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Source and Speciation of Arsenic in the Groundwater of the Paleoproterozoic Basement of Burkina Faso

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Abstract

Arsenic in drinking water causes serious health problems in many regions of the world, and Burkina Faso is not an exception. In Burkina Faso, few studies have examined the speciation of arsenic and identified its source. However, health problems linked to its presence in drinking water are evident in several regions of the country. The purpose of this study is to identify the origin and forms of arsenic in groundwater from the Paleoproterozoic basement of Burkina Faso. To this end, arsenic-contaminated water samples from boreholes in the Yadga, Oubri, and Nakambé regions were analyzed. Geological sections showed that the boreholes were drilled into shales and granitoids. The highest As concentration (98.7 µg/L) was found in the Yatenga volcanic-sedimentary shales in Ouahigouya. The results of the physicochemical parameter analyses showed that the analyzed waters are consistent with those of the basement, and the very strong correlation between conductivity and bicarbonates (0.98) reflects their natural mineralization. The strong correlations between electrical conductivity, HCO_3^-, Ca^{2+}, Mg^{2+}, Na^+, and As along the F1 axis indicate that the As originates from the aquifer, while the correlation between As and SO_4^{2-} axis indicates that the arsenic originates from sulfide minerals in the mineralized basement. Furthermore, the speciation of arsenic shows that As(III) is the predominant form. Since this form is the most toxic, it exposes populations to serious health conditions such as hemolysis and kidney problems.

Keywords

Burkina Faso, Drinking Water, Arsenic, Source, Speciation, Diseases

1. Introduction

Arsenic is a metalloid of geological origin [1]. In the environment, its sources include the ongoing use of arsenic-containing compounds including pesticides as well as accidental releases during gold and lead mining and coal combustion. Anthropogenic activities such as artisanal gold mining and agriculture result in its presence in wells and reservoir lakes [1] [2]. It is widely believed that arsenic in groundwater originates from the dissolution of sulfide ore bodies or young sedimentary aquifers in alluvial plains and deltas, which are the focus of most arsenic research [3]. In the context of Burkina Faso's crystalline basement (which accounts for 80% of the country's geological formations), arsenic is increasingly found at high concentrations in groundwater, most often exceeding the WHO standard. The PDSEAII study (2006) documented such cases in the Bankui, Nakambé, and Yaadga regions. The National Office for Water and Sanitation (ONEA, 2020) also reported cases in the Nakambé and Oubri regions. In February 2026, ONEA identified a new case in the Nazinon region, Zoundweogo Province, specifically in the commune of Nobéré.

In the context of Burkina Faso, very few studies [3] have focused on determining the source of arsenic, and this is what we aim to do through geological sections and water chemistry analyses in the bedrock aquifers of Burkina Faso.

2. Geological and Hydrogeological Context of the Studied Aquifers

The geology of Burkina Faso comprises three main types of geological formations (**Figure 1**; [4]), which are:

- The Paleoproterozoic (~2 Ga) e bedrock, consisting of metamorphic rocks also known as Birimian formations and igneous rocks. This bedrock belongs to the Baoulé-Mossi domain of the Man/Léo Ridge in the southern part of the West African craton and accounts for 80% of Burkina Faso's geological formations.

- The Neoproterozoic sedimentary cover extends across the western, northern, and southeastern margins and belongs to the Taoudéni and Volta basins.

- The Cenozoic formations of the terminal continental margin occupy small areas in the northwestern and far eastern parts of the country.

The Nakambé, Oubri, and Yaadga regions, which are the subject of this study, are almost entirely occupied by the Paleoproterozoic basement. Only a small portion of the Yaadga region, in its northwestern part, is covered by the Terminal Continental formations (**Figure 1**).

Crystalline rocks are impermeable in their undamaged state. However, tectonic stresses have developed networks of fractures within these compact formations that are sufficiently dense and open to convey and store infiltrating water. Overlying the mechanically formed discontinuities are physicochemical weathering processes that increase the porosity and permeability of the layer of rock exposed to atmospheric agents. The nature and thickness of the weathered overburden are determined by the nature of the bedrock, climatic conditions, and the intensity of

fracturing. Under these conditions, the bedrock and its overburden form a two-layer aquifer system comprising a discontinuous, transmissive lower reservoir and a continuous upper reservoir, which, due to its high porosity, serves as a storage reservoir [5].

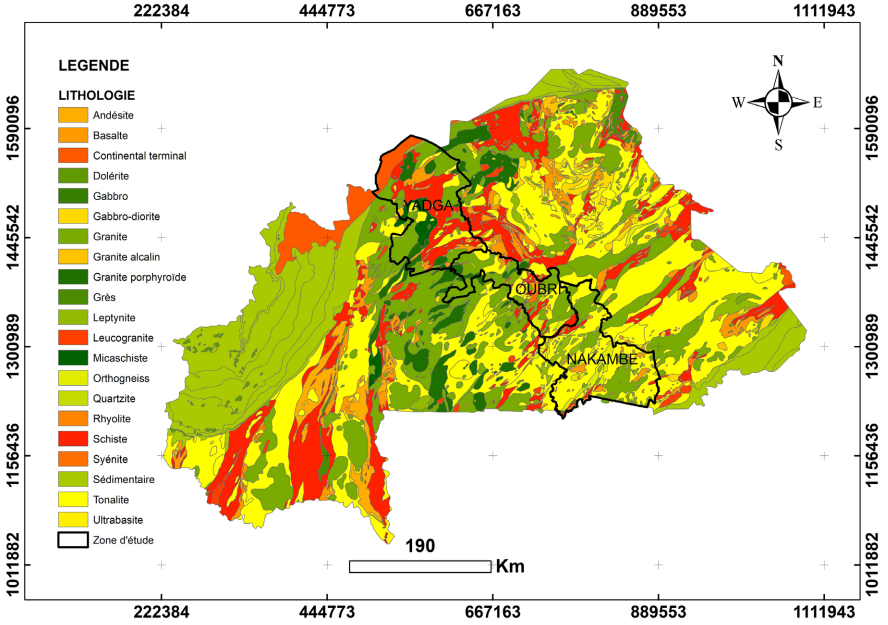

Figure 1. Location of the study area on the geological map of Burkina Faso [6].

In Burkina Faso, it is these aquifers in fractured environments or networks of fractures and fissures with highly variable widths and lengths that are exploited for village water supply programs, drinking water supply systems (AEP) serving major population centers, and the development of multi-village drinking water supply systems. The sustainability of this reservoir is determined by the location of the piezometric level relative to the top of the bedrock, by the continuity of recharge from weathered rock, and by the interconnection of the various fracture networks [5].

Depending on the geometry of the fissures and fractures and the degree of interconnection among the various fracture networks, these zones can induce regional flow that is sometimes significant [5] and is often responsible for the physicochemical variability of the water.

In this study, we focus on the source and geochemistry of arsenic in the aquifers of the lower confined groundwater table of the bedrock in Burkina Faso.

3. Materials and Methodology

3.1. Materials and Existing Data

For this study, the data used include technical borehole logs (FY13 and F8), the 1:1,000,000 geological map of Burkina Faso [4], the results of arsenic analyses from boreholes equipped with human-powered pumps conducted as part of Phase

II of the Program to Support the Development of the Water and Sanitation Sector in the Northern Region (PDSEAII-Nord) in 2006, and data from our own field and laboratory work carried out between 2020 and 2024. These data include physicochemical parameters and arsenic analyses. The PADESAII data were used to create the arsenic map and identify the boreholes for the water sampling campaigns from 2020 to 2024.

3.2. Sampling and Analysis Methods

3.2.1. Sampling Methods

For the 2006 campaigns, water was collected directly from wells equipped with hand pumps; for wells without such equipment, a specialized sampler was fabricated for sampling. Of the two samples collected from each borehole, one is mixed with hydrochloric acid to stabilize heavy metals, and the other is preserved as is. These samples are stored in coolers until they are sent to the analysis laboratory of the Burkina Office of Mines and Geology (BUMIGEB).

For the campaigns from 2020 to 2024, water samples were collected from boreholes equipped with submersible pumps and from the PD28 relief well located downstream of the Ziga Dam embankment, which has a continuous flow. The water from these boreholes shares a common characteristic: it contains arsenic.

New one-liter containers, previously cleaned with distilled water, were used. Before sampling, each container was rinsed at least three times with the water to be sampled. The samples were preserved with ice. With the exception of on-site analyses, all analyses were conducted the morning after the day of sampling.

3.2.2. Methods for Analyzing Chemical Parameters

Total arsenic content was measured using the BUMIGEB's AA-7000 spectrometer.

The characterization of major and trace metal elements was performed by the XENEXEL laboratory in Ouagadougou and the ONEA environmental laboratory in Ziga.

The various experiments were conducted at the station's laboratory and the ONEA environmental laboratory based in Ziga. An arsenator was used to monitor arsenic concentrations, and a multiparameter meter was used to measure pH, conductivity, and temperature both in situ and in the laboratory. Heavy metal analyses were performed using the DR3900.

The BV Dacheng (Zhejiang) Testing Technical Service Co., Ltd. laboratory in China analyzed the total arsenic content of each sample using an HJ 700-2014 inductively coupled plasma mass spectrometer and determined the arsenic speciation (trivalent arsenate and pentavalent arsenate) using the Atomic Fluorescence Spectrophotometer/PF52/E113-01. **Table 1** summarizes the various methods used by the XENEXEL laboratory.

The data obtained were analyzed using descriptive statistics (histograms, Pearson's correlation, principal component analysis) with Excel and XLTAT software, and the hydrochemical facies were determined using the Piper diagram. The re-

sults of interpreting the chemistry of the samples using the Piper diagram and binary diagrams provided insight into the mineralization of the groundwater, while principal component analysis (PCA) helped identify the sources of variability in the affected waters. All balances from the 2023 and 2024 sampling campaigns are less than 10%.

Table 1. Sample analysis methods used by the XENEXCEL laboratory.

Parameters	Reference Method	Instrumentation
Ag, As, Au, Ba, Be, Bi, Ca, Cd, Co, Cu, Fe, Hg, K, Li, Mg, Mn, Mo, Na, Ni, Pb, Se, Sb, Si, Sn, Sr, Ti, Tl, Zn, Zr	EPA Method 200.7, modified in-house	Agilent MP-AES 4210 Plasma Atomic Emission Spectrometer
Cl^-, SO_4^{2-}, NO_3^-, NH_4^+	Colorimetry	HANNA 83300 Spectrophotometer
HCO_3^-, CO_3^{2-}	TA-TAC Volumetry	Burette
Hardness	Calculated Method for Ca, Mg	
COD	Internal Titration Method	Burette
pH, Conductivity, Temperature, Eh	Electrochemistry	HACH HQ40d Multi-Parameter Meter

4. Results

4.1. Geological Cross-Sections

Based on the geological map adapted from [4] (**Figure 2**) and geological cross-sections of the boreholes, we observe that the aquifer formations consist of schists in the Yadga region, tonalites in the Oubri region, and granite in the Nakambé region.

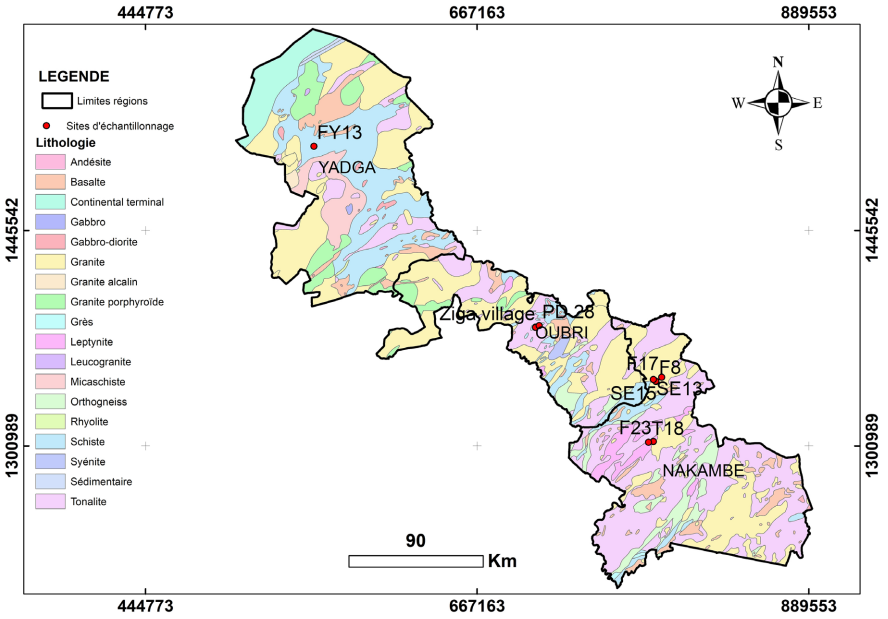

Figure 2. Location of boreholes on a geological map of Burkina Faso [6].

Analysis of the geological logs from the FY13 borehole in Ouahigouya and the F8 borehole in Koupéla (**Figure 3** and **Figure 4**) shows that the aquifers consist of pink mylonites and shales for the FY13 borehole in Ouahigouya and migmatites for the F8 borehole in Koupéla. These observations are consistent with those of [4] (**Figure 2**).

4.2. Water Chemistry

4.2.1. General Hydrochemical Context

In general, the results of the physicochemical analyses show that the parameters analyzed comply with drinking water supply standards, with the exception of arsenic. The presence of iron oxide (9.8 mg/L) in the water from PD28 in Ziga had been observed at the site since 2011. The results of the analyses are presented in **Table 2** below.

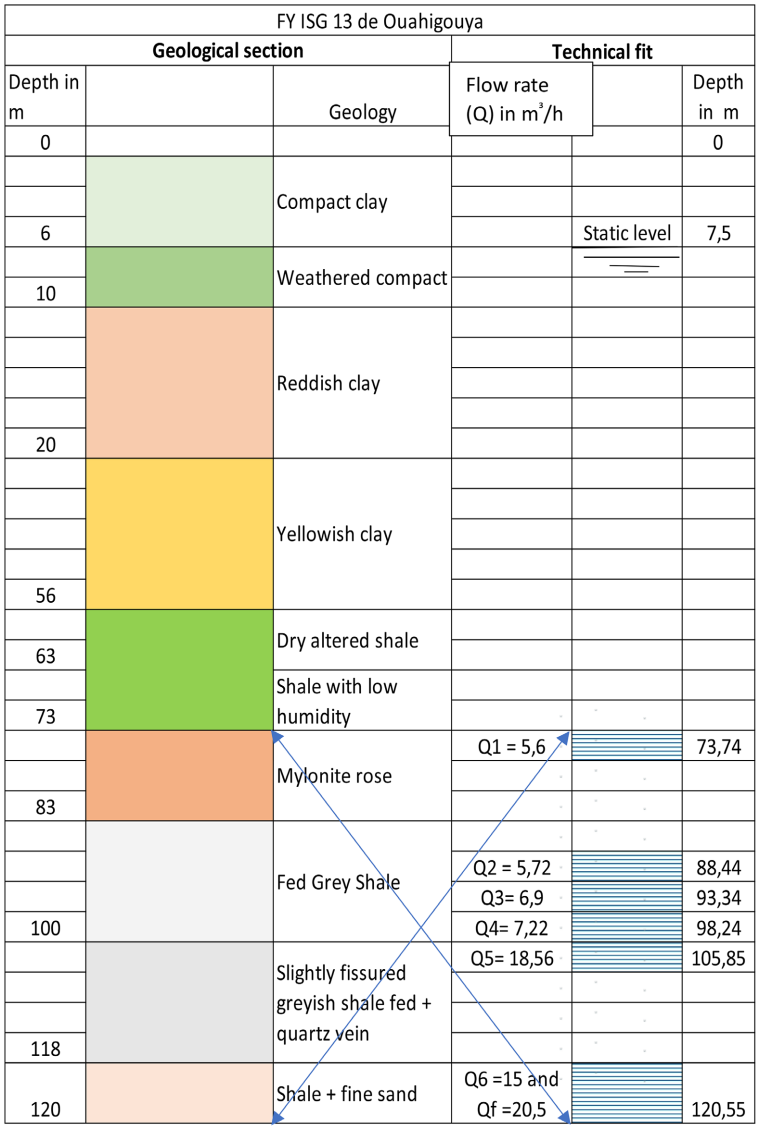

Figure 3. Technical specifications for the FY13 well in Ouahigouya (Source: ONEA, 2018).

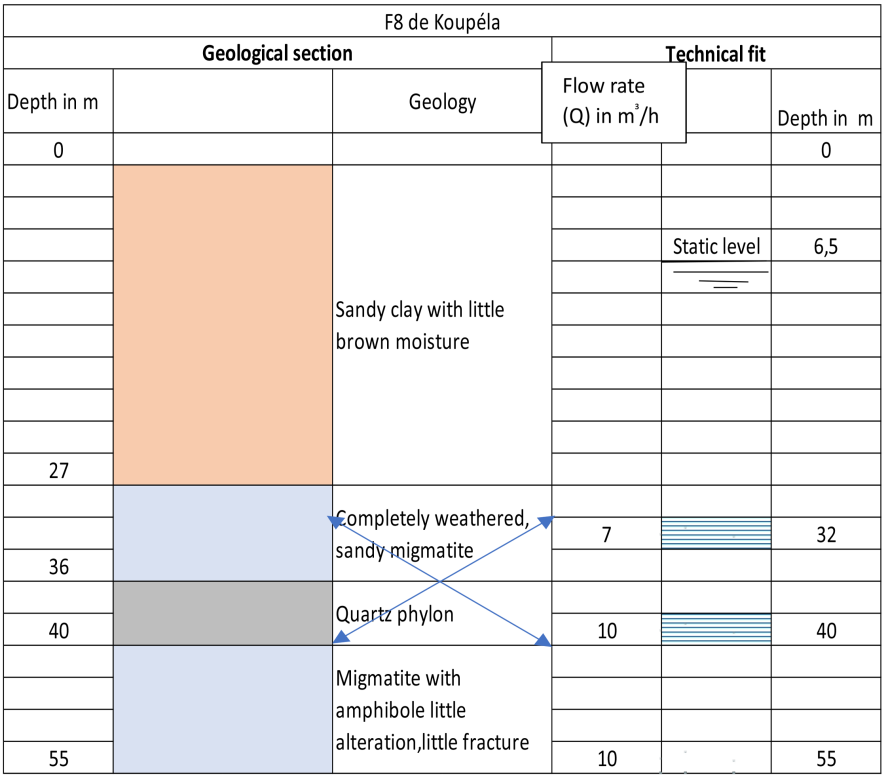

Figure 4. Technical data sheet for the F8 well in Koupéla (Source: ONEA, 2012).

Based on these data (**Table 2**), we observe that the order of abundance of cations and anions is as follows:

$$Ca^{2+} > Na^{+} > Mg^{2+} > K^{+}$$

$$HCO_3^- > SO_4^{2-} > NO_3^- > Cl^-$$

The variations in pH values between June and September (**Figure 5**) could be explained by the fact that June corresponds to low water levels and a more pronounced water-rock interaction, which releases basic ions such as Ca^{2+}, Mg^{2+}, and HCO_3^-, thereby increasing mineralization [7].

4.2.2. Piper Diagram

The Piper diagram indicates a calcium bicarbonate pole (**Figure 6**). Only sample F23 from Tenkodogo tends toward the chloride zone (16.9 mg/L for Cl^-), which could reflect pollution due to human activities. Indeed, chloride levels are generally low in natural groundwater from bedrock aquifers [7].

4.2.3. Correlations

Table 3 shows a positive correlation between Ca^{2+}, Mg^{2+}, HCO_3^-, SO_4^{2-}, Na^+, and As, as well as a very strong correlation (0.98) between conductivity and bicarbonates.

A very strong correlation (0.98) is also observed between conductivity and bicarbonates (**Table 3**).

Table 2. Results of physicochemical parameter analyses conducted at the XENEXEL laboratory and of arsenic (As) analyses conducted at the XENEXEL and BV Dacheng laboratories.

Well Identifiers	°C	pH	at 25°C	eH	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	HCO_3^- (mg/L)	CO_3^-	Cl^- (mg/L)	SO_4^{2-} (mg/L)	PO_4^- (mg/L)	NO_3^- (mg/L)	Fe^{2+} (mg/L)	NH_4^+ (mg/L)	As (µg/L) XENEXEL	As (µg/L) BV Dacheng	Hardness	COD (O_2/L)
F23	27.5	8.29	127	−76.1	17.1	9.3	19.8	3.4	59	0	16.9	2	0.44	89.5	0	0.05	0	0	81	0.3
F17	27.4	8.66	180	−97.9	42.8	19.5	21.5	5.6	246	14.4	3.8	6	0.3	12.5	0.004	0.1	16	14.5	187.3	0.5
SE18	27.4	8.57	173	−92.6	43.5	16.9	23.1	1.4	244	4.8	5.2	15	0.16	17.9	0.003	0.11	3	3.52	178.5	0.89
SE15	27.7	8.61	196	−95	57.9	27.2	27.2	5.3	288	19.2	1.6	39	0.16	0	0.001	0.11	0	1.06	256.7	0.48
F8	27.4	8.6	186	−94.4	46.7	22.8	23	2.5	266	12	5.3	11	0.37	21.4	0.004	0.14	20	18.5	210.5	0.32
SE13	26.9	8.74	145	−102.7	31	13.3	21.6	2.9	181	21.6	1	5	0.33	0	0.003	0.02	0	2.15	132.3	0.91
Drilling	26.7	8.16	67	−68.4	29.3	7.4	9.2	1.8	161	0	0	0	0.9	7.8	0.002	0	0	0.4	103.7	0.57
PD28	26.9	6.99	152	0.6	22.5	13.7	23	2.8	207	0	0.3	1	0.21	0	9.8	2.17	6	6.11	112.7	3.8
Q18	27	8.35	71	−79.7	9.7	7.1	10.7	3.4	85	4.8	0.3	3	0.4	1.9	0.002	0.05	0	0	53.7	1.01
FY13	28	7.5	612	−48.2	36.8	25.5	44.9	1.8	293	0	0.4	75	0.41	0	0.003	0.07	96	98.7	197.2	0.31
Minimum	26.7	6.99	67	−102.7	9.7	7.1	9.2	1.4	59	0	0	0	0.16	0	0	0	0	0	53.7	0.3
Maximum	28	8.74	612	0.6	57.9	27.2	44.9	5.6	293	21.6	16.9	75	0.9	89.5	9.8	2.17	96	98.7	256.7	3.8
Average	27.29	8.25	190.90	−75.44	33.73	16.27	22.40	3.09	203.00	7.68	3.48	15.70	0.37	15.10	0.98	0.28	14.10	14.49	151.36	0.91
Standard deviation	0.41	0.57	154.65	31.40	14.71	7.34	9.72	1.42	81.48	8.45	5.14	23.81	0.21	27.34	3.10	0.66	29.68	30.27	64.41	1.05

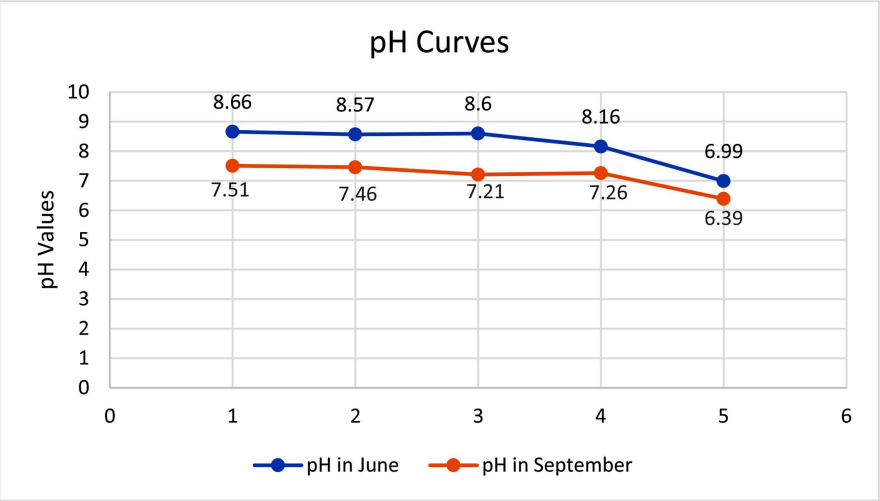

Figure 5. Comparison of pH values in June and September.

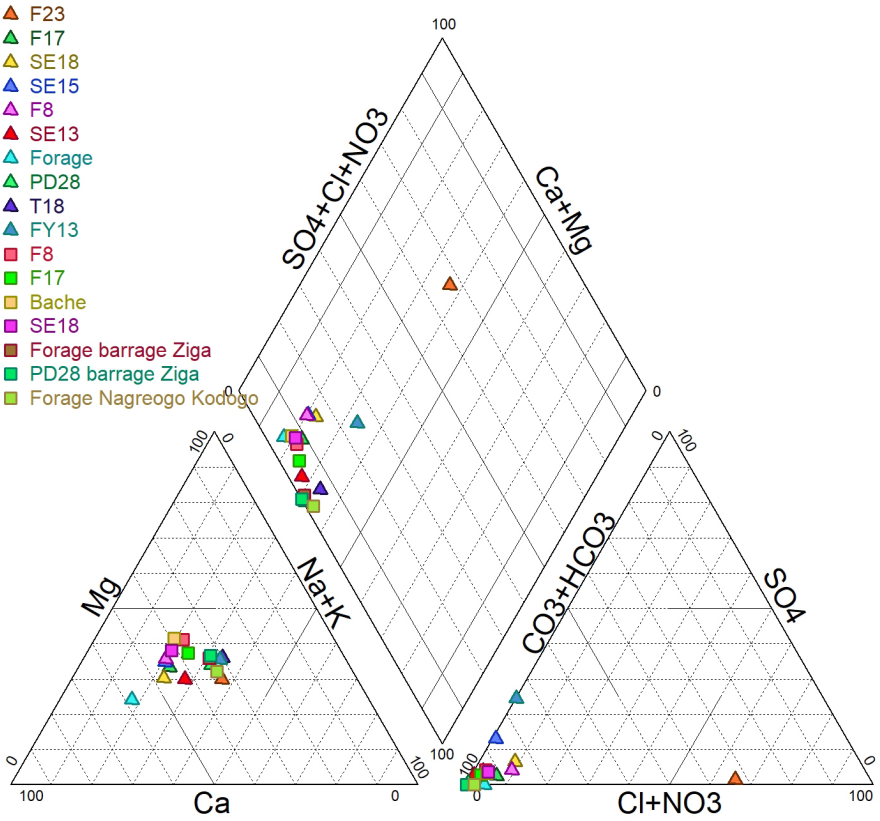

Figure 6. Piper diagram of the waters.

Table 3. Pearson's correlation between the various chemical element.

Variables	T˚C	pH	c25˚C	eH	Ca	Mg	Na	K	HCO_3^-	Cl	SO_4	PO_4	NO_3	Fer	NH_4	Ag	As	Zn	Dureté
T˚C	**1**																		
pH	0.497	1																	
c25˚C	0.983	0.426	1																

Continued

eH	−0.497	−1.000	−0.426	1															
Ca	0.973	0.541	0.975	−0.541	1														
Mg	0.984	0.450	0.997	−0.450	0.983	1													
Na	0.907	0.169	0.874	−0.169	0.837	0.870	1												
K	0.419	0.320	0.306	−0.320	0.332	0.331	0.540	1											
HCO_3^-	**0.986**	0.366	**0.987**	−0.366	**0.962**	**0.988**	**0.934**	0.392	1										
Cl	0.761	0.708	0.799	−0.708	0.856	0.818	0.447	0.034	0.726	1									
SO_4	0.882	0.611	0.917	−0.611	0.916	0.907	0.640	0.119	0.843	0.896	1								
PO_4	−0.839	−0.354	−0.763	0.354	−0.784	−0.774	−0.858	−0.385	−0.831	−0.505	−0.558	1							
NO_3	0.740	0.595	0.800	−0.595	0.854	0.803	0.473	0.018	0.713	0.923	0.931	−0.391	1						
Fer	−0.059	−0.714	−0.087	0.714	−0.160	−0.090	0.308	0.058	0.050	−0.505	−0.441	−0.323	−0.549	1					
NH_4	0.225	−0.388	0.162	0.388	0.034	0.152	0.495	0.313	0.281	−0.319	−0.176	−0.501	−0.457	0.814	1				
Ag	0.484	0.665	0.526	−0.665	0.572	0.564	0.144	0.036	0.456	0.868	0.623	−0.241	0.671	−0.548	−0.316	1			
As	**0.729**	0.169	**0.799**	−0.169	**0.689**	**0.784**	**0.653**	0.311	**0.760**	**0.561**	**0.744**	−0.304	**0.623**	−0.183	0.126	0.452	1		
Zn	0.332	0.063	0.468	−0.063	0.429	0.471	0.103	−0.554	0.386	0.674	0.531	−0.135	0.586	−0.171	−0.185	0.670	0.431	1	
Dureté	0.983	0.497	0.991	−0.497	0.995	0.996	0.857	0.333	0.980	0.840	0.916	−0.782	0.831	−0.125	0.095	0.570	0.741	0.452	1

4.2.4. The Different Forms of Arsenic in the Studied Waters

For the waters under study, the speciation results show that As exists in oxidation states III and V (Figure 7) in the groundwater of the three regions, and is therefore in inorganic form. These results are similar to those of [8]-[11]. According to these authors, at natural pH levels, free arsenic occurs primarily in inorganic form at oxidation states III and/or V. It therefore appears that within the pH range of the groundwater ($5.5 \leq pH \leq 9$), the predominant forms of As(V) are anionic: $H_2AsO_4^-$ and $HAsO_4^{2-}$; for As(III), the predominant form is the uncharged species: H_3AsO_3 [10].

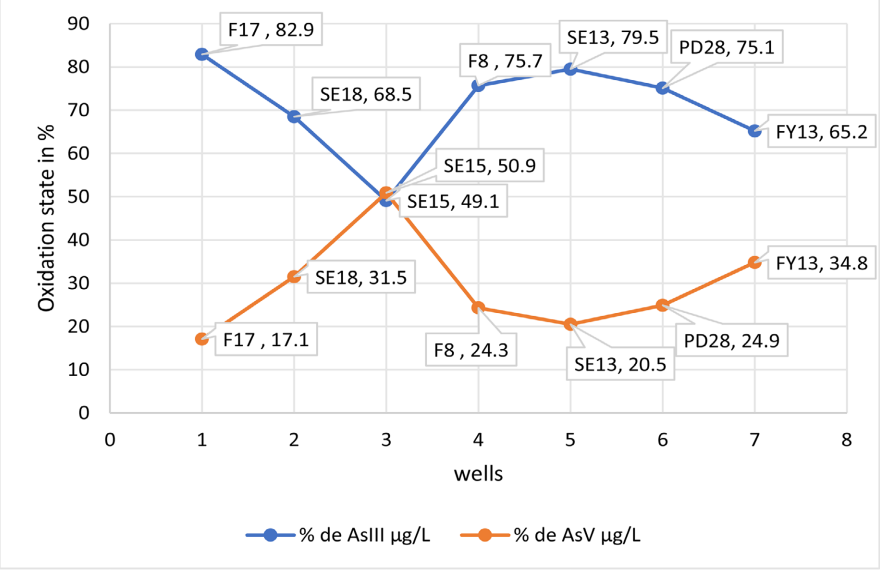

Figure 7. Oxidation state of As in water from different wells.

Figure 7 also shows that As (III) is predominant, which means that the water from all three regions is toxic. Indeed, according to [9] [12], arsenites are 60 times more toxic than arsenates. The ranking of the various mineral forms of arsenic according to toxicity, as per [13], is $AsH_3(g) > As_2O_3(s) > As_2O_5(s) > As(s)$. Arsine, with the formula $AsH_3(g)$, is the most toxic mineral compound of arsenic; exposure for just a few minutes to a concentration of 5 to 10 ppm of arsine can lead to the destruction of red blood cells (hemolysis) and kidney problems.

5. Discussions

Log data from boreholes FY13 and F8 showed that their aquifers draw water from Paleoproterozoic basement formations, notably schists, mylonites, and migmatites, which are potentially mineralized with arsenopyrite [4].

Furthermore, the order of abundance of the major ions ($Ca^{2+} > Na^{+} > Mg^{2+} > K^{+}$ and $HCO_3^- > SO_4^{2-} > NO_3^- > Cl^-$) indicates that the waters are calcium bicarbonate-rich and therefore consistent with those of the basement, according to [14].

The temperatures measured in situ ranged from 31.81˚C to 32.57˚C during the September field campaign and fall within the temperature range for deep boreholes (31 to 34 $^{\circ}C$) documented by Yameogo (2008). Their slight decline after September is attributable to recharge from rainfall. pH values ranging from 6.5 to 8.5 are also indicative of closed systems, particularly those of deep aquifers [15].

The calcium bicarbonate pole on the Piper diagram is a characteristic of bedrock aquifers, according to [14]. Neither the cation nor the anion triangles indicate a particular dominance of any single ion, suggesting that the water's mineralization is natural and, consequently, that the arsenic also has a natural origin.

These results corroborate those of the PEEN final synthesis report (2010), which indicated that the Birimian volcano-sedimentary formations are among the primary sites with high arsenic concentrations, as is the case with the shales in the Yatenga region (As = 98.7 µg/L for FY13). According to [1], arsenic and its derivatives (arsenides, sulfides, oxides, arsenates, and arsenites) are rare in nature but occur in some mineralized zones, and arsenopyrite (FeAsS) is the most abundant arsenic-bearing mineral in these zones. Authors such as [16] have also reported high arsenic concentrations (185 - 1025 mg/kg) in soils overlying the mineralized bedrock at the Ashanti Mine in central Ghana, which may have resulted from the excavation and exposure of arsenopyrite. Indeed, [17]-[19] have shown that arsenic is of geological origin, generally present in volcanic sediments, sulfide minerals, metal oxides, and upwelling from hydrothermal sources, which, through various biogeochemical processes, can dissolve in water and reach aquifers and watercourses.

Where arsenopyrite-rich veins are present in the geological environment, arsenic concentrations are locally high due to water-rock interactions. These concentrations may decrease or disappear over time following the complete dissolution of the vein.

However, in cases where arsenopyrite mineralization is disseminated (e.g., the Koupéla granite), there is a strong correlation between the rock's mineral components and arsenic. Thus, an increase in As concentration may be observed during low-water periods when groundwater has more time to interact with the rocks.

The positive correlation between Ca^{2+}, Mg^{2+}, HCO_3^-, SO_4^{2-}, Na^+, and As, as well as the very strong correlation (0.98) between conductivity and bicarbonates, indicates that the water's mineralization is natural and that the arsenic likely originates from the bedrock.

The very strong correlation (0.98) between conductivity and bicarbonates indicates that bicarbonates constitute the bulk of the mineralization and that this mineralization is natural.

Furthermore, since the analysis of major elements showed that the water is generally potable in terms of its physicochemical parameters, the very strong correlation between conductivity and bicarbonates indicates that the water's alkalinity consists primarily of hydrogen carbonates HCO_3^- [15].

Indeed, according to these authors, in bedrock aquifers, alkalinity stems primarily from the weathering of silicate minerals. Soil water rich in CO_2 attacks aluminosilicates, releasing constituents such as Na^+, Ca^{2+}, K^+, and Mg^{2+} into solution. The main product of this weathering process—and generally the first to form—is kaolinite, according to the following reactions.

$$2NaAlSi_3O_8 + 2H^+ + 9H_2O \rightarrow Al_2Si_2O_5(OH)_4\,(\text{Kaolinite}) + 2Na^+\,(\text{Sodium}) + 4H_4SiO_4\,(\text{Silica})$$

$$2KAlSi_3O_8 + 9H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2K + 4H_4SiO_4$$

$$Na + 2H_2CO_3 + 9H_2O \rightarrow \text{Kaolinite} + 2Na^+$$

These equations confirm the strong correlations between electrical conductivity, Ca^{2+}, Mg^{2+}, HCO_3^-, SO_4^{2-}, Na^+, and As, and also confirm that the arsenic originates from the rocks of the mineralized basement.

The principal component analysis (PCA) shows that the F1 (60.011%) and F2 (20.4%) axes account for more than 80% of the variance (**Table 4**) and confirm the natural mineralization of the water.

Table 4. Correlation between variables and factors.

	F1	F2	F3
Variability (%)	60.011	20.402	10.391
˚C	0.965	0.245	−0.064
pH	0.608	−0.531	−0.540
at 25˚C	0.973	0.194	0.097
eH	−0.608	0.531	0.540
Ca	0.985	0.094	−0.002

Continued

Mg	0.980	0.181	0.076
Na	0.778	0.609	−0.080
K	0.315	0.377	−0.752
HCO_3^-	0.943	0.329	0.046
Cl	0.900	−0.380	0.121
SO_4	0.949	−0.174	0.095
PO_4	−0.725	−0.495	0.165
NO_3	0.869	−0.373	0.159
Iron	−0.266	0.895	0.209
NH_4	0.002	0.899	−0.016
Ag	0.668	−0.513	0.099
As	0.742	0.138	0.221
Zn	0.479	−0.288	0.787
Hardness	0.987	0.139	0.038

Accounting for 60% of the variance, the F1 axis represents the first dimension of the PCA. On this axis, electrical conductivity, Ca^{2+}, Mg^{2+}, HCO_3^-, SO_4^{2-}, Na^+, and As are correlated (Table 5 and Figure 8 of the active variables). This confirms that arsenic originates from the same source as these mineral elements (the bedrock, which in this case is the basement).

Table 5. Relationship between observations and axes.

Coordinates of the observations	F1	F2	F3
Obs1	4.231	0.667	0.691
Obs2	2.568	0.571	−2.758
Obs3	2.649	−1.464	1.931
Obs4	1.642	−1.480	−0.106
Obs5	−3.647	−1.344	−1.065
Obs6	−2.203	4.315	0.718
Obs7	−5.240	−1.266	0.589

The strong correlation between sulfates and As (0.74) indicates that As originates from sulfide minerals. The angular deviation between the two in Figure 8 can be explained by dissolution, which led to the decoupling of the two parameters [3]. Indeed, the retention of arsenic through adsorption is a possible process. Ar-

senic's high affinity for metal oxides [10] means that arsenic would normally undergo much greater retention through adsorption than SO_4. Furthermore, if arsenides or secondary oxides are the sources of arsenic in groundwater, it is possible that the SO_4^{2-} released during the initial oxidation of sulfide may have been leached from the aquifer long ago [1].

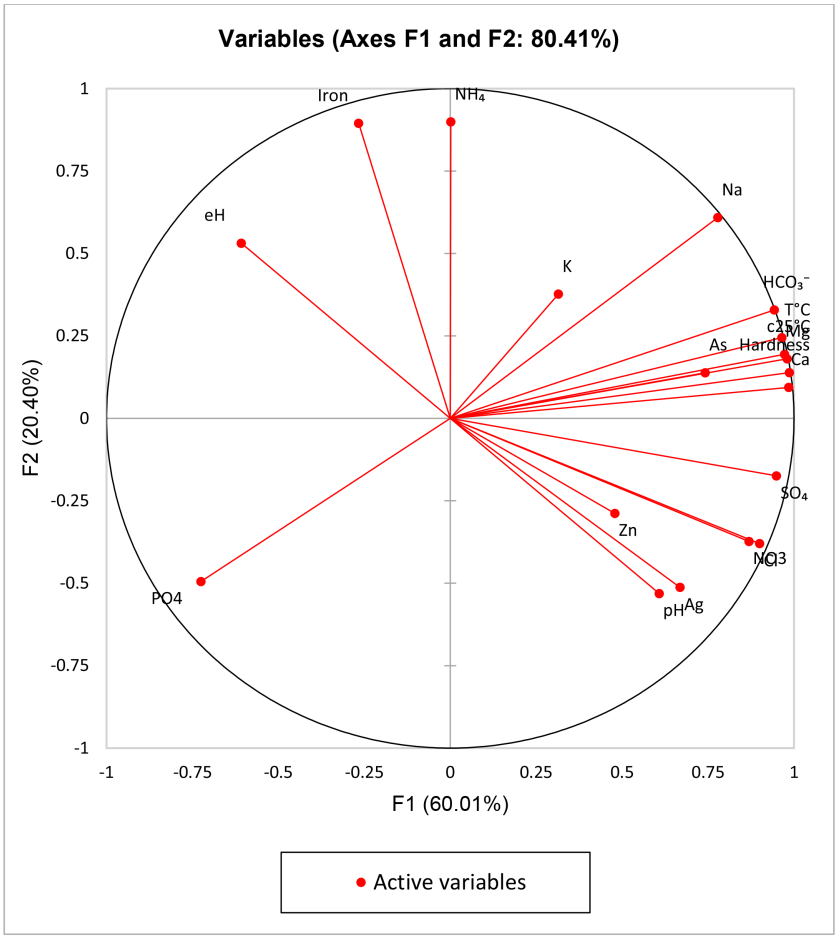

Figure 8. Active variables on the axes.

Arsenic concentrations in aqueous media can also be explained by oxidation and/or precipitation reactions depending on atmospheric conditions [20], as shown by the following equations:

➢ $4FeAsS + 13O_2 + 6H_2O = 4Fe^{2+} + 4HAsO_4^{2-} + 4SO_4^{2-} + 8H^+$

Here, arsenic is released, along with iron and sulfate.

The oxidation of pyrite, FeS_2, by oxygen can be described by the following reaction:

➢ $FeS_2 + 7/2\,O_2 + H_2O = Fe^{2+} + 2SO_4^{2-} + 2H^+$

Arsenic treated with nitric acid yields arsenic acid, which is present only in an aqueous medium. This slow oxidation reaction is sometimes described as dissolution.

$$3\,\mathrm{As}\left(\text{crystalline solid}\right)+5\,\mathrm{HNO_3}\ \mathrm{aq}\left(\text{strong concentrated acid}\right)+2\,\mathrm{H_2O}$$
$$\rightarrow 3\,\mathrm{H_3AsO_4}\ \mathrm{aq}\left(\text{arsenic acid}\right)+5\,\mathrm{NO\ gas}$$

The poor correlation between iron and As indicates that the As originates from other sulfides such as orpiment (As_2S_3) or realgar (As_2S_2) in mineralized zones [1] or in the form of native arsenic, arsenides, and arsenates.

Observations 1 and 2 (4.231 and 2.568) in **Table 5** and **Figure 9** confirm the correlations between axis F1, Ca^{2+}, Mg^{2+}, HCO_3^-, SO_4^{2-}, Na^+, and As. These results confirm that axis F1 is the primary axis of mineralization and that the arsenic in the studied boreholes originates from the mineralized basement.

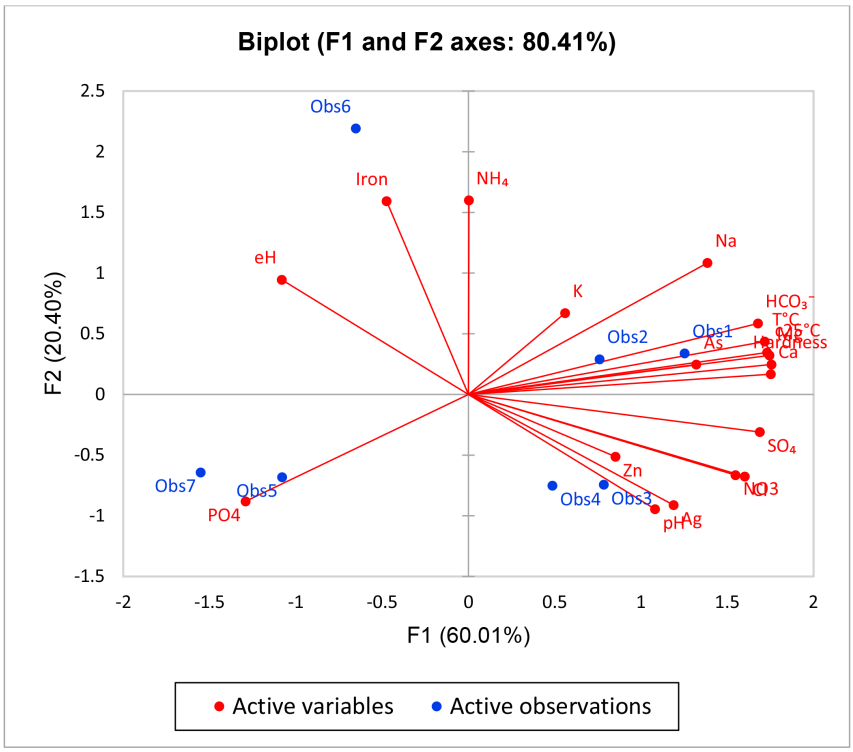

Figure 9. Relationship between observations, variables, and axe.

Arsenic speciation analysis also showed that As(III) is the predominant form, indicating that we are in a reducing environment (bedrock aquifers).

Furthermore, according to [1], the symptoms caused by prolonged exposure to arsenic appear to vary among individuals, population groups, and geographic areas. There is therefore no universal definition of arsenic poisoning, which complicates the assessment of the burden of disease. In the mineralized bedrock, the predominance of the more toxic As(III) as is the case here could explain the manifestations of arsenic-related toxicity (cancers, hyperkeratosis, melanosis, and pigmentation) in the northern region, and more specifically in Yatenga Province [21]. In this region, arsenic concentrations often exceed the WHO standard of 10 µg/L. High concentrations of up to 1630 µg/L have sometimes been recorded and are associated with Birimian volcanic-sedimentary formations mineralized with

sulfides, including arsenopyrite [3]. This is the case for the FY13 borehole in Ouahigouya (98.7 µg/L).

6. Conclusion

Based on well logs, physicochemical analysis, and arsenic speciation, this study shows that the arsenic in the studied waters originates from the mineralized basement. The As(III) form, one of the most toxic Ar, predominates because it is characteristic of reducing environments such as the aquifers under study. The study also shows that arsenic speciation which is not taken into account by legislation and knowledge of the source of arsenic are essential for understanding the symptoms resulting from exposure.

Author Contributions

Conceptualization, Kabore Zourata; methodology, Kabore Zourata; software, Kabore Zourata; validation, Kabore Zourata, Naba Seta, and Nakolendoussé Samuel; formal analysis, Naba Seta; investigation, Kabore Zourata; resources, Kabore Zourata; data curation, Nakolendoussé Samuel; writing—original draft preparation, Kabore Zourata; writing—review and editing, Naba Seta; visualization, Naba Seta; supervision, Naba Seta; project administration, Kabore Zourata; funding acquisition, Kabore Zourata. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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