundwater resources, through acidic pH values recorded on some samples. Values close to the critical threshold for electrical conductivity are also observed. Similar results have been reported in the Democratic Republic of Congo [30], as well as in the Republic of Ivory Coast [37]. The work of [38] confirms the influence of dilution on the physicochemical parameters of groundwater, depending on whether it is a period of high or low water.

3.3. Trace Metal Element (TMEs) Contents

The contents of nine trace metal elements (TMEs) in

groundwater samples were determined to assess the existence or absence of pollution (Table 2). This was an assessment of single-element pollution. The individual analysis of the TMEs studied in relation to the standards in force in Burkina Faso indicates variations from one TME to another.

As for aluminium, two samples show values higher than the standards in force (0.2 mg/l): GWF21 (0.23 mg/l) and GWF23 (0.57 mg/l).

With regard to arsenic, only one sample has a content above the threshold value (0.05 mg/l): GWP06 (0.057 mg/l).

As for cadmium, thirty samples have values significantly above the standards and three others have values equal to the limit value of 0.003 mg/l (GWF11, GWF17 and GWP04).

As for iron, six samples show values that are higher than the standard of 0.3 mg/l, namely GWF03 (2.5 mg/l); GWF06 (3.42 mg/l); GWF11 (0.9 mg/l); GWF19 (0.31 mg/l); GWF21 (0.47 mg/l); GWF23 (0.33 mg/l) and GWP04 (12.93 mg/l).

Concerning mercury, only one sample has a content higher than the standard of 0.001 mg/l (GWP03: 0.004 mg/l) and another has a content equal to the threshold value (GWP11).

Seven samples have lead contents whose values are equal to that of the standard in force (0.01 mg/l).

The chromium, manganese and zinc contents are those whose values comply with the standards in force in Burkina Faso, which are respectively 0.05 mg/l, 0.5 mg/l and 3 mg/l.

In summary, the TMEs contents compared to the standards in force in Burkina Faso in accordance with WHO guidelines indicate that out of the 38 samples studied, only four samples (GWF01, GWF05, GWF08 and GWF25) have contents that comply with the standards.

This approach to assessing single-element pollution allows us to identify 10.53% of samples whose contents comply with the standards and 89.47% with contents for certain TMEs above the threshold values in force.

Cadmium contents for 97.06% of the samples are higher than the standards in force. The majority of the samples therefore have cadmium contents which do not comply with the standards in force, while for the others, the elements incriminated are Cd, Al, Fe, As, Pb, and Hg (Table 2).

Table 2. TMEs contents and groundwater pollution index (PI).

Trace Metal Element (mg/l)										
Sample	Al	As	Cd	Cr	Fe	Hg	Mn	Pb	Zn	PI (%)
GWF01	<LD	<LD	<LD	<LD	0.132	<LD	<LD	<LD	<LD	4.4
GWF02	0.023	<LD	0.006	<LD	0.061	<LD	0.011	<LD	<LD	23.4
GWF03	0.056	0.006	0.005	<LD	2.498	<LD	0.022	<LD	0.227	105.1
GWF04	<LD	<LD	0.006	<LD	0.021	<LD	<LD	<LD	<LD	20.7
GWF05	<LD	0.02	<LD	<LD	<LD	<LD	<LD	<LD	<LD	04.0

Trace Metal Element (mg/l)										
Sample	Al	As	Cd	Cr	Fe	Hg	Mn	Pb	Zn	PI (%)
GWF06	<LD	0.006	0.005	<LD	3.424	<LD	0.02	<LD	0.036	132.5
GWF07	<LD	0.012	0.006	<LD	0.011	<LD	<LD	<LD	<LD	22.8
GWF08	<LD	<LD	<LD	<LD	0.016	<LD	<LD	<LD	<LD	0.5
GWF09	<LD	0.006	0.007	<LD	0.01	<LD	0.028	<LD	0.048	25.6
GWF10	<LD	0.008	0.005	<LD	0.29	<LD	0.036	<LD	0.256	29.5
GWF11	<LD	<LD	0.003	<LD	0.902	<LD	0.007	<LD	0.109	40.6
GWF12	0.121	<LD	0.004	<LD	0.175	<LD	<LD	<LD	0.042	25.3
GWF13	0.071	0.005	0.005	0.004	0.145	<LD	0.011	<LD	<LD	27.1
GWF14	<LD	0.008	0.006	<LD	<LD	<LD	0.013	<LD	<LD	21.8
GWF15	<LD	<LD	0.005	<LD	<LD	<LD	0.222	<LD	<LD	21.1
GWF16	0.074	0.009	0.005	<LD	0.242	<LD	0.026	0.01	<LD	30.7
GWF17	0.02	<LD	0.003	<LD	0.02	<LD	0.031	<LD	<LD	12.3
GWF18	0.022	<LD	<LD	<LD	0.072	<LD	<LD	0.01	<LD	3.5
GWF19	<LD	<LD	0.006	0.008	0.305	<LD	<LD	<LD	<LD	31.7
GWF20	<LD	<LD	0.005	<LD	0.02	<LD	<LD	<LD	<LD	17.3
GWF21	0.23	<LD	0.004	0.005	0.466	<LD	0.02	0.01	<LD	41.8
GWF22	<LD	0.008	0.005	<LD	0.014	<LD	<LD	<LD	<LD	18.7
GWF23	0.568	<LD	0.004	<LD	0.332	<LD	0.013	0.01	<LD	53.1
GWF24	<LD	0.012	0.005	0.003	0.015	<LD	<LD	<LD	<LD	20.2
GWF25	0.021	<LD	<LD	<LD	0.013	<LD	<LD	<LD	<LD	1.5
GWF26	<LD	0.005	0.005	<LD	<LD	<LD	<LD	0.01	<LD	17.7
GWF27	0.025	0.013	0.005	<LD	0.227	<LD	<LD	<LD	0.024	28.2
GWP01	0.089	<LD	0.005	<LD	0.187	<LD	0.015	<LD	<LD	27.6
GWP02	<LD	0.037	0.004	<LD	0.199	<LD	<LD	0.01	0.051	27.5
GWP03	0.023	<LD	0.005	<LD	0.148	0.004	0.018	<LD	<LD	63.1
GWP04	0.027	<LD	0.003	<LD	0.062	<LD	0.054	<LD	0.022	14.6
GWP05	<LD	0.009	0.006	<LD	12.925	<LD	0.163	<LD	0.032	456.0
GWP06	0.022	0.057	0.006	<LD	0.011	<LD	<LD	<LD	<LD	32.9
GWP07	<LD	0.009	0.005	0.002	<LD	<LD	<LD	<LD	<LD	18.5
GWP08	0.021	0.018	0.006	<LD	0.01	<LD	<LD	<LD	<LD	25.0
GWP09	<LD	0.007	0.005	<LD	<LD	<LD	<LD	<LD	<LD	18.1
GWP10	<LD	<LD	0.005	<LD	<LD	<LD	0.015	<LD	<LD	17.0
GWP11	0.023	<LD	0.006	0.007	0.016	0.001	<LD	0.01	<LD	33.1
Mim.	0.02	0.005	0.003	0.002	0.01	0.001	0.007	0.01	0.022	0.5
Max	0.568	0.057	0.007	0.008	12.925	0.004	0.222	0.01	0.256	456.0
Average	0.084	0.013	0.005	0.005	0.741	0.003	0.040	0.010	0.085	39.9
Standards -BF 2005 [21]	0.2	0.05	0.003	0.05	0.3	0.001	0.5	0.01	3	

3.3.1. Pollution Risk Index (PI)

The pollution index (PI) developed by [39] and improved by [40], makes it possible to assess the overall pollution of water bodies by TMEs [41-43]. This index corresponds to multi-element pollution by its formula. Thus, the formula used is that proposed by [44], modified by [45].

$$PI (\%) = \frac{\sum_{i=1}^n \frac{C_{sample}}{C_{ref}}}{n} * 100$$

Where C_{sample} is the sample concentration and C_{ref} : reference concentration (Table 2) [21] and n : the number of TMEs considered.

Depending on the PI value, the pollution risk can be divided into 4 classes [45]:

1. for $PI = 0$, this indicates that there is no risk of pollution;
2. If $PI < 100\%$, the risk of pollution is low;
3. $PI = 100\%$, corresponds to the threshold of the risk of pollution or moderate pollution;
4. for $PI > 100\%$, the risk of pollution is high or high pollution.

The results of the groundwater pollution risk assessment around the former Poura gold mine are reported in Table 2.

The minimum PI value is 0.5% and the maximum is 456%, with an average of 39.9%. 35 samples correspond to a $PI < 100\%$, or 92.1% of all samples, and for an $PI > 100\%$, only 3 samples are observed: GWF03 ($PI = 105.1\%$); GWF06 ($PI = 132.5\%$) and GWP05 ($PI = 456\%$), or 7.90% of the samples. In view of these results, it is important to generally point out the existence of pollution in the study area. Furthermore, 7.90%

of the samples show high levels of pollution and are therefore unfit for consumption [46]. These results corroborate those of [15] in the same area, of [45] in Ivory Coast.

3.3.2. Pearson Correlation Matrix

The Pearson correlation matrix (Table 3) made it possible to identify some correlations observed between the physico-chemical parameters on the one hand, and with the TMEs on the other hand. It is observed that pH is positively correlated with electrical conductivity (EC) ($r = 0.504$) and with TDS ($r = 0.509$), while it is negatively correlated with some TMEs such as Al ($r = -0.382$) and Cr ($r = -0.330$). It is also observed that if the pH increases, the Al and Cr contents are low and vice versa. Thus, high Al and Cr contents correspond to acidic pHs and low contents to neutral to alkaline pHs (Table 1). We could therefore establish a correlation between the acidity of the groundwater around the old Poura gold mine and the high Al and Cr contents, and therefore the TMEs. CE and TDS are also very strongly correlated ($r = 0.999$). Thus, we see that EC, TDS and pH are closely related. This link is justified by the fact that these parameters are linked to mineralization in the study area. However, the relationship of temperature with other parameters remains discreetly expressed. Similar results were obtained in Congo [35] and Ivory Coast [47], on the study of hydro-chemical evaluation and chemical contamination of groundwater. However, correlations between other TMEs and/or with physicochemical parameters are less expressed, requiring exploration with Principal Component Analysis (PCA).

Table 3. Pearson correlation matrix of physicochemical parameters and TMEs.

Variables	pH	T	EC	TDS	Al	As	Cd	Cr	Fe	Hg	Mn	Zn
pH	1											
T	-0.186	1										
EC	0.504	0.168	1									
TDS	0.509	0.173	0.999	1								
Al	-0.382	0.249	-0.264	-0.268	1							
As	0.096	0.118	0.229	0.230	-0.088	1						
Cd	0.086	-0.001	-0.219	-0.223	-0.215	-0.005	1					
Cr	-0.330	-0.006	-0.268	-0.266	0.006	0.095	0.119	1				
Fe	-0.185	0.102	-0.214	-0.214	0.011	-0.159	0.158	0.014	1			
Hg	0.135	0.086	-0.073	-0.043	-0.118	0.000	-0.001	0.018	-0.048	1		
Mn	-0.145	0.044	-0.042	-0.043	-0.096	0.024	0.117	0.027	0.488	-0.095	1	
Zn	0.047	-0.081	-0.112	-0.111	0.011	-0.132	0.020	0.000	-0.134	0.000	-0.164	1

Values in bold are different from 0 at a significance level $r=0.05$

3.3.3. Principal Component Analysis (PCA)

The analysis of the different variables of the 38 ground-water samples from the PCA was carried out from the first five important factorial axes in decreasing order (F1 to F5), corresponding to them alone, 68.63% of the total variability. Only axes with an eigenvalue greater than or equal to 1 are retained, because they constitute factors which have at least

one significantly expressed variable (Table 4). The contribution of each factor retained corresponds respectively to: F1 (23.42%), F2 (13.40%), F3 (12.80%), F4 (10.07%) and F5 (8.95%) (Figure 3). These low rates of factors show that the mechanism responsible for the mineralization of salts in groundwater comes from various sources linked to the context of the study area, whether natural or anthropogenic.

Table 4. Correlations between variables and factors.

Factor	F1	F2	F3	F4	F5
Percentage (%)	23.42	13.40	12.80	10.07	8.95
pH	0.624	-0.233	-0.494	-0.059	0.171
T	0.050	0.437	0.437	0.195	0.509
CE	0.925	0.241	0.096	-0.045	-0.063
TDS	0.927	0.238	0.093	-0.036	-0.043
Al	-0.395	0.012	0.695	-0.188	0.129
As	0.277	0.185	0.062	0.676	-0.171
Cd	-0.370	-0.030	-0.581	0.252	0.119
Cr	-0.355	0.010	0.095	0.606	-0.355
Fe	-0.397	0.623	-0.295	-0.262	0.141
Hg	0.025	-0.202	-0.143	0.339	0.752
Mn	-0.216	0.714	-0.340	-0.112	-0.089
Pb	0.000	0.000	0.000	0.000	0.000
Zn	-0.063	-0.523	0.010	-0.212	-0.015

In F1, pH (0.624), EC (0.925) and TDS (0.927) are expressed significantly with positive values on the axis (Figure 3a). The good correlation between CE and TDS on the one hand and between pH, CE and TDS on the other hand, indicates that the F1 axis represents the axis of global mineralization, all origins combined. As a reminder, EC and TDS represent respectively the electrical conductivity and the total quantity of all solids dissolved in water, all origins combined. On this axis, the mineral contributions are varied. Some variables such as temperature, arsenic and mercury are expressed positively, but are not significant. They belong to the same group with pH, CE and TDS and can be linked by the same source or origin. However, other variables such as Al, Cd, Fe, Zn, Mn and Cr, are negatively correlated on the F1 axis, even if the values are not very significant. This state of affairs expresses a common source between these variables, but indicates a different origin of the CE and TDS group. Mineralization of one group implies demineralization of the other group depending on the factor F1. The observation is that we can claim that the origin of TMEs (As and Hg) is different from that of other TMEs (Al, Cd,

Fe, Mn, Cr and Zn).

In F2, T, CE, TDS, Al, As, Cr, Fe and Mn are positively correlated with the axis (Figure 3a). pH, Cd and Hg are negatively correlated with F2. This means that if the first group which constitutes the positive variables with F2 increases, the variables expressed negatively tend to decrease, or even disappear. The most important observation is that, Mn (0.714), Fe (0.623), and Zn (-0.523) correlate very significantly with F2 (Table 4). Fe and Mn mineralization appears to be from the same geological source and influenced by temperature unlike Zn (Table 4 and Figure 3a), as observed with the Pearson correlation matrix (Table 3). These two elements are frequently found in iron- to manganese-bearing minerals and in sulfides of basic to ultrabasic rocks, such as pyroxene, amphibole, peridot and other minerals related to the geological context. They are generally found dissolved in groundwater, including mineral water. Fe and Mn are soluble in the reduced state but insoluble in the oxidized state [48]. A high proportion of one group implies a low proportion of the other group, or even its absence

(Figure 3a). The F2 axis would therefore correspond to that of the oxidation-reduction processes leading to the release of iron

and manganese in the water, opposed to the reduction of Zinc.

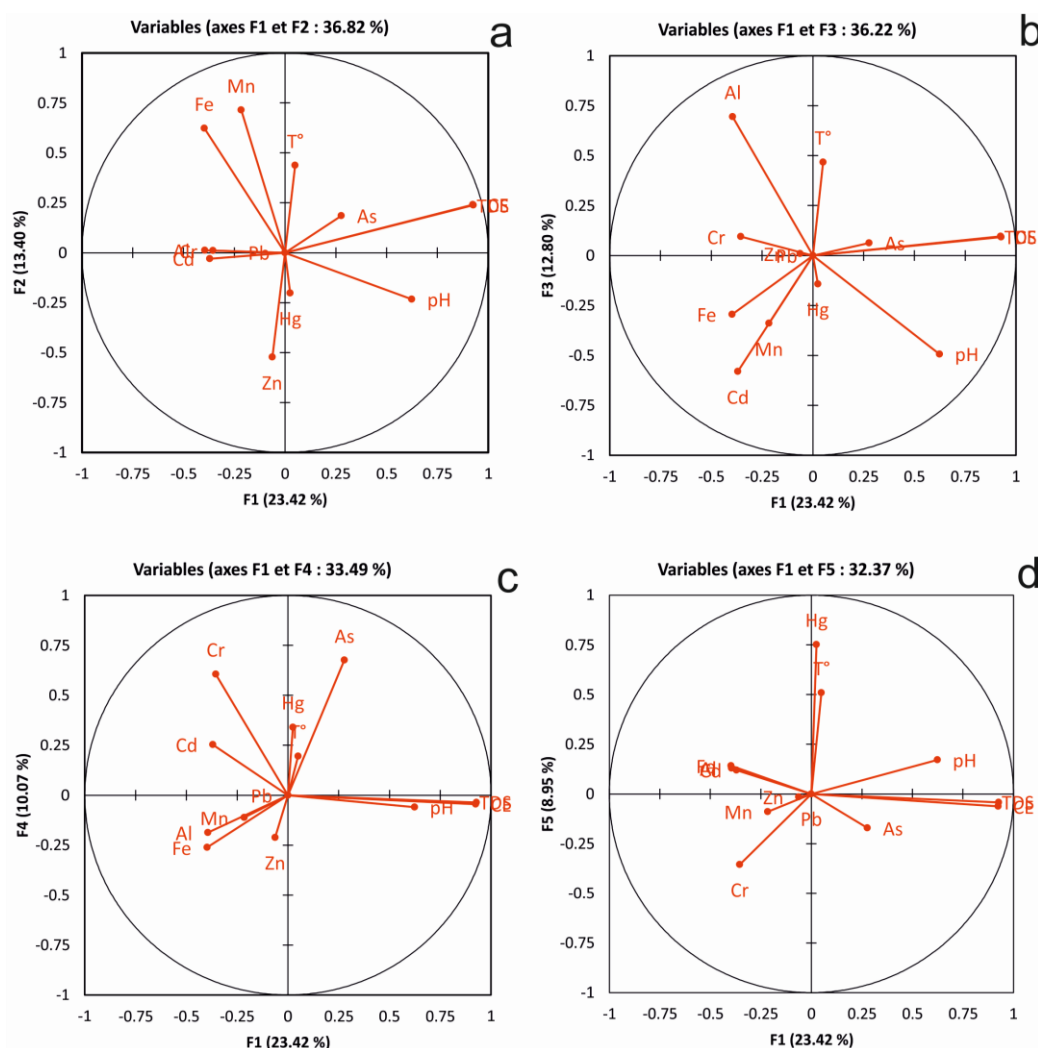


Figure 1. Principal component analysis of groundwater (a: axes F1/F2; b: axes F1/F3; c: axes F1/F4; d: axes F1/F5).

In F3, there are two groups of correlation variables. The first group, consisting of pH, Cd, Fe, Hg and Mn, correlates negatively with F3 (Table 4 and Figure 3b). The second group, composed of CE, TDS, T, Al, As, Cr and Zn, is positively correlated with F3. The decrease in positive variables implies the increase in negative variables and vice versa. In this factor F3, Al and Cd are the two variables strongly correlated to the axis, but in an opposite way (Figure 3b). The presence of one seems to indicate the absence of the other. This could also reflect that these two TMEs come from different sources. The study area being essentially made up of silicate rocks whose mineral composition contains abundant aluminum in positive correlation with the temperature would indicate a natural source of this element, linked to a high degree of weathering of silicate minerals in the area. Cd being negatively correlated with Al, this suggests an anthropogenic source. Since Cd is positively correlated with pH, its origin in groundwater could be linked to leaching and infiltration of mining waste. Axis F3

would therefore represent contamination by mining waste.

In F4, there are two variables that show a very significant correlation with the axis. These are As and Cr, which express positive values (Table 4). These TMEs present, according to this F4 axis, a similar evolution or origin. It is also observed that Cd and Hg are positively correlated with F4 (Figure 3c). Generally, the origin of arsenic in groundwater is lithogenic, therefore natural, coming from certain rocks and minerals such as sulfides, arsenides and sulfo-arsenides such as realgar, arsenopyrite, orpiment [49-51]. Having a positive correlation with As, we could say that chromium has the same origin as that of arsenic.

Finally, in F5, the positive variables on the factorial axis are pH, T, Al, Cd, Fe and Hg. As for the negative variables, these are CE, TDS, As, Cr, Mn and Zn. As in the previous axes, the negative sign would indicate the absence or low proportion of the variables concerned compared to the positive variables. T and Hg are the two variables that show a very significant positive

correlation with F5 (Table 4 and Figure 3d). Since Hg is not present in the original composition of the rocks present, its origin can only be linked to mining activity, particularly in the artisanal amalgamation of the ore [52]. The positive correlation of Hg and T to the F5 axis shows that Hg concentrations in these waters vary depending on the temperature. Since sampling is carried out in August, Hg concentrations in the water tend to increase during hot periods (April, May).

In summary, these observations show that the origin and mobilization of the elements Al, As, Cd, Cr, Fe, Hg and Pb would be attributable to natural mineralization and anthropogenic activities such as mining activities [28, 33] and favored by the infiltration of water into the subsoil [33, 53]. This infiltration, which reflects the mobility of TMEs, is favored by fractures and geological faults [54], a signature of the basement zone [55, 56].

4. Conclusion

The assessment of groundwater pollution around the old Poura gold mine was carried out through physicochemical parameters and trace metal element contents. The values of temperature, electrical conductivity and dissolved solids comply with the potability standards set by current regulations. However, four groundwater samples have an acidic pH (GWF18, GWF19, GWF23 and GWP01) with values between 5.99 and 6.44, which do not comply with the standards in force (6.5 to 8.5) with regard to the potability of the water. As regards trace metal elements, the comparison of their contents with the standards in force in Burkina Faso indicates that for 34 samples (89.47%) at least one of these trace metal elements (Cd, Fe, Al, As, Hg and Pb) has a value higher than the standard.

The pollution risk index shows that 35 samples are very slightly polluted with PI values ranging from 0.5% to 63.1%, and 3 very polluted samples with PI values between 105.1% and 456% (GWF03, GWF06 and GWP01).

Pollutants would be mobilized through anthropogenic activities such as artisanal mining activities. The mobility pathways of these TMEs remain the infiltration of water through fractures and faults.

Abbreviations

MP-AES	Microwave Plasma Atomic Emission Spectrometer
ONEA	National Office of Water and Sanitation
SOREMIB	"Société de Recherche et d'Exploitation Minière du Burkina"
TTG	Tonalites, Trondhjemites, Granodiorites
WHO	World Health Organization

Acknowledgments

The authors thank the mineral and environmental analysis

laboratory Senexel Sarl, and particularly Mr. SENOU Aboubacar, of said laboratory for his support.

Author Contributions

Adama Yameogo: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Writing – original draft

Nicolas Kagambega: Conceptualization, Formal Analysis, Methodology, Project administration, Supervision, Validation, Visualization, Writing – review & editing

Isso Felix Bado: Formal Analysis, Supervision, Validation, Visualization

Abdoul-Azize Barry: Formal Analysis, Supervision, Validation, Visualization

Funding

This work is not supported by any external funding.

Data Availability Statement

The data supporting the outcome of this research work has been reported in this manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

References

- [1] Aka, A. M., Kouamé A. F., Aka, C. A. et Coulibaly, A. S. Caractérisation hydrologique et morpho-sédimentaire d'une zone de dragage en Lagune Ebrié et risques de contamination de la nappe d'Abidjan: cas du secteur lagunaire Abatta-Bingerville. International Journal of Scientific Research and Management (IJSRM). 2020, Volume 08 Issue 08 Pages EL-2020-1572-1587.
- [2] Leduc, C., Favreau, G. and Schroeter, P. Long-term rise in a sahelian water table: The Continental Terminal in South-West Niger. Journal of Hydrology, 2001, 243 (1-2), p. 43-54. [https://doi.org/10.1016/S0022-1694\(00\)00403-0](https://doi.org/10.1016/S0022-1694(00)00403-0)
- [3] Amadou, H., Laouali, M. S. et Manzola, A. S. Caractérisation hydro chimique des eaux souterraines de la région de Tahoua (Niger). Journal of Applied Biosciences, 2014, (80): 7161-7172. <http://dx.doi.org/10.4314/jab.v8i1.6>
- [4] Merbouh, C., Belhsaien, K., Zouahri, A. and Iounes, N. Evaluation of the Physico-chemical Quality of Groundwater in the Vicinity of the Landfill of Mohammedia-Benslimane: (Preliminary Study). Europeann Scientific Journal. Edition 2020, vol.16, N°6. <http://dx.doi.org/10.19044/esj.2020.v16n6p455>

- [5] Agarwal, A., Angeles, M. S. D., Bhatia, R., Chéret, I., Davila-Poblete, S., Falkenmark, M., Villareal, F. G., Jønh-Chlausen, T., Kadi, M. A., Kindler, J., Rees, J., Roberts, P., Rogers, P., Solanes, M. et Wright, A. La gestion intégrée des ressources en eau. TAC Background Papers, 2000, n°4. Novum Grafiska AB Suède, 2000, 80 p.
- [6] Yao, T. K., Oga, M. S., Fouché O., Baka, D., Pernelle, C. et Biéni, J. Evaluation de la potabilité chimique des eaux souterraines dans un bassin versant tropical: cas du Sud-Ouest de la Côte d'Ivoire. *International Journal of Biological and Chemical Sciences*, 2012, 6 (6): 7069-7086.
- [7] Ghazali, D. et Zaid, A. Etude de la qualité physico-chimique et bactériologique des eaux de la source Ain Salama-Jerri (Region de Meknes-Maroc). *Larhyss Journal*, 2013, n°12, p 25-36.
- [8] Tankari Dan-Badjo, A., Tidjani, D. A., Idder, T., Guero, Y., Dan Lamso, N., Matsallabi, A., Ambouta, K. J. M., Feidt, C., Sterckeman, T. et Echevarria, G. Diagnostic de la contamination des eaux par les éléments traces métalliques dans la zone aurifère de Komabangou-Tillabéri-Niger. *International Journal of Biological and Chemical Sciences*, 2014, 8(6): 2849-2857.
- [9] Hounsounou, E. O., Agassounon Djikpo Tchibozo, M., Kelome, N. C., Vissin, E. W., mensah, G. A. et agbossou, E. Pollution des eaux à usages domestiques dans les milieux urbains défavorisés des pays en développement: Synthèse bibliographique. *International Journal of Biological and Chemical Sciences*, 2016, 10 (5): 2392-2412.
- [10] Mukherjee, A., Scanlon, B.R., Aureli, A., Langan, S., Guo, H., McKenzie, A.A. *Global Groundwater: Source, Scarcity, Sustainability, Security, and Solutions*. Elsevier, Global Groundwater, 2021, 18 p.
- [11] Cobbina, S. J., Myilla, M., Michael, K. Small Scale Gold Mining And Heavy Metal Pollution: Assessment of Drinking Water Sources In Datuku In The Talensi-Nabdam District. *Int. J. Sci. Technol. Res.*, 2013, 2 (96-100).
- [12] Kpan, J.D.A., Opoku, B.K., Gloria, A. Heavy Metal Pollution in Soil and Water in Some Selected Towns in Dunkwa-on-Offin District in the Central Region of Ghana as a Result of Small-scale Gold Mining. *J. Agric. Chem. Environ.*, 2014, (3), 40–47. <https://doi.org/10.4236/jacen.2014.32006>
- [13] Mimba, M. E., Mbafor, P. U. T., Nguemhe Fils, S.C., Nforba, M.T. Environmental impact of artisanal and small-scale gold mining in East Cameroon, Sub-Saharan Africa: An overview. *Ore Energy Resour. Geol.*, 2023 (15), 100031. <https://doi.org/10.1016/j.oreoa.2023.100031>
- [14] Sako, A., Bamba, O. and Gordio, A. Hydrogeochemical processes controlling groundwater quality around Bomboré gold mineralized zone, Central Burkina Faso. *Journal of Geochemical Exploration*, 2016, 170 (2016) 58-71. <http://dx.doi.org/10.1016/j.gexplo.2016.08.009>
- [15] Kagambèga, N., Sawadogo, S. and Gordio, A. High arsenic enrichment in water and soils from Sambayourou watershed-Burkina Faso (West Africa). *International Journal of Environmental Monitoring and Analysis*, 2014, 2(3): 6-12.
- [16] Ouedraogo, B., Kagambèga, N., Ouédraogo, M. Méthodes prédictives géochimiques statiques et plan de fermeture de mine. Cas de la mine d'or de Youga-Burkina Faso. *J. Sci.*, 2018 (18), 13-23.
- [17] Lemoalle, J. and De Condappa, D. Water atlas of the Volta Basin-Atlas de l'eau dans le bassin de la Volta. Challenge Program on Water and Food and Institut de Recherche pour le Développement, Colombo, Marseille, 2009, 96 p.
- [18] Castaing, C., Vidal, M., Bila, M., Cocherie, A., Delpont, G., Feybesse, J. L., Guerrot, C., Itard, Y., Jezequel, P., Milési, J.P., Pedroletti, V., Thiéblemont, D., Teygey, I., Ki, J.C. et Zunino, C. Notice Explicative de la carte géologique à 1/200 000 Feuille ND-30-VI Boulsa. 1^{ère} édition, 2003, 68 p.
- [19] US EPA -821-R-01-010. (U.S. Environmental Protection Agency): method 200.7 trace elements in water, solids, and biosolids by inductively coupled plasma-atomic emission spectrometry (Rev.5.0). Office of Science and Technology Ariel Rios Building 1200 Pennsylvania Avenue, N.W. Washington, 2001, D.C. 20460, 68 P.
- [20] Centre d'Expertise en Analyse Environnementale du Québec (CEAEQ). Détermination des métaux: méthode par spectrométrie de masse à source ionisante au plasma d'argon. MA. 200-M et 1.2 (Révision 5), 2014, 36 p.
- [21] Ministère de l'Agriculture, de l'Hydraulique et des Ressources Halieutiques et le Ministère de la Santé (MAHRH/MS). Arrêté conjoint n°00.019/ MAHRH/MS du 13/03/2005, portant fixation des normes de potabilité de l'eau, 2005, 21 p.
- [22] OMS: Directives de qualité pour l'eau de boisson: 4^{ème} édition intégrant le premier additif (Guidelines for drinking-water quality, 4th ed. incorporating first addendum), 2017, ISBN978-92-42549959, 564 p.
- [23] Müller, G. Index of geo-accumulation in sediments of the Rhine River, *Geology Journal*, 1969, 2(3): 108-118.
- [24] Konan, K. S., Kouamé K. B., Konan, F. K., Boussou, K. C., and Kouakou, K. L. Pollution des eaux à usages domestiques par les éléments traces métalliques des activités anthropiques: cas du sous bassin versant du fleuve Sassandra en amont du barrage de Buyo, Côte d'Ivoire. *Proc. IAHS*, 2021, 384, 85-92. <https://doi.org/10.5194/piahs-384-85-2021>
- [25] Smedley, P.L., Knudsen, J. et Maiga, D. Arsenic in groundwater from mineralised Proterozoic basement rocks of Burkina Faso. *Applied Geochemistry*, 2007, 22(2007) 1074-1092.
- [26] Ouandaogo-Yameogo, S., Blavoux, B., Nikiema, J. et Savadogo, A. N. Characterization of the functioning of the basement aquifers in the area of Ouagadougou through a study of water chemical quality. *Revue des Sciences de l'Eau*, 2013, 26(3) (2013) 173-191. <https://doi.org/10.7202/1018784ar>
- [27] Bakouan, C., Guel, B. et Hantson, A. L. Caractérisation physico-chimique des eaux des forages des villages de Tanlili et Lilgomdédans la région Nord du Burkina Faso - Corrélation entre les paramètres physico-chimiques. *Afrique Science*, 2017, 13(6) (2017) 325-337.

- [28] Bretzler, A., Lalanne, F., Nikiema, J., Podgorski, J., Pfenninger, N., Berg, M. and Schirmer, M. Groundwater arsenic contamination in Burkina Faso, West Africa: Predicting and verifying regions at risk. *Science of the Total Environment*, 2017, 584-585 (2017) 958-970.
<http://dx.doi.org/10.1016/j.scitotenv.2017.01.147>
- [29] Gouaidia, L. Influence de la lithologie et des conditions climatiques sur la variation des paramètres physico-chimiques des eaux d'une nappe en zone semi-aride, cas de la nappe de Meskiana nord-est Algérien, Thèse de Doctorat, Université Badji Mokhtar, Annaba, Algérie, 2008, 131p.
- [30] Balloy Mwanza, P., Katond, J. P. et Hanocq, P. Evaluation de la qualité physico chimique et bactériologique des eaux de puits dans le quartier spontané de Luwuwoshi (RD Congo). *Tropicultura*, 2019, Volume 37, n° 2 (2295-8010), 627.
- [31] Assemanian, E. A., Kouame, F. K., Djagoua, É.V., Affian, K., Jourda, J., Adja, M., Lasm, T. et Biemi, J. Étude de l'impact des variabilités climatiques sur les ressources hydriques d'un milieu tropical humide: cas du département de Bongouanou (Est de la Côte d'Ivoire). *Revue des sciences de l'eau / Journal of Water Science*, 2013, 26(3), 247-261.
<https://doi.org/10.7202/1018789ar>
- [32] Soro, G., Soro, T. D., Fossou, N. M. R., Adjiri, O. A. et Soro, N. Application des méthodes statistiques multivariées à l'étude hydrochimique des eaux souterraines de la région des lacs (centre de la Côte d'Ivoire). *Int. J. Biol. Chem. Sci.*, 2019, 13(3): 1870-1889.
- [33] Sako, A., Semdé S. and Wenmenga, U. Geochemical evaluation of soil, surface water and groundwater around the Tongon gold mining area, northern Côte d'Ivoire, West Africa. *Journal of African Earth Sciences*, 2018, 145 (2018) 297-316.
<https://doi.org/10.1016/j.jafrearsci.2018.05.016>
- [34] Amani, E. M. E., Akobé A. C., Amani, A. B. J. et Mondé S. Détermination ponctuelle des paramètres physico-chimiques d'une colonne d'eau de la baie du banco (LAGUNE EBRIE, CÔTE D'IVOIRE). *International Journal of Development Research*, 2020, 10(06), pp, 36389-36394.
<https://doi.org/10.37118/ijdr.18946.06.2020>
- [35] Matini, L., Moutou, J. M., et Kongo-Mantono, M. S. Evaluation hydro-chimique des eaux souterraines en milieu urbain au Sud-Ouest de Brazzaville, Congo. *Afrique Science*, 2009, 05(1), 82-98.
- [36] Mehounou, J. P., Josse, R. G., Dossou-Yovo, P., Senou, S. F. et Toklo, R. M. Caractérisation physico-chimique et microbiologique des eaux souterraines et superficielles dans la zone de production cotonnière d'Aplahoué. *Journal of Applied Biosciences*, 2016, 103, 9841-9853.
<http://dx.doi.org/10.4314/jab.v10i31.6>
- [37] Orou, R. K., Soro, G., Soro, D. T., N'guessan Fossou, R. M., Zahibo Onetie, O., Kouassi Ahoussi, E. et Soro, N. Variation saisonnière de la qualité physicochimique des eaux souterraines des aquifères d'altérites du Département d'Agboville (Sud-Est de la Côte d'Ivoire). *European Scientific Journal*, 2016, vol.12, n°17 (213-240).
<https://doi.org/10.19044/esj.2016.v12n17p213>
- [38] Gouaidia, L., Laouar, M. S., D'afilia, N. et Zenati, N. Origine de la minéralisation des eaux souterraines d'un aquifère dans une zone semi-aride, cas de la nappe de la Merdja, Nord-Est Algérien. *International Journal of Environment and Water*, 2017, Vol 6, Issue 2 (104-118).
- [39] Nishida, H., Miyai, M., Tada, F. and Suzuki, S. Computation of the index of pollution caused by heavy metals in river sediment. *Environ. Pollut., Series B, Chemical and Physical*, 1982, Vol 4 (241-248). [https://doi.org/10.1016/0143-148X\(82\)90010-6](https://doi.org/10.1016/0143-148X(82)90010-6)
- [40] Mohan, S. V., Nithila, P., and Reddy, S. J. Estimation of heavy metals in drinking water and development of heavy metal pollution index. *J. Environ. Sci. Health*, 1996, 31A: 283-289. ICA n°M-3951. <https://doi.org/10.1080/10934529609376357>
- [41] Prasad, B. and Bose, J. M. Evaluation of the heavy metal pollution index for surface and spring water near a limestone mining area of the lower Himalayas. *Environ Geol.* 2001, 41: 183-188. <https://doi.org/10.1007/s002540100380>
- [42] El-Hamid, H. T. A. and Hegazy, T. A. Evaluation of water quality Pollution Indices for groundwater resources of New Damietta, Egypt. *MOJ Eco Environ Sci.*, 2017, 2: 1-5.
- [43] Giri, S. and Singh, A. K. Assessment of metal pollution in groundwater using a novel multivariate metal pollution index in the mining areas of the Singhbhum copper belt. *Environmental Earth Sciences*, 2019, 78: 1-11.
<https://doi.org/10.1007/s12665-019-8200-9>
- [44] Hosik, L., Md. Imran, K., Phil, S. K., Jong, M. K., Jeong, G. K., Seung, H. H., Yeon, T. R., Myoung, S. B., Eul, R. R. and Myung, S. J. Contamination Assessment of Abandoned Mines by Integrated Pollution Index in the Han River Watershed. *The Open Environmental Pollution and Toxicology Journal*, 2009, 1, 27-33.
- [45] Djadé P. J. O., Traoré A., Koffi, K. J. T., Keumean, K. N., Soro, G. et Soro, N. Evaluation du niveau de contamination des eaux souterraines par les éléments traces dans le département de Zouan-Hounien (Ouest de la Côte d'Ivoire). *Journal of Applied Biosciences*, 2020, 150: 15457-15468.
- [46] Aloueimine, B. B., Kankou, M. O. and Belghyti, D. An indexing approach for the assessment of heavy metals in drinking water produced by Mauritanian water treatment plant. *Scientific Study and Research: Chemistry and Chemical Engineering, Biotechnology, Food Industry*, 2017, 18(3), 319-328.
- [47] Gbamdé K. S., Konan, K. S., Kouassi, K. L., Brou, L. A., Konan, K. F. et Bini, K. D. Evaluation de la Contamination Chimique des Eaux Souterraines par les Activités Anthropiques: Cas de la Zone d'Ity-Floleu Sous-Préfecture de Zouan-Hounien, Ouest de la Côte d'Ivoire. *European Scientific Journal*, 2020, édition, February 2020, Vol.16, n° 6 (247-274).
- [48] Lopoukhine, M. Le traitement du fer et du Manganèse dans les eaux minérales. *Rapport BRGM n°R40566*, 1999, 48p.
- [49] Barbier, J. Arsenic in groundwaters and other media, Massif central, France, Western Europ. *Cahiers de l'Association Scientifique Européenne pour l'Eau et la santé* 2005, Volume 10, n°1 (3-10).

- [50] Dassonville, F. Arsenic dans les eaux destinées à la consommation humaine: actions menées dans les Alpes-Maritimes pour respecter la réglementation. *Eur. j. water qual.*, 2013, 43(2012) 89-116.
- [51] Proust, N., Picot, A. Toxicologie de l'arsenic et de ses composés: importance de la spéciation. *EMC - Pathologie professionnelle et de l'environnement*, 2019, 0(0): 1-21 [Article 16-002-A-30].
- [52] Niamké K.H., Efebi, K.R., N'Dri, B.E., Gontonan, K.F. et Oga, Y.M.S. " Caractérisation des paramètres physiques et du taux de mercure des eaux dans un environnement d'orpaillage: cas de Kouaméla dans le département d'Oumé (Centre de la Côte d'Ivoire)" *IOSR Journal of Applied Geology and Geophysics (IOSR-JAGG)*, 2020, 8(1), pp. 48-56.
- [53] Roulet, M., Point, D., Goix, S., Tapia, J., Audry, S., Viers, G., Oliva, P., Polve, M., Huyata, C., Duprey, J. L., De la Galvez, E., Herbas, C., Ugarte, L., Gibon, F. M., Moya, N., Molina, C., Ibanez, C., Oberdorff, T., Mazurek, H., Pereira, D., Rojas, L., Centellas, J., Barbieri, F., Ruiz, M., Paco, P., Zambrana, S., Ascarrunz, M., Tirado, N., Terceros, P., Casiot, C., Freydier, R. et Gardon, J. Origine des pollutions polymétalliques et impact sur l'environnement, la santé et la société: étude dans une ville minière de l'altiplano bolivien. In: Colloque bilan des projets financés dans le cadre du programme SEST 2006. Paris: ANR, 2011, Colloque Santé-Environnement Santé-Travail, 2011/01/20-21, Paris, 15 p.
- [54] Barry, A.A. Étude biogéochimique et isotopique dans les eaux souterraines au voisinage des décharges d'ordures en milieu fracturé et urbain: cas de la commune de Ouagadougou (Burkina Faso). Thèse de Doctorat de l'Université d'Avignon (France) et de l'Université Joseph Ki-Zerbo (Ouagadougou, Burkina Faso), 2023, 258 p.
- [55] Babine, A., Sanfo, H., Hédié A., Nakolendoussé S., Dzikowski, M., Brondel, D. et Nicoud, G. La surexploitation de la nappe profonde du socle au Burkina Faso: l'exemple de Ouahigouya vers une catastrophe annoncée. *Géologues*, 2021, n°207, (106-112).
- [56] Bonssara, I., Toko Mouhamadou, I., Paré T., Arab Boye, R. et Yabi, I. Analyse géospatiale du potentiel en eau souterraine de la commune de Tanghin-Dassouri, Burkina Faso. *Rev. Ivoir. Sci. Technol.*, 2023, (42) 265-286.