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UNDERSTANDING GROUNDWATER POLLUTION OF SISSILI CATCHMENT AREA IN BURKINA-FASO

COMPREHENSION DE LA POLLUTION DE L'EAU SOUTERRAINE DU SOUS BASSIN VERSANT DE LA SISSILI AU BURKINA-FASO

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ABSTRACT

In Burkina Faso, groundwater in hard rock aquifers represents a major asset for the rural populations. But this water is subject to anthropic and natural pollutions as is the case with the sub-watershed of Sissili for which few studies are available. Therefore, it is appropriate to follow their state of pollution. This study aims at a physicochemical characterization of the groundwater quality in order to highlight its relationship to the human and natural environments. As a result, 67 groundwater boreholes were analyzed according to WHO recommendations (2008) and techniques for assessing the quality of groundwater described by Rodier (2009). The results show that the chemical quality of water comes from several processes, which leads to a very complex situation. Water is strongly corrosive and is saturated with calcites. The groundwater is bicarbonated calcic and magnesian. The values of the electric conductivity of water show that the groundwaters are slightly mineralized with a maximum of 639 µ*S* / cm. The value of the pH oscillates around 7 which is generally acid. The chemical hydro analysis revealed the contents in arsenic, fluorine, cyanide, lead, iron, potassium, phosphate, and aluminum exceeding

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WHO recommendations. The attention must be paid to the minor ions, heavy metals, and metalloids.

Keywords: Analyze factorial, groundwater, Physicochemical, Hydrochemical, Hydrofacies, Sissili

RESUME

Au Burkina Faso, les eaux souterraines en milieu de socle représentent un atout majeur pour les populations rurales. Mais ces eaux sont confrontées à une pollution anthropique et naturelle comme c'est le cas du sous bassin de la Sissili où peu d'études existent. Aussi, convient-il de suivre leur état de pollution. L'objectif vise à une caractérisation physico-chimique de la qualité des eaux souterraines afin de mettre en évidence leur relation avec les environnements. Pour ce faire, soixante-sept puits de forage ont fait l'objet d'analyses selon les techniques d'évaluation de la qualité de l'eau décrites par Rodier (2009) et des recommandations de l'OMS (2008). Les résultats montrent que la qualité chimique des eaux provient de plusieurs processus, ce qui entraine une situation très complexe. Les eaux sont fortement corrosives et présentent une saturation en calcites. Les eaux souterraines sont classées bicarbonatées calciques et magnésiennes. Les valeurs de la conductivité électrique de l'eau montrent que les eaux souterraines sont faiblement minéralisées avec une valeur maximale de 639 µ*S*/cm. La valeur du pH oscille autour de 7, généralement acide. L'analyse hydro chimique a révélé des teneurs en Arsenic, fluor, cyanure, plomb, fer, potassium, phosphate et aluminium dépassant les recommandations de l'OMS. L'attention doit être portée sur les ions mineurs, métaux lourds et les métalloïdes.

Mots-clés : Factor analysis, Eau souterraine, Physico-chimique, Hydrochimie, Hydrofaciès, Sissili

INTRODUCTION

The research and the exploitation of groundwater in hardrock aquifers remained at the prospective stage compared to similar aquifers (Maréchal and *al.,* 2006; Courtois and *al.,* 2009; Bamba and *al.,* 2013; Sako and al., 2016, Soro *and al.,* 2017). The Sissili sub-catchment belongs to these zones where the groundwaters are generally located in the weathered zones and borrow privileged corridors which are fractures (Rabilou and *al.,* 2018). Weathered layers and fractured rocks are products of the effect of prolonged in situ chemical weathering of the source rock and tectonic movements, respectively (Dewandel and al., 2006). Consequently, the chemistry of groundwater in hardrock aquifers is directly related to the mineralogical composition of the bedrock and the various processes of deterioration (Sako, 2016). Previous work carried out in the sub-basin (Sawadogo, 1974, 1984) aimed to find solutions to the problem of drinking water supply through the exploitation of groundwater. Today, there is a deficit in rainfall, drying of surface water, and a decrease in rainfall which contributes to the non-dilution of water and reflects that groundwater resources are frequently exposed to various sources of contamination. This sub-basin has, for a few years, been subjected to a strong anthropic activity, in particular mining, and agricultural activities, but also in association with mineralization. The old water analyzes are incomplete and were carried out using portable Kits and the doubt on their precision led us to review the state of pollution and its evolution (Savadogo, 1984).

The Burkinabé State, with the aim of improving access to water for the rural population, regularly launches a qualitative monitoring campaign and monitoring the risks of pollution linked to water resources. The 2012 analysis campaign showed a high degree of certain chemical parameters in the Sissili sub-basin which can affect the water quality, and makes hydrochemical studies of these environments complex. In the Sissili sub-basin, this pollution has a strong impact on the taste of water and the health of the rural population, which leads to the closure or abandonment of some groundwater wellbores (Sauret, 2007, Ouagando, 2008). (Sauret, 2005; Ouandaogo, 2008). In this study, we selected 67 boreholes from the 2012 campaign, of which we know the geological framework. The objectives of this study are to characterize the hydrochemistry and water quality of the aquifers captured by the boreholes. This will allow us to assess the state of evolution of water quality, the age of some waters, and to identify the origin of pollutants from basement boreholes using different methods. This will allow us to answer the question of how to understand the origin and the mechanisms of the different types of the identified pollution in order to assess their evolution.

STUDY ZONE

The Sissili sub-watershed is located in the south of Burkina Faso (Figure 1). It covers an area of 7,559 km2. It extends between longitudes 1 ° and 2 ° West and latitudes 11 ° and 12 ° North. The relief is characterized by the location of small rock massifs. There are also small drearies (elephant back), chaos of balls (granite) and barely marked croups. The average slope of the hydrological units is 2.03m / km, the overall slope index is 0.2m / km.

The Sissili sub-basin brings together 3 types of land use namely agricultural zones, pastoral zones and wetlands. The agricultural zones include rainfed crops, crops under agroforestry parks or agroforestry territories, mosaics of fallow crops and important natural areas and forest and irrigated plantations. These are the most important from the point of view of space occupation. This tree cover is generally equal to or greater than 25% of the total area. The mosaic areas / natural spaces are vast areas of natural formations (savannah or steppe) dotted with fields. These are the grazing areas where small ruminants are kept especially in the winter season. It’s Sudanese (southern Sudanese) climate located south of the 11 ° 30'N parallel covers the entire Sissili sub-basin. It is characterized by an average annual rainfall greater than 900 mm; a rainy season that lasts more than 6 months of the year, fairly low annual thermal amplitudes.

Hydrographically, the study site is crossed by the Sissili River (tributary of the Nazinon) which gives its name to the province. It is 322km long with an average slope of 1.48m / km over the first 42 km.

From a geological point of view, the formations encountered are varied and can be grouped into two large geological groups of Proterozoic ages namely the plutonic group and the sedimentary volcano group. In terms of hydrogeology, hydraulic productivity is defined by geological formation. Plutonic formations such as granodiorites, tonalites, and quartziferous diorites, have the highest hydraulic productivity with permanent flow rate that can exceed 20 m3 / h. Then follow the formations such as orthogneisses, the mica schists with disthene, leptynites with garnet, the mica schists with garnet, sillimanites and staurolites that show an average productivity of about 20 m^3/h.

Low hydraulic productivities are generally encountered in volcano-sedimentary formations. It can exceed 5m3 / h but it can drop due to blockages. The weakest are at the level of intrusive plutons and can hardly reach 2m^3 / h.

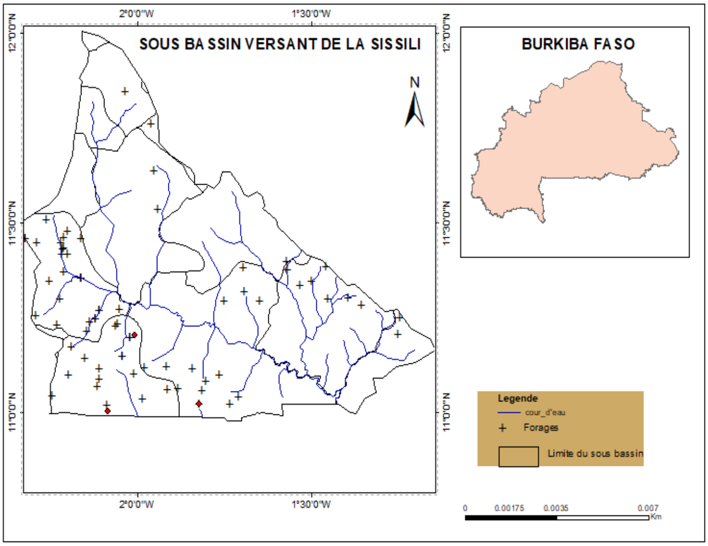


Figure 1: Localization of the study zone of study

MATERIALS AND METHODS

Sampling

Water samples from 67 boreholes worked out from the 2012 sampling campaign for the detection of harmful chemical elements in high concentrations in the waters of certain localities, were provided according to the databases of Burkina.

As part of the study, twenty-three parameters on water quality were taken into account in order to characterize the overall quality of the water and identify any pollution. These analytical parameters are grouped into physical parameters, chemical parameters, heavy metals and metalloids. The depth of the boreholes varies from 30m to 80m. The water sample is taken from the pump outlet fitted to the borehole which undergoes intensive pumping. For each sampling point, four water samples are taken from flasks and five samples from mine sites for analysis.

Methodology

Many countries developed their own methods, adapted to the local conditions and while being possibly inspired by one or other existing methods.

Correction and critical

Thus, the methodology used within the framework of this study is, at first, the method of correction and critical. The first step is to verify the administrative division of the sub-basin. At this stage, the geographic coordinates of the boreholes were assigned to the village coordinates and were corrected and harmonized. Second, the correction consists of a statistical analysis to fill in the missing data. And thirdly, the correction consists of the ion balance, since in previous studies sodium and potassium were not taken into account which made the results incomplete. It reflects the state of equilibrium between the cations and anions of the major elements. The comparison of the two global sums anions (A-) and cations (C +) makes it possible to identify the samples which deviate too far from the bisector where there is an equivalence between the anions and the cations and to eliminate them (Ouagando, 2008).

Multivariate analysis:

The approach of multivariate statistical analysis methods is established to study the phenomena that are at the origin of water mineralization and is based on the principal component analysis. Statistical techniques such as mode R have been widely used to decrypt samples of groundwater and/or physicochemical variables. According to Kumar and Muttan (2006) and Pages (2004), a high correlation analysis close to +1 or -1 means a good relationship between two variables, positively or negatively correlated. A value around zero does not signify any relationship between them. A correlation greater than 0.7 corresponds to highly correlated data while a correlation between 0.5 and 0.7, corresponds to moderately correlated data. This analysis makes it possible to synthesize and classify a large number of data in order to extract the main factors that are behind the origin of the simultaneous evolution of the variables and their reciprocal relationships. In addition, this study will determine the different hydrogeochemical facies, the origin of the mineralization, and the chemical facies of the waters. Statistical analysis was carried out using software R.

Determination of the hydrofacies using the piper's diagram

To study the chemical evolution of Sissili groundwater, the chemistry of the water samples was introduced into the Piper mineralization diagram. It has three parts, including the triangle of cations, the triangle of anions, and a rhombus used to determine the Hydrofacies. The study of water behavior will be considered in each part of the diagram (Lghoul, 2014).

Aggressivity of groundwater

From the contents of major chemical elements, one can know the state of equilibrium of the waters with respect to primary or newly formed minerals. This makes it possible to know certain properties and behaviors of the waters, in particular, the corrosive or scaling character. To do this, the saturation index (IS); IS = log (PAI) - log (T) of groundwater used to study different forms of mineral phases such as precipitation, dissolution and adsorbed phases, and the Ryznard index or Ryznard stability index (RSI); RSI = 2pHs - pH which allows defining the aggressive or scaling tendency of water were calculated.

RESULTS AND DISCUSSIONS

Correction and critical

This consists of finding the boreholes in the municipalities according to the hydrogeological division. However, the major difficulty lies in the fact that the coordinates of the villages are assigned to those of the boreholes. At this stage, a recognition campaign was initiated to correct and harmonize the said coordinates while verifying their operating state. In addition, some parameters were missing or had negative values (Figure 1). We then performed a statistical analysis to fill in the missing data. The principle is to select the data which are similar and which are closest to the data located at a distance. The correlation matrix (Table 2) gives us an idea of the correlation between two variables. Finally, according to the results of analyzes carried out, the ionic balance was checked and taking into account certain high ionic loads which border those of the results of Ouagando in the same basement environment. The limit of validity of 10% was retained. Firstly, after eliminating all the analyzes which have a balance greater than 10%, the data of all the samples were processed without considering their origin. In a second step, the treatment was carried out after the separation of different groups according to the origin of the water and the depth on each of the water families.

Characterization of the physicochemical parameters and Origin

Based on the results of the samples of the nature of water, it was possible to establish a synthesis of the analyses carried out. Table1 gives the results of the physicochemical analyses.

Table 1: Average statistics of physicochemical and chemical parameters of groundwater

	T°	**PH**	**Ce**	**Ca^{2+}**	**Mg^{2+}**	**Na^+**	**K^+**	**Fe^{2+}**
Average	30,31	6,47	274,77	28,43	13,39	6,82	2,28	0,19
Standard deviation	0,93	0,64	131,65	31,71	21,11	4,95	1,85	0,48
Minimum	28,30	5,69	96,60	7,80	-135,08	1,90	0,80	0,00
Maximum	32,00	10,93	639,00	265,44	47,87	29,20	14,10	2,90

	$NH4^+$	**Cl^-**	**$SO4^{2-}$**	**$NO2^-$**	**$NO3^-$**	**$Po4^-$**	**P**	**F**
Average	0,05	1,46	4,43	0,02	6,51	0,88	0,29	0,49
Standard deviation	0,13	1,56	6,06	0,03	10,60	0,70	0,23	0,40
Minimum	0,01	0,30	0,00	0,00	0,44	0,18	0,06	0,01
Maximum	1,02	9,90	31,00	0,22	52,80	4,63	1,51	1,95

	CN^-	**Al**	**As**	**Cr**	**Pb**	**Zn**	**$HCO3^-$**
Average	0,07	1,67	15,69	0,01	0,02	0,12	139,55
Standard deviation	0,10	1,29	15,21	0,03	0,02	0,22	88,86
Minimum	0,00	0,00	2,76	0,00	0,00	0,00	0,00
Maximum	0,41	5,37	76,42	0,22	0,07	1,44	341,97

Results of the physical parameters analysis

Temperature

The temperature ranges from 28.3 °C (Kilounguin) to 32 °C (darsalam), with an average of 30.31 °C. These temperatures are on the whole quite higher than the air temperature which is 25 °C. Their daily monitoring would be very important to observe the vulnerability of waters to pollution. Indeed, studies carried out by Ouagando (2008) and corroborated by Ahoussi et al. (2012), Eblin et al. (2014) have shown that groundwater, according to the daily variations in the atmosphere, is vulnerable to pollution.

Potential for hydrogen

The groundwater's potential of hydrogen varies from 5.69 (darsalam) to 10.93 (Pore), with an average of 6.47 which is acidic. The higher pH value would indicate a basic aquifer. The lower pH is linked to acidic drainage processes related to the widespread gold panning in the locality. The low pH values can also be linked to the low carbonate minerals contained in the altered layer (Sako, 2016).

Electrical conductivity

The electrical conductivity varies between 96.6 µS / cm (Yelbouga) and reaches a maximum of 639 µS / cm (Karaya). The high values are minimal compared to the standard of 1000 µS / cm. While in reports of drilling studies and during field trips in Sissili province, the population complains of difficulties in urinating. This is due to the strong mineralization. It can be said that the low conductivity of drilling water reflects the low mineralization.

This reflects the independence of the water pockets from each other. Mineralization corresponds to all of the dissolved salts contained in water (Kuicha et. Al., 2013). The cations are in the following order of importance: Ca2 +> Mg2 +> Na +> K +.

Calcium

Calcium is the most abundant cation in the groundwater of the sub-basin. The average concentration is of 28,43 mg/l (Table 1). The concentration varies between 7.8 mg/l and 265.44 mg/l and no value exceeds the standard. The high concentration values come from boreholes whose waters have a high mineral load compared to all boreholes. According to Vicat et al. (2002), this could be explained by the leaching of the profile of soils rich in calcium minerals. The low calcium concentration in groundwater can be explained by the presence of plagioclases present on shales and granito-gneiss in the sub-basin.

Magnesium

The magnesium concentration values are between 0.29 mg / l and 47.5 mg / l. The maximum values are much more observed at the level of the province of Nahouri. It can be assumed that their composition is probably influenced directly or indirectly by natural pollution phenomena. The geology of the province of Nahouri also shows us that this part of the basin is essentially composed of shales. However, it can also come from the alteration of ferromagnesian minerals from biotites or amphiboles.

Sodium

The values for the concentration of this element are between 1.9 mg/l and 29.2 mg/l, thus indicating that no value exceeds the recommendation of 200 mg/l. Its presence in groundwater shows that it comes from the decomposition of feldspar but also from the alteration of micas. This can be explained by the fact that the concentration of sodium (Na^+) is higher than that of potassium (K^+), which translates according to Kuicha (2013), on the one hand, by the greater stability of the feldspar and potassium micas and on the other hand by the absorption and mobilization of positive potassium ions (K^+) in the minerals newly formed during the alteration. The concentrations of these two ions are also moderately correlated (R2 = 0.64). The dominance of sodium ions (Na+) over potassium ions (K^+) is also due to the selective absorption of clays; potassium (K^+) having a higher atomic mass than sodium (Na^+), it follows that the waters contain more sodium than potassium (Kuicha, 2013; Ahoudi et al., 2015).

Potassium

This element shows great variability with the concentration values of a minimum of 0.80 mg/l and a maximum of 14.1 mg/l. According to the 10 mg/l recommendations, only three boreholes located in the village of Tabou exceed this limit. These high and punctual levels show that the waters are subject to anthropogenic pressures. The low values can be explained, according to soil scientists, by the fact that potassium is 10 times more abundant than its absorption by plants. The sodium and potassium ions could come from the decomposition of minerals such as feldspaths, pyroxenes, micas and amphiboles, and ionic exchanges with clay minerals and as well as pollution from human activities (Kuicha, 2013).

Bicarbonates

Bicarbonates make up the bulk of the mineralization of waters and dominate the other anions. The concentration values are between 32.22 mg/l and 341.97 mg/l. Above 200 mg/l this assumes that CO_2 is produced in the aquifer from the mineralization of organic matter. Nevertheless, it can be said that its high concentration in groundwater can translate the leaching of rocks by infiltration of well water (the dissolution of CO_2 originating from the atmosphere and the soil). In addition, the alteration of the feldspars releases ions which, when combined, give bicarbonate when it contains carbonate minerals. Its low content can also be explained by the pH values of groundwater since the release of bicarbonates is favored when the pH of the medium increases (Michard, 2002).

Nitrates

The nitrate concentrations are between 0.44 mg/l and 52 mg/l. Only three of the samples do not meet the authorized standard of 50 mg / l in the municipality of Bieha. Several sources are possible in this specific case in addition to the normal nitrogen cycle in water (fertilizer, from oxidation, animal husbandry, industry). So groundwater is vulnerable to point sources of pollution. This phenomenon can be explained by the contribution of pollutants from the immediate surface of each borehole, since there is no correlation between nitrate (NO_3^-) and chlorine (Cl^-) and between nitrate (NO_3^-) and sulfate (SO_4^{2-}).

Chlorides and Sulfates

Chlorides and sulfates have low values compared to the accepted standard in Burkina, ie 250mg/l each. According to Travi et al. (1985) and Ahoussi et al. (2012), their low values show that they come from granites and its presence is a characteristic of basement countries. However, the studies of Sawadogo (1984) and Sako (2016), carried out in Burkina, have shown a correlation between chlorine and magnesium with high concentrations. Kuicha's study (2016) in Yaoundé also shows a correlation between chlorine, sodium and potassium. However, this is not the case in the results of the analyzes. These parameters are not correlated in this study, which can be explained by the fact that the water from the boreholes is received by direct infiltration from the unclogged rock. The infiltration of these waters through the alterites undergoes leaching which leads to a low concentration of chlorine. Also the clay cover does not make the circulation of water difficult, if this were not the case there would be an accumulation involving significant concentrations. The low values of sulphate show that the geological formations are poor in sulfurous minerals like pyrites, and its presence would be linked to the decomposition of these.

Minor ions

The concentrations of minor ions show anthropogenic pollution. Fluorine has concentrations varying between 0.01 mg/l and 1.95 mg/l, while the rate not to be exceeded is 1.5 mg/l. There are two samples that exceed this standard. This can be explained by the granitic intrusion into local lithology (BGS, 2002). They are scattered over all three provinces and are located in agricultural fields. The fluorine in water comes mainly from the dissolution of natural minerals found in rocks and in the soils with which water reacts. Fluorite (CaF_2), cryolite (Na_3AlF_6), fluorapatite ($Ca_5F\ (PO_4)$), and micas are the main minerals that contain it (Matini, 2009). The waters are rich in iron with contents varying between 0.00 mg/l and 2.95 mg/l, for a standard of 0.3 mg/l in Burkina Faso. Nevertheless, twelve samples exceed this standard. Studies on the chemistry of the breastplates show that there can be an accumulation in the breastplate of five times more Fe than the rocks contain. But the low values indicate that although iron is present in the lateritic horizons, it is not mobilized by water infiltrated under climatic conditions. The study carried out by Sako (2016) in the central area of Burkina, shows that the high concentration of Fe_2^+ present in groundwater is due to the presence of iron at the level of the altered layer which is generally lateritic.

Correlation between the different physico-chemical and chemical variables

To do this, 67 samples are submitted to this correlation. Table 2 shows the correlation matrix between the different ions and physicochemical parameters.

The significant links which exist between the different parameters taken two by two are given by the correlation matrix in Table 2. These links are translated by the different correlations which exist between the studied variables. There is a correlation between HCO_3^- and Ca_2^+ (R2 = 0.61), Mg_2^+ (R2 = 0.79), Na^+ (R2 = 0.60) and between ammonium and iron (R2 = 0.87). It is the alteration of the silicates which leads to an increase in the concentrations of cations and bicarbonates. The infiltrated water crosses the ground, becomes charged with CO_2^- and this water rich in CO_2^- will attack the aluminosilicate minerals (plagioclase, biotite, etc.) of the reservoir rock. According to Ouandaogo (2008), the alteration of silicates increases the concentrations of cations and silica. As the soluble elements are washed out, the insoluble parts remain on-site as they are or recombine with the available ions. It is charged with CO2- and this water rich in CO_2^- will attack the aluminosilicate minerals of the rocks of the reservoir. Poorly crystallized intermediate compounds, sections of silicate chains and ions in solution recombine into neoformation minerals, mainly clays. Organizations can intervene at all stages of this process. They provide in particular mineral or organic materials.

The relationships between cation and HCO_3^- concentrations are similar to those highlighted by Ouandaogo (2008). We can also note a less significant correlation between cations and HCO_3^- deducing that the alteration of silicates is not only influenced by these ions. This observation confirms that of the principal component analysis which indicates that potassium and sodium could have an external origin to the water-rock system, which is the consequence of a strong anthropic pressure.

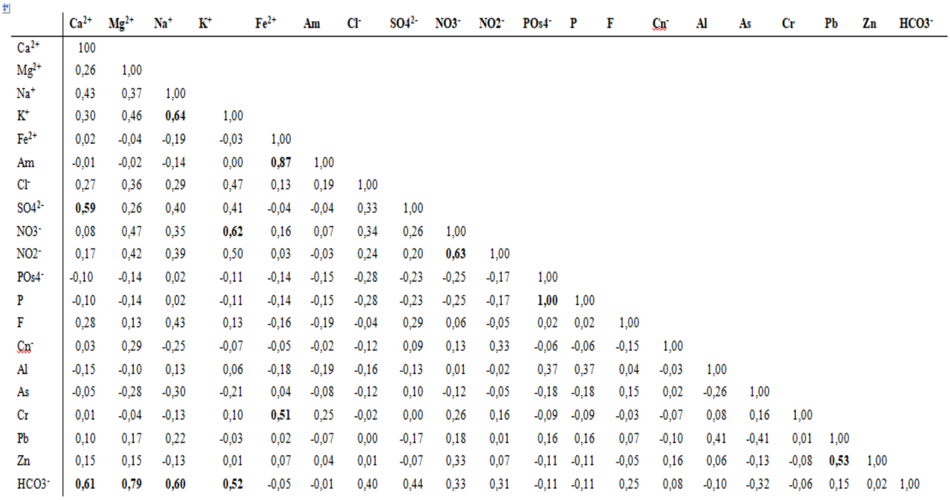
For calcium, it is clear that the dissolution from calcium aluminosilicate minerals under the action of CO_2^- dissolved in water is the dominant process Ca = f (HCO_3^-). The system studied being open, the CO_2^- biogenic diffuses very easily into the aquifer in areas where the piezometric surface is very shallow during periods of high water.

The relationship is poor for sodium and potassium, but better for magnesium due to a probable external supply to the aquifer system.

The relationships between cation and Cl concentrations show that there are quite a few isolated samples for sodium and potassium concentrations. Note that the sodium (Na^+) and potassium (K^+) concentrations increase as much as that of the chlorine (Cl^-) decreases. We can think that the concentrations seem independent of the chloride concentration in the basin. This is normal since there are no chloride-rich minerals in the rocks in the study area. Chlorides are found only in apatite which is included in biotite (Travi et al., 1986). For magnesium, it is observed in the waters least mineralized in chlorides and the waters most mineralized in chlorides. This suggests that there are specific sources of pollution in the environment.

For the relationships between anion contents and Cl^-, no relationship exists between chlorine and sulfate and no value exceeds the recommendations. For bicarbonate ions, the linear correlation $R^2 = 0.15$ is not remarkable with chlorides which seems to confirm that the origin of chlorides in water is not directly related to the alteration of silicates. There is a grouping in the relationship between nitrates and chloride. Three structures with a high nitrate concentration stand out in the village of Koumbogoro, which is located in the commune of Bieha, and the village of Don in the municipality of Leo; for which a common anthropogenic origin (agriculture) is likely. Chloride values are not accompanied by high nitrate values. These may disappear by denitrification or are absent in the source of pollution. For the relationship between orthophosphates and chlorides, two trends are observed as in the case of the relationship sulfates/chlorides. The extreme points would correspond to domestic polluting sources by nitrates or by chemical fertilizers used in the fields.

Table 2: Stamp correlation between the various ions and physicochemical parameters



	Ca^{2+}	Mg^{2+}	Na^+	K^+	Fe^{2+}	Am	Cl^-	$SO4^{2-}$	$NO3^-$	$NO2^-$	$POs4^-$	P	F	Cn^-	Al	As	Cr	Pb	Zn	$HCO3^-$
Ca^{2+}	100																			
Mg^{2+}	0,26	1,00																		
Na^+	0,43	0,37	1,00																	
K^+	0,30	0,46	**0,64**	1,00																
Fe^{2+}	0,02	-0,04	-0,19	-0,03	1,00															
Am	-0,01	-0,02	-0,14	0,00	**0,87**	1,00														
Cl^-	0,27	0,36	0,29	0,47	0,13	0,19	1,00													
$SO4^{2-}$	**0,59**	0,26	0,40	0,41	-0,04	-0,04	0,33	1,00												
$NO3^-$	0,08	0,47	0,35	**0,62**	0,16	0,07	0,34	0,26	1,00											
$NO2^-$	0,17	0,42	0,39	0,50	0,03	-0,03	0,24	0,20	**0,63**	1,00										
$POs4^-$	-0,10	-0,14	0,02	-0,11	-0,14	-0,15	-0,28	-0,23	-0,25	-0,17	1,00									
P	-0,10	-0,14	0,02	-0,11	-0,14	-0,15	-0,28	-0,23	-0,25	-0,17	**1,00**	1,00								
F	0,28	0,13	0,43	0,13	-0,16	-0,19	-0,04	0,29	0,06	-0,05	0,02	0,02	1,00							
Cn^-	0,03	0,29	-0,25	-0,07	-0,05	-0,02	-0,12	0,09	0,13	0,33	-0,06	-0,06	-0,15	1,00						
Al	-0,15	-0,10	0,13	0,06	-0,18	-0,19	-0,16	-0,13	0,01	-0,02	0,37	0,37	0,04	-0,03	1,00					
As	-0,05	-0,28	-0,30	-0,21	0,04	-0,08	-0,12	0,10	-0,12	-0,05	-0,18	-0,18	0,15	0,02	-0,26	1,00				
Cr	0,01	-0,04	-0,13	0,10	**0,51**	0,25	-0,02	0,00	0,26	0,16	-0,09	-0,09	-0,03	-0,07	0,08	0,16	1,00			
Pb	0,10	0,17	0,22	-0,03	0,02	-0,07	0,00	-0,17	0,18	0,01	0,16	0,16	0,07	-0,10	0,41	-0,41	0,01	1,00		
Zn	0,15	0,15	-0,13	0,01	0,07	0,04	0,01	-0,07	0,33	0,07	-0,11	-0,11	-0,05	0,16	0,06	-0,13	-0,08	**0,53**	1,00	
$HCO3^-$	**0,61**	**0,79**	**0,60**	**0,52**	-0,05	-0,01	0,40	0,44	0,33	0,31	-0,11	-0,11	0,25	0,08	-0,10	-0,32	-0,06	0,15	0,02	1,00

Heavy metals and metalloids

Unlike organic pollutants, metals cannot be degraded biologically or chemically. Heavy metals at certain concentrations can characterize types of natural contamination or anthropogenic pollution, for example, chromium reveals the presence of a tannery; lead is linked to diffuse pollution; the zinc is evacuated by industries which practice galvanization or preparation.

Regarding Cyanide, nineteen samples have parameters above the Burkina standards of 0.07 mg/l. These samples are found in areas of gold panning or traditional mining, in boreholes surrounded by trees, in garbage dumps, on farms. The cyanide concentration values are between 0.001 mg/l and 0.4 mg/l. Moreover, massive cattle deaths have already been recorded in the area and attributed to cyanide effluents (Bamba, 2013). The contamination of groundwater near these ore processing sites cannot therefore be ruled out without a study on an appropriate scale.

Arsenic

Regarding arsenic, it is naturally present in the subsoil of Burkina Faso over the entire extent of the territory according to a study by BUMIGEB at various concentrations and in different elements such as pyrite, arsenopyrite etc.… Analysis statistics show that thirty-one boreholes have high values exceeding the authorized standard of 0.01 mg/l and are once again in connection with gold panning sites or their proximities, or through faults. However, if the sulphide walls are reached, these risks will be high with a possible mobilization of potentially toxic trace elements in groundwater systems (Bamba et al., 2013). It should therefore be emphasized that from the point of view of domestic use, groundwater is drinkable apart from drilling with a high rate of arsenic correlable to the very nature of the ore which contains arsenopyrite. According to Guissou et al. (2009), the high arsenic concentrations in borehole water expose the consuming population to a risk of intoxication (skin lesions such as hyperpigmentation, warts). These symptoms usually appear after a period of exposure ranging from five to fifteen years. According to many authors (Smedley et al., 2007; Lindberg et al., 2005), the alkaline pH favors the presence of a high concentration of arsenic. Smedley et al. (2007) believe that the arsenic concentration would be higher in aquifers for which the dissolved oxygen concentrations would be below 2 mg/l.

Aluminum

Thirty five boreholes have concentrations ranging from 0.5 mg/l to 5 mg/l which exceed the standard of 0.02 mg/l. This could be explained by its mobility which seems to be greater than that of other metals. Fekhaoui et al. (1993) explain it by a preferential fixation on fine particles. In its natural state, it is very finely dispersed in the form of microcrystals of various aluminosilicates, essential constituents of clays. Its concentrations can be considered as representative of natural concentrations in groundwater.

Chromium

The chromium standard of 0.05 mg/l in our sub-basin is respected. However, this is not the case with drilling around our study area. This is the case of Kakadouna near To in Sissili, Kongoussi in Bam on a crystalline base. This presence is associated with industrial activities, and tanneries (Khawaja et al., 2001). The sector studied hosts all these activities. The control well waters show low chromium concentrations which suggests that the high concentrations can only come from industrial sources.

Characterization of groundwater from principal component analysis

To establish the correlations between the different physico-chemical and chemical variables, a multivariate analysis is necessary. The aim is to determine the relationships between the different variables and possibly to group the samples that show a similar type of variation. This analysis follows the correlation matrix between the different variables which were commented on in the previous paragraph.

The results of the PCA (axis 1: 9.68% and axis 2: 5.46%) as shown in Figure 2, give an indication of the dispersion of the sources of variability in the chemical composition of the waters. It shows that the chemical quality of water is linked to several processes, which leads to a very complex situation. It seems that the mineralization of the waters is influenced by the residence time with the leaching of the rocks and the chemical reactions that could take place in the aquifer during the dry season. Table 4 gives the cumulative eigenvalues according to the three dimensions. The contribution of the different variables in the definition of the main factors is given in Table 3. Each factor is defined by a certain number of essential variables in highlighting the mechanism of mineralization and water pollution. However, the correlation matrix comes in supportn to corroborate these statements. The abundance of bicarbonate in the waters of this aquifer shows that it comes mainly from the dissolution of silicate rocks and they provide information on the residence time of water in the aquifer (Lasm et al., 2011).

Axis 1 shows a positive correlation between HCO_3^-, Ce, Mg^{2+}, Ca_2^+, K^+, SO_4^{2-}, which are indicators of the environment influenced by water with a long dissolution time following water-rock contact. As hydrolysis is a slow process, axis 1 accounts for the conditions under which water chemistry is acquired. (Eblin et al., 2014; Amadou et al., 2014).

Axis 2 shows a correlation between NH4, Fe^{2+}, Al, PO_3^{4-}, P, and translates an exchange coming from the ground which would indicate a strong contribution of anthropic activities. A correlation is less positive between this group of chemical elements with the group Zn, As, NO_3^-, T. Indeed, in this grouping, the association of these ions corresponds to the anthropic pole of water mineralization. The ACP has shown that two other phenomena participate in the mineralization of the waters in the study area (Gnamba et al., 2019). These are the leaching of soils and the intervention of anthropogenic activities.

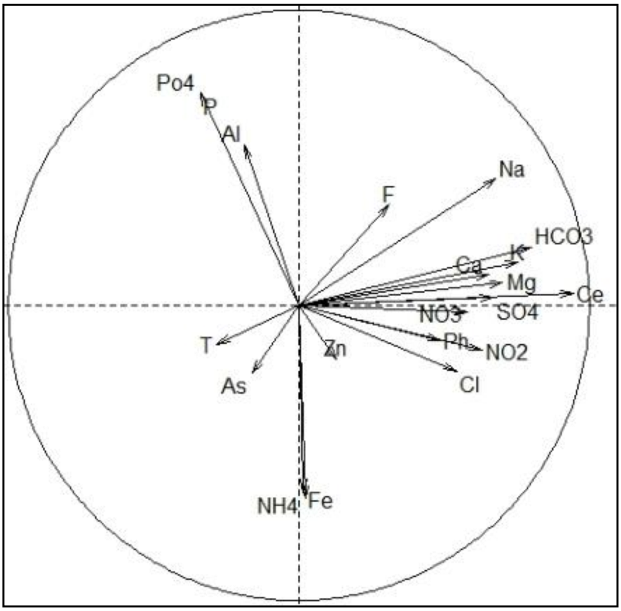


Figure 2: Principal component analysis of physicochemical data. Projection of the point cloud in space

Table 3: Contributions of the variables based on the correlations

	T°	**PH**	**Ce**	**Ca^{2+}**	**Mg^{2+}**	**Na^{+}**	**K^{+}**	**Fe^{2+}**	**NH_4^{+}**	**Cl^{-}**	**SO_4^{2-}**
Axis1	0.280	0.486	0.944	0.652	0.702	0.677	0.754	0.024	0.017	0.542	0.666
Axis2	0.131	0.118	0.041	0.104	0.077	0.428	0.145	0.654	0.633	0.222	0.026

	NO_2^{-}	**NO_3^{-}**	**Po_4^{-}**	**P**	**F**	**Al**	**As**	**Zn**	**HCO_3^{-}**
Axis1	0.629	0.579	0.338	0.338	0.310	0.186	0.161	0.130	0.798
Axis2	0.152	0.024	0.719	0.719	0.340	0.543	0.228	0.182	0.197

Table 4: cumulative eigenvalues

	Eigen value	**Proportion**	**Cumulative**
Axis 1	6.58296	9.68082	9.68082
Axis 2	3.71340	5.46088	15.14169
Axis 3	3.07695	4.52492	19.66662

Chemical facies of groundwater

In order to characterize the hydrofacies of groundwater, an approach will be used through the DIAGRAMME software. The Piper diagram presented in Figure 3 concerns all of the drilling water samples. But the approach makes it possible to distinguish other hydrofacies.

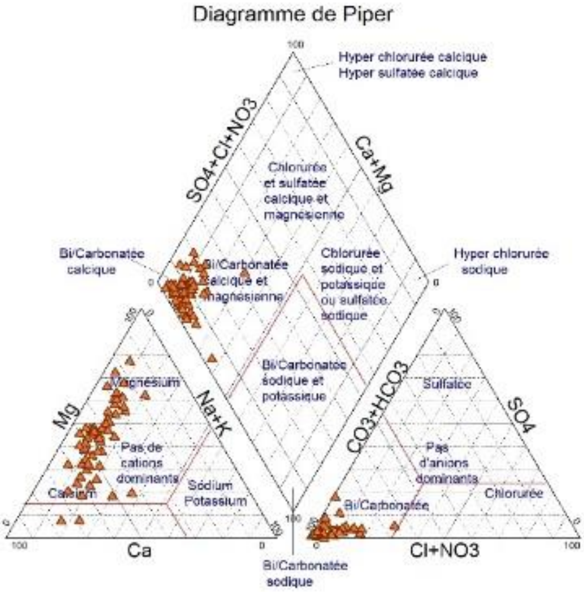


Figure 3: Piper diagram

The Piper diagram presents hydrofacies which are of the calcium bicarbonate types (found in alluvium, the base of armor, granodiorites) and magnesium (basic formation, amphibole) in great majority. We see that the majority of the results are located in the triangle of cations where we can note that scattered wells reflect dominance. We note in the triangle of anions that there is no dominance; we have a beginning of evolution from the bicarbonated pole towards the pole chlorides_nitrates translating a certain anthropic attack. This is particularly true for certain boreholes with standards higher than the recommendations of Burkina. In the triangle of anions, the majority of bicarbonate waters belong to the layer of cracks. The study conducted by Ouandaogo (2008) in the same basement context, reports concentrations of nitrates in sumps and wells. This concentration can come from the lack of sanitation, but in our case it can be linked to agriculture. In the triangle of cations, we notice that some waters are close to the calcium pole while some stand out clearly towards the sodium pole. Shallow wells are distinguished by their low concentration of Na and K (present in clay alterites). In this study, it was interesting to see the temporal evolution of the ions, but alas it was not possible because there was no monthly monitoring at the level of the samples. Many authors who have studied hydro-chemistry in West Africa, only in the basement area, have concluded that the calcium bicarbonate facies is most abundant in groundwater. This bicarbonate predominance can be justified by the bicarbonate contents recorded in the waters of this aquifer. Figure 3 illustrates this predominance well.

Aggressiveness of groundwater

We have seen that from the contents of major chemical elements, we can know the state of equilibrium of the waters towards the minerals. This makes it possible to know certain properties and behaviors of the waters, in particular, the corrosive or scaling character.

Ryznard index

It makes it possible to define an aggressive (corrosive) or scaling tendency for water (Tables 5 and 6). The trend gives aggressive, highly corrosive waters for the entire basin except in the case of the Yaké drilling in the municipality of To which has incrusting water. In other studies, authors have shown that water is aggressive in an acid rock (granites, migmatite, quartzite, sandstone, gneiss and shale), but when the rock is basic with a pH greater than 7 the water is not aggressive (basalt, dolerite). Therefore, it will depend on the carbonic acid concentration, the PH, and the Ryznard index which can play a decisive role in the ion balance. This reflects in this sub-basin that aggressiveness is linked to the geological facies. Water corrosion depends on its ion concentration, but also on its concentration in other ions capable of entering into redox reactions. This is clearly visible in the Koudougou area where a CREPA study has shown this aspect giving the water a reddish color, which has led people to abandon the boreholes. The studies carried out by Sauret (2005) in Mouhoun have also shown this fact. Several orders of magnitude of RSI are defined in relation to the aggressive power of water.

Table 5: Statistical parameters indices of Ryznard

	Ryznard	***pH***
Average	9,280	6,351
Médian	9,285	6,355
Standard deviation	0,867	0,295
Minimum	7,090	5,690
Maximum	11,870	7,090

Table 6: Parameters of comparison of the indices of *Ryznard*

RSI> 7	Water is aggressive and corrosive
RSI<7	Water is encrusting
Si RSI ≤6.5	Water is no corrosive tendency
RSI>6.5 et ≤7.2	Water is slight corrosion
RSI>7.2 et ≤8.5	Water is severe corrosion
RSI> 8.5	corrosion important

Groundwater saturation indices (SI)

They are used to study different forms of mineral phases such as precipitation, dissolution and adsorbed phases. If we consider a chemical reaction between water and a mineral, the thermodynamic equilibrium constant of this reaction would be the product of ionic activity. The equilibrium deviation is defined by the IS saturation index. The analysis in Table 7 shows a saturation of the groundwater with respect to the calcites. Relatively high concentrations of calcite and extensive water-rock interaction in boreholes tend to increase pH values, with calcite saturation indices approaching equilibrium. This increased association between pH and calcite saturation can lead to deprotonation of the mineral surfaces of the aquifer (Sako, 2013). No water is saturated compared to other element. On the other hand, gypsum and anhydrite present a state of equilibrium favorable to dissolution. These results are similar to those observed by Ouagando (2008) who concluded that the SI does not allows to understand the geochemical mechanism of demineralization of water from the precipitation of carbonate minerals (calcite) generally absent in basement rocks granite. It is clear that the dissolution of calcium aluminosilicate minerals under the action of $CO2^-$ dissolved in water is the dominant process in the acquisition and evolution of the groundwater mineralization

Table 7: Statistical parameters of the saturation indices (IS)

	Is Calcite	*pHs Calcite*	*Is Aragonite*	*pHs aragonite*	*Is Dolomite*	*pHs dolomite*	*Is Gypse*	*Is Anhydrite*
Average	-1,465	7,816	-1,605	7,956	-2,779	7,741	-3,417	-3,614
Médian	-1,465	7,785	-1,605	7,925	-2,74	7,695	-3,57	-3,76
Standard deviation	0,543	0,352	0,543	0,352	1,144	0,392	0,434	0,432
Minimum	-3	7,09	-3,14	7,23	-6,28	7	-3,97	-4,16
Maximum	0	8,87	-0,14	9,01	0,09	9,01	-2,11	-2,31

Table 8: Parameters of comparison of the saturation indices

IS= 0	The water is in balance with the mineral
IS < 0	The water is undersaturated, and capable of dissolving the mineral
IS > 0	The water is supersaturated, and capable of precipitating the mineral

CONCLUSIONS

The various previous studies had highlighted pollution in the Sissili sub-basin. But nowadays it has increased and health risks are then foreseeable. Some water points have been abandoned by the population. The saturation index and factor analysis allowed a better understanding of the water quality in this region of Burkina Faso. Groundwater has a generally acidic pH. The electrical conductivity values suggest strong mineralization and translate into an independence of the water pockets from each other. This mineralization and this conductivity are in perfect agreement with the mode of deposit. We also note that the elements of cations and anions increase as a function of the distance of the path traveled by percolation. Also, calcium and magnesium vary very little from one drilling to another, which is the reverse for chlorine and sodium. Bicarbonates make up the bulk of the mineralization of waters and dominate the other anions. The vast majority of groundwater is bicarbonate calcium or magnesium. They are also aggressive, very highly corrosive, for the entire basin with the exception of the Yaké borehole located in the municipality of to. These waters are also saturated with calcites. Multivariate analysis methods have shown that mineralization is governed by soil leaching, anthropogenic activities, and the acid hydrolysis of rock minerals.

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