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The use of hydrogeochemistry and stable isotopes to characterize water resources in Savannah region in Northern Togo

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Abstract: The Savannah region is located in the North of Togo. It is comprised of crystalline rocks of the West Africa Craton and sedimentary rocks of the Volta basin. It is characterized by a semi-arid climate, and limited surface water resources. Therefore, groundwater is an alternative and a good source for domestic and agricultural water supply. A good understanding of the geochemical evolution of groundwater in Northern Togo is crucial to ensure a sustainable use of the water resources. Surface water and groundwater samples were collected and analyzed in order to investigate mineralization processes, water origin, and recharge sources. Stable isotopes and geochemical composition of the collected samples are used to provide a better understanding of the groundwater mineralization process. Results show that groundwater is weakly to moderately mineralized, and can be classified into two major water facies: Ca-Mg-HCO3 and the Ca-HCO3. Water Quality Index shows that groundwater is "good" to "excellent", therefore it is suitable for drinking. The major reactions responsible for the chemical evolution of groundwater in the Savannah region can be subdivided in three categories: waterrock interactions, the hydrolysis of silicate minerals and the decomposition of ferro-magnesian minerals. Anthropogenic pollution and cation exchange reactions play also a role in groundwater chemical evolution. The isotopic data shows that groundwater in the study area is not significantly affected by evaporation, which suggests direct and an episodic recharge by precipitation. Nevertheless, the slight evaporation noticed in the crystalline basement aquifer shows the contribution of surface water in the recharge process.

1. Introduction

Water is a vital natural resource for living organisms as well as natural ecosystems. Access to drinking water and sanitation services remains challenging, especially in the developing world. It is estimated that more than 2 billion people do not have access to drinking water, and more than the double do not have safe sanitation services (UNICEF, (2007)). Thus, ensuring access to water and sanitation for all, remains a priority of the sustainable development goals (ONU, (2018)).

In Africa, the majority of population do not have access to drinking water, where groundwater is the main source of it. The use of water for irrigation has increased dramatically to combat growing food insecurity. In 2010, a study by WHO/UNICEF Joint Water Supply and Sanitation Monitoring Program named 'target for safe drinking water for 2015', reveals that in 2015, 663 million people had

no access to water worldwide (WHO/UNICEF, (2015)). About half of those people who had no access to water were from sub-Saharan Africa. Worldwide, water scarcity is projected to increase from 47% in 2000 to 65% in 2025, even though by 2010 the actual number of people using improved drinking water sources had increased by 11% since 1990 (UNEP, (2013); Koffi, (2017)).

In developing countries such as Togo, safe water supply is constrained by the availability of groundwater resources since surface water bodies have been scarce and less reliable to sustain socioeconomic development (Akpataku et al., 2019). This explains the rapid expansion of borehole programs in many sub-Saharan countries over recent decades (Langenegger, (1990), Foster *et al.* (2012)). Thus, the assessment of groundwater resources represents a critical step to support sustainable groundwater extraction for drinking, domestic, agricultural and industrial purposes (Langenegger 1990, Foster *et al.* (2012), Ganyaglo *et al.* (2017)). However, water consumption has increased because of population growth and long drought events due to climate change.

In the savannah region in northern Togo, the problem of drinking water supply exists mainly in semi-urban and rural areas (85% of the population) (RGPH, (2010)). Groundwater potential in the Savannah region is not well understood, however extraction is increasing with the economic growth. An assessment was carried out to better understand the potential impact of climate change on the availability of water resources in the different regions of Togo. The different scenarios used in the assessment integrate current population growth rates of the different regions, and estimate of annual water consumption (22.5m³/person). Results of the assessment show that the Savannah region is the second most vulnerable region and will exhaust its groundwater reserves by 2053 for the extreme scenario and 2055 for the medium scenario (PNUD, (2014)). It is thus crucial to understand groundwater recharge and the geochemical mechanisms that influence water chemical composition, for a sustainable use of water resources. This study aims at investigating geochemical mechanisms responsible for water mineralization in the Birrimian basement and Volta basin sedimentary aquifers, in the Savannah region.

The Savannah region consists of two major geologic domains: the Birrimian crystalline rock in the North (basement aquifer) and the Volta basin in the South (sedimentary aquifer). These aquifer systems are the major source of water supply for the region. The research questions investigated in this study are in relation with the origin of the water mineralization processes. This study aims to improve the knowledge about groundwater processes, current and future groundwater recharge, and the integrated management of water resources.

2. Material and Methods

2.1 Site description, Climate, Geology and Hydrogeology

The Savannah region is one of the economic regions in Togo and lies between 0 °- 1 ° East and 10 ° and 11 °North. This region occupies a surface area of about 8533 km² or 15% of national territory where 13.5% of the national population lives. One-third of its area is occupied by flora and fauna reserves. It is bounded on the North, East and West by the national borders separating Togo from Burkina Faso, Benin and Ghana respectively, and to the South by Kara region (Figure 1). Savannah region has a long time suffered from an enclavement that kept it away from modern commercial channels. This isolation, is more due to the inadequacy of communication infrastructure than to the distance from the capital Lomé; this was more or less broken following the asphalting of the axis Lomé – Ouagadougou. However, this region stayed where monetary income remains at a particularly low level and where the food situation is periodically alarming (URD, (2006)). The study area has a Sudano-Guinean climate and the annual rainfall based on 25 years (1991-2016) data from Dapaong

and Mango weather stations, ranges from 950 mm to 1200 mm with a mean of 1100 mm. The climate regime is unimodal consisting of one dry season and one rainy season. The rainy season starts in April/May, peaks in August, and ends in September/October. The remainder of the year corresponds to the dry season which is characterized by the Harmattan and maximum temperature reaching 38-39°C. Vegetation of the area consists of grass with scattered drought resistant trees such as the shea (*Vitellaria paradoxa*), the baobab (*Adansonia digitata*), dawadawa (*Parkia biglobosa*), acacias and neem (*Azadirachta indica*) that form the guinea savannah woodland vegetation belt.



Figure 1: Location of the study area

The geology of the Savannah region consists of two main geologic domains: the Birimian basement in the North and the Volta basin in the South. The Birimian basement is a part of the West African shield, and consists of plutonic and metamorphic rocks with ages ranging from Archean to the paleozoic inferior. In the extreme North of the Savannah region, birrimian rock are migmatites, and archean gneisses (300-260 Million years). The southern part of the Birimian domain is comprised of fragmented volcanic acidic rocks such as diorite-granite and tonalite; these rocks outcrop in Dapaong. Most rocks of West Africa shield and are granitic with an alteration mantle that is sandy, and sandy-clayey.

The Volta Basin in Savannah region, is comprised of Bombouaka and Oti supergroups (**Figure 2**). The Bombouaka supergroup is made up of sandstones, quartzite-sandstones, conglomerate, and silt.

Bombouaka's sandstones are characterized by stripped and tabular lavers whose alteration products allow for the formation of deep red soils down slope. The Oti supergroup is mostly composed of fine greenish clays (tillites), sandstones, arkoses, and conglomerates arranged in subhorizontal beds. Gushing erosion structures are also observed in the Oti supergroup. The Volta basin rocks formed 20 Million years ago and are characterized by a tabular structure. The topography in norther Togo is mared by monoclinal structures, cuesta, and cliffs. Laterite is developed in the superficial layer and extends at depth. The thickness of the surface layer to the weathered zone is on average of 12 m (5 m minimum to 20 m maximum).



Figure 2: Geological map of the Savannah region showing the crossing cut.

Two distinct aquifer systems are exploited for community drinking water supply. The main aquifer system is that of the weathered basement. It is overlain by a clay layer, about 10 meters thick. The weathered horizon plays a captive role. The depth to the water table varies between 7 and 8 meters. Recent pumping tests carried out in the area (during the construction of boreholes) indicate variable specific capacity values, between 2 and 9 m³/h/m.

The basement aquifer in the Savannah region consists of a weathered horizon and fractured layer. The hydraulic conductivity of the weathered horizon is generally low (1 to 9x10-7 m/s) and the porosity is in the order of 2 to 5%. The transmissivity values of the fractured layer are commonly in the range 10–6 to 10–4 m2/s and are very heterogeneous, even within the same geological formations. The thickness of the weathered layer is highly variable, with values ranging from 5 m to 35 m. The depth of the boreholes varies between 37 m and 80 m in the basement zone and up to 110 m in the sandstones.

In addition to the basement aquifers, heterogeneous alluvial deposits (sand and clays) are present along streams. The thickness of these alluvial deposits generally does not exceed 10 m and their lateral extension remains limited around non-perennial streams. These deposits form quasiautonomous hydraulic systems, with low transmissivity and low storage capacities.

The study area is a vast peneplain with sandy or arenitic soil, presenting a chaotic landscape; there are granites, granodiorites and migmatites. Towards the South, it is limited by the first cliffs formed by Dapaong sandstones which lies unconformably on the basement and constitute the base formations of the Volta basin (Figure 3).



Figure 3: Hydrogeological section of the study area from the Northwest to the Southeast.

2.2 Sampling, fields measurements and Laboratory analysis

In the framework of this study, two sample collection periods were observed. The first period took place in the dry season (45 water samples) and the second period in the rainy season (54 water samples). The spatial distribution of the sampling location is shown in Figure 4. Surface water samples were collected from 8 different locations. The water sampling protocols as proposed by Barcelona et al., 1985 were followed as much as possible. These water samples were collected for the determination of hydrogeochemical parameters including major elements. The samples were collected in different locations using pre-cleaned sterilized poly propylene plastic bottles with necessary precautions. For each sampling point (boreholes, rivers) two samples were collected in bottles of 500 ml each: the sample used for cations analysis was treated with concentrated nitric acid (HNO₃) until the pH value reached 2, whereas the other sample intended for the analysis of anions was left untreated. Acid-treatment of samples intended for the analysis of cations aims at stabilizing water samples and preventing the precipitation of metals.

In the field, Electric Conductivity (EC), pH and temperature were measured using a multi-meter Inolab "WTW", and samples were stored in a cooler containing ice blocks in order to keep the temperature of the samples low and constant. Global Positioning System (GPS) was used to determine the locations coordinates of sampling points and the elevations. These samples were automatically analyzed according to AFNOR methods at the Laboratory of Applied Hydrology and Environment which is affiliated with the University of Lomé. The major elements Ca²⁺, Mg²⁺ were determined by complexometry with EDTA 0,01M after titration; Na+ and K+ by direct reading using a photometer of JENWAY flame mark PFP7. Ions Cl- were determined by the argentimetric method, NO3- and SO4²⁻ by molecular spectrophometry of absorption after calibration. Total alkalinity (HCO₃⁻ and CO₃²⁻) was determined by titration with a hydrochloric acid solution (0.1 M) by using phenolphthalein and helianthin as color indicators.



Figure 4: Sampling points in the study area

Analytical results were validated for charge balance according to Freeze and Cherry (1979):

$$Error = \left[\frac{\sum z.m_c - \sum z.m_a}{\sum z.m_c + \sum z.m_a}\right] \times 100$$
(1)

Where Z represents the absolute value of the ionic valence, m_c the molality of cationic species and m_a the molality of the anionic species. The analytical error on all samples is between -5% and + 5%.

Stable isotopes (δ^{18} O, δ^{2} H) analysis was performed by Laser Absorption Spectrometry measurements LGR DLT 100 (Penna *et al.* (2010)) in the Laboratory of Radio-Analysis and Environment (LRAE) of Sfax in Tunisia. The results are expressed as relative deviations δ (in per mil) adopting the international standards of the Vienna Standard Mean Ocean Water (VSMOW). Isotope ratios are reported in delta per mil (δ ‰) relative to the VSMOW (Clark and Fritz, (1997)) as:

$$\delta(\mathscr{O}_{oo}) = \left[\frac{R_{sample} - R_{std}}{R_{std}}\right] \times 1000$$
(2)

which is the ratio of the less abundant heavier isotope of interest to the most abundant isotope either ${}^{18}\text{O}/{}^{16}\text{O}$ or ${}^{2}\text{H}/{}^{1}\text{H}$ of the sample, R_{sample} and standard, R_{Std}. The analytical precision of stable isotope analysis (one sigma) was in the order of ± 0.2 ‰ for $\delta^{18}\text{O}$ and ± 1 ‰ for $\delta^{2}\text{H}$.

The chemical composition of groundwater is mainly determined by the mineral composition of host rocks, but other geochemical processes also play a key role in determining the amount of chemical constituents in groundwater (Razowska-Jaworek, (2014)). The chemical composition of the water samples is analyzed using Piper Diagram, this helps to identify the different geochemical facies. This diagram is often used and gives very good results (Yermani *et al.* (2003); Alayat and Lamouroux, (2007); Kouassi *et al*, (2010); Ahoussi *et al*, (2011); Ahoussi *et al*, (2012); Ahoussi *et al*, (2013)). Weathering of rocks has been found to be one of the processes controlling the geochemical cycling of elements. Middelburg *et al.* (1988) stated that the rate and nature of chemical weathering which vary widely are controlled by many variables, including parent-rock type, topography, climate and biological activity. In order to understand the weathering processes taking place in the study area, different methods were used. Data analysis is performed using the DIAGRAM software. The second approach is based on the use of the statistics multi varied starting from the Analysis in Principal Components (ACP) and Ascending Hierarchical Classification (CHA). Statistical analysis was performed on 73 samples and 10 variables (electric conductivity (EC), the pH, Na⁺, Ca²⁺, Mg²⁺, K⁺, Cl⁻, HCO3⁻, SO4²⁻, and NO3⁻), using the XLSTAT 2007 software.

The Water Quality Index (WQI) is a water classification technique that is based on the comparison of water quality parameters with international standards. In other words, the WQI sums up large amounts of water quality data in simple terms (e.g. excellent, good, bad... etc.), generating a score that describes the qualitative state of water for domestic use. This method was initially proposed by Horton, 1965 and Brown et al., 1970. The WQI was calculated according to the method proposed by Yidana and Yidana, (2010). In this approach, a numerical value called weight, between 2 and 5, is assigned to each parameter, reflecting its degree of influence on the quality of the water (Kamur *et al.* (2013); Krishna kumar *et al.* (2015); Varol. et Davraz, (2015)). A maximum weight of 5 has been assigned for NO3-, 4 for TDS and pH, 3 for TAC and a minimum weight of 2 for TH, Ca²⁺, Mg²⁺, Na⁺ and K⁺ (Srinivasamoorthy, *et al.*, 2008). The weights assigned to the various physicochemical parameters are presented in Table 1.

The relative weight (Wi) is calculated by the following equation:

$$Wi = \frac{Wi}{\sum_{i=1}^{n} Wi}$$
(3)

where wi is the relative weight of each parameter and n is the number of parameters. The quality (qi) rating scale for each parameter is calculated by dividing the concentration of each parameter by the respective WHO standard and multiplying by 100.

$$qi = \left(\frac{Ci}{Si}\right) \times 100 \tag{4}$$

where q_i is the quality rating scale, *Ci* is the concentration of each parameter in mg/l, and *Si* is the WHO standard for each parameter in mg/l.

Chemical	WHO standard		Relative weight
parameter	(2011)	Weight (w _i)	(W_i)
EC (µS/cm)	1500	5	0.143
TDS (mg/l)	1000	5	0.143
pН	7-8.5	4	0.114
Na ⁺ (mg/l)	200	3	0.086
K^{+} (mg/l)	3	1	0.029
Ca^{2+} (mg/l)	200	2	0.057
Mg ²⁺ (mg/l)	150	3	0.086
Cl ⁻ (mg/l)	250	3	0.086
SO ₄ ²⁻ (mg/l)	250	3	0.086
HCO ₃ ⁻ (mg/l)	380	1	0.029
$NO_3^-(mg/l)$	50	5	0.143
		$\sum w_i=35$	$\sum W_i = 1$

 Table 1: Weight of the physico-chemical parameters (Dhanasekarapandian, et al., 2016).

To calculate the Water Quality Index, the Sub Index (SIi) is the first index to determine. From the sum of the Sub-Indices of each parameter, the WQI of each sample is determined as follows:

$$SIi=Wi\times qi$$
(5)
$$WQI = \sum SIi$$
(6)

Four quality classes can be identified according to the values of the quality index of water (Table. 2).

Table 2: Classification of water acco	rding to the	WQI (Sahu e	et Sikdar,	(2008))
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WQI range	Water type
< 50	Excellent water
50 - 100	Good water
100 - 200	Poor water
200 - 300	Very poor water
> 300	Unfit for drinking

3. Results and Discussion

3.1 Hydrochemistry data

3.1.1. Chemical composition of groundwater and hydrochemical facies

Table 1 summarizes some descriptive statistics of physico-chemical and hydrogeochemical parameters for 82 water samples analyzed in this study. For each parameter, minimum and maximum values, average, median, standard deviation and the coefficient of variation are presented. In situ

parameters such as temperature, pH, electric conductivity (EC) and total dissolved solids (TDS) together with the analytical data of major ions in groundwater samples are presented in **Table 2**. The temperature of surface water ranges between 27.0 °C and 30.8°C with an average of 29.1°C. These values are akin to that of ambient temperature at the sampling time. It is even for groundwater where temperature varies between 26.2°C and 32.9°C with an average of 30.8°C. Thus, this slight variation is attributed to present environmental temperature. Although temperature variation could be linked to the sampling time and to the thermic equilibrium between aquifer system and the atmosphere, there is a depth increasing trend from surface to deep boreholes probably due to geothermal gradient. The pH values range between a minimum of 5.64 and a maximum of 8.86 with an average of 7.02. More than 80% of the samples have pH near neutrality. The pH values lie within the range of most natural waters

The Electric conductivity (EC) in the study area varies considerably between 54.1 µs/cm (at reference temperature of 25 °C) (quartzite sandstones) and 1670 µS/cm (sandstones well water sample) with an average of 473 µS/cm. About 60% of the samples have EC values less than 500 µS/cm and more than 95% of them less than 1000 µS/cm. Therefore, only a few samples have a conductivity reaching 1000 µs/cm, these are the boreholes F3 (1013 µs/cm in the sandstones of Gando), F18 (1322 µs/cm in the sandstones), F41 (1310 µs/cm in shales) and F72 (1670 µs/cm in sandstones). The high value of the standard deviation observed in the values of electrical conductivity (314 µS/cm) with the coefficient of variation (about 0.66) shows significant variations in mineralization of the aquifers consisting of several geological formations. This feature, common to all crystalline aquifers in the Sahel region, can be explained by the confinement of water by laterite layers developed through rock weathering (Akiti, (1980); Dray et al. (1989)). The geochemical facies are essentially calcium bicarbonate. However, the TDS values range between 41.4 mg/l and 1425 mg/l with an average of 396 mg/l and a CV of 0.66. The TDS displays heterogeneous distributions as illustrated by the CV. The lower and higher values are related to the geographical position. However, relatively low values of TDS (TDS <400 mg/L) characterize the basement aquifer in the North of the study area. The slightly high values observed come from the sandstone aquifer in the Volta basin (Figure 5). This indicates that the study area is characterized by important heterogeneities and the TDS values are affected by different geochemical processes. There is no health-based guideline for TDS but an upper limit of 1000 mg/l for drinking water has been set based on taste considerations (WHO, (2008)).

A quick inspection of Table 3 reveals substantial variations for most hydrochemical parameters as evidenced by very high coefficients of variation, which may be compatible with the geological environment of basement crystalline rocks. Indeed, extreme variations in the quality of groundwater, even over short distances, have been reported in several rocky environments, resulting from the complexity of groundwater flow and weathering processes (e.g. Foster *et al.* (1999)). Overall, the relative abundance of ions in the analyzed water samples is follows: $Na^+ > Ca^{2+} > Mg_2^+ > K^+$ and $HCO_3^- > SO_4^{2-} > Cl^- > NO_3^-$ for cations and anions, respectively.

Na⁺ contents varied between 1 and 376 mg/l with an average value of 62.3 mg/l. The concentrations of HCO_3^- , which is the main anion in silicate terrains, vary between 12.2 mg/l and 884.5 mg/l with an average of 256.5 mg/l. The high CV of Na⁺ and HCO_3^- which are 1.18 and 0.69 respectively shows the relative heterogeneity of the formations in the study area. The least abundant anion is nitrate which ranges from 0 to 74.4 mg/l with an average value of 8.8 mg/l. Only two boreholes have a nitrate concentration (74.4 mg/l at F69 and 50.2 mg/l at F48) exceeding the safety limit of 50 mg/L (WHO/UNICEF, (2011)).

Variables	Min	Max	Average	Median	Std Dev	CV	Surf water
pH lab	5.6	8.7	7.02	7.03	0.59	0.084	6.92 ± 0.48
Cond	54.1	1670	473.1	373	314.2	0.664	62.3 ± 15.3
Temp	26.2	32.9	30.8	31	1.16	0.038	$29.1{\pm}1.09$
TDS-(mg/l)	41.4	1425	395.6	318.8	262.5	0.664	43.9 ± 16.4
HCO ₃ ⁻ (mg/l)	12.2	884.5	256.5	207.4	176.8	0.690	27.6 ± 17.2
Cl ⁻ (mg/l)	1.0	108	9.2	4.0	15.27	1.663	1.45 ± 0.92
NO ₃ -(mg/l)	0.0	74.4	8.8	1.6	14.70	1.667	2.05 ± 1.63
$SO_4^{2-}(mg/l)$	0.0	355.5	17.8	6.0	51.92	2.917	4.6 ± 3.9
Na ⁺ (mg/l)	1.0	376.0	62.3	26.0	73.66	1.182	2.44 ± 1.29
K ⁺ (mg/l)	0.6	19.5	3.5	2.9	2.73	0.787	3.19 ± 1.48
Mg^{2+} (mg/l)	1.0	43.6	10.9	8.6	9.22	0.844	2.82 ± 1.67
Ca^{2+} (mg/l)	4.2	83.2	25.2	20.8	16.05	0.636	4.43 ± 1.81

 Table 3: Statistical Summary of the Hydrogeochemical Parameters

 Table 4: Hydrochemical characteristics of the analyzed samples in the study area.

N°	Depth (m)	pH lab	CE (µS/cm)	T°C	HCO3 ⁻ (mg/l)	Cl ⁻ (mg/l)	NO3 ⁻ (mg/l)	SO4 ²⁻ (mg/l)	Na ⁺ (mg/l)	K ⁺ (mg/l)	Mg ²⁺ (mg/l)	Ca ²⁺ (mg/l)	TDS (mg/l)	Balance Ionique	$\delta^2 H~(\%)$	δ ¹⁸ O (‰)
F1	55.0	7.6	675	31	439.2	3.0	0.3	12.1	114.0	3.4	13.4	28.0	613	0%	-26.5	-4.67
F2	65.0	7.6	505	31.4	280.6	11.0	1.3	5.7	95.0	3.2	3.4	16.0	416	2%	-28.3	-4.48
F3	55.3	7.5	1013	31.4	640.5	3.0	0.7	17.7	202.0	3.8	14.9	12.8	895	1%	-33.7	-5.25
F4	36.0	6.2	210	29.4	109.8	3.0	3.9	7.2	25.0	1.3	7.7	7.2	165	0%	-22.41	-4.4
F5	60.5	7.2	510	32.7	231.8	4.2	0.5	24.3	61.0	3.3	3.0	4.2	332	-1%	-32.4	-5.18
F6	55.0	7.1	232	32.9	134.2	2.0	0.2	14.2	8.3	11.8	3.8	31.2	206	2%	-29.99	-4.97
F7	109.0	8.1	340	31.5	183.0	4.0	1.0	18.5	56.0	2.0	2.9	16.0	283	0%	-27.7	-4.66
F8	49.0	7.4	613	30.8	384.3	3.0	0.2	18.3	78.0	2.9	18.2	40.0	545	1%	-26.6	-4.86
F9	31.0	7.1	293	30.7	195.2	1.0	0.0	0.0	11.6	3.9	8.6	38.4	259	0%	-23.2	-3.92
F10	92.0	7.0	268	30.9	164.7	2.0	0.1	2.0	18.0	3.5	7.2	28.0	225	1%	-28.5	-4.84
F11	100.0	6.3	178	31.1	97.6	1.0	1.4	<1	11.6	3.0	5.8	12.0	132	0%	-24.1	-4.29
F12	-	8.9	400	31.0	12.2	37.0	<0.5	46.2	71.0	0.8	1.0	4.8	209	0%	-30.5	-5.03
F13	112.0	7.8	529	29.7	355.0	3.7	1.6	6.5	30.3	2.6	20.4	58.6	479	1%	-23.2	-4.23
F14	85.7	7.3	631	30.4	396.5	12.0	<0.5	3.4	82.0	4.1	18.7	34.0	551	0%	-30.1	-5.18
F15	-	7.5	942	31.3	366.0	108.0	<0.5	4.9	178.0	2.3	4.8	19.2	683	0%	-32.3	-5.32
F16	130.5	6.6	443	30.8	256.2	2.0	<0.5	6.2	50.0	6.0	10.0	24.8	355	0%	-30.1	-5.06
F17	92.0	6.7	361	31.0	280.6	3.8	0.3	6.0	44.7	6.9	5.1	45.5	393	0%	-32.8	-5.19
F18	110.0	6.4	1322	31.4	185.4	37.6	7.2	355.5	243.9	2.5	2.4	17.2	852	0%	-27.3	-4.58
F19	61.0	7.0	407	30.4	244.0	12.0	2.3	4.3	16.0	3.7	11.5	55.2	349	0%	-22.2	-4.15
F20	140.5	7.4	590	31.9	274.5	15.0	<0.5	46.7	89.0	2.2	5.0	30.0	462	0%	-35.0	-5.62
F21	43.0	6.9	819	30.4	555.1	3.0	1.7	11.8	80.0	3.6	36.4	56.0	748	0%	-23.3	-4.27
F22	37.0	6.5	348	28.9	170.8	8.0	0.0	30.2	15.0	7.6	11.0	37.6	280	0%	-26.97	-4.53
F23	55.0	5.6	54.1	29.5	24.4	1.0	0.8	4.3	1.0	3.2	1.9	4.8	41	1%	-25.33	-4.15
F24	37.6	7.5	847	31.1	530.7	8.0	0.2	25.0	112.0	4.2	36.0	28.0	744	1%	-24.7	-4.42
F25	28.0	6.2	147.7	29.5	61.0	5.0	7.0	8.0	7.0	6.3	5.3	11.2	111	1%	-22.82	-3.83
F26	38.0	7.3	441	30.2	280.6	5.0	0.0	8.7	27.6	6.3	9.6	54.4	392	1%	-30	-5.08

F27	-	6.5	67.3	30.6	18.3	1.0	13.5	2.8	2.5	1.8	1.4	6.4	48	1%	-21.4	-4.1
F28	55.0	7.6	769	32.0	396.5	33.0	0.9	22.1	159.0	1.5	1.4	16.0	630	0%	-33.2	-5.26
F29	87.0	7.2	446	31.6	292.8	5.0	0.3	2.0	55.0	3.3	7.2	38.4	404	0%	-29	-4.86
F30	110.0	7.9	805	32.7	500.2	1.0	0.0	13.0	176.0	1.5	3.4	12.0	707	0%	-29.3	-5.04
F31	-	7.5	791	31.4	500.2	3.0	<0.5	3.5	172.0	1.6	1.4	16.0	698	0%	-28.5	-4.88
F32	90.0	7.5	792	31.1	512.4	2.0	0.0	6.0	154.0	2.9	10.6	16.0	704	1%	-25.4	-4.56
F33	66.0	7.4	733	29.5	469.7	10.0	0.0	7.2	128.0	1.5	10.6	30.4	657	1%	-25.98	-3.94
F34	40.4	7.6	927	29.5	573.4	5.0	0.0	11.8	203.0	1.7	2.4	16.0	813	0%	-28.77	-4.78
F35	98.0	7.9	882	31.6	555.1	2.0	0.6	11.8	186.0	2.2	4.8	16.0	779	0%	-29.5	-4.95
F36	55.6	7.7	528	31.7	305.0	2.0	14.8	5.0	112.0	1.2	1.9	6.4	448	0%	-24.5	-4.21
F37	85.7	6.7	515	30.8	381.9	2.9	0.6	15.6	55.7	4.4	25.2	40.2	527	0%	-27.3	-4.47
F38	79.8	6.9	820	30.1	549.0	2.0	<0.5	10.3	76.0	4.5	43.6	47.2	733	1%	-23.6	-4.37
F39	73.7	6.8	775	31.0	524.6	5.0	2.5	4.2	72.0	4.2	30.2	62.4	705	0%	-24.9	-4.73
F40	-	7.1	521	31.5	305.0	1.0	<0.5	17.1	9.6	1.5	5.2	15.2	355	0%	-28.0	-4.62
F41	83.0	7.5	1310	31.3	359.9	47.1	<0.5	276.6	270.0	2.0	2.0	20.8	978	0%	-34.7	-5.57
F42	-	6.8	597	31.0	390.4	3.0	<0.5	16.0	30.8	5.4	13.4	83.2	542	1%	-27.0	-4.69
F43	49.2	7.0	221	31.1	91.5	5.0	32.8	0.0	19.0	1.8	4.3	17.6	172	-1%	-21.7	-3.86
F44	67.5	7.2	320	29.8	183.0	9.0	4.9	2.7	22.0	1.9	16.3	24.0	264	2%	-23.15	-4.02
F45	40.0	7.0	275	31.4	152.5	1.0	23.1	0.0	20.0	1.5	11.5	20.8	230	0%	-20.7	-3.78
F46	54.2	7.3	423	29.1	170.0	21.0	44.8	12.3	9.0	5.0	32.6	24.0	319	1%	-21.85	-3.61
F47	63.0	7.4	373	30.8	152.5	16.0	39.9	13.5	23.0	1.8	14.4	32.0	293	1%	-19.1	-3.55
F48	43.1	6.8	300	29.6	115.9	5.0	50.2	4.6	16.0	1.3	13.4	24.0	230	1%	-23.04	-3.38
F49	73.0	7.1	311	29.5	170.8	4.0	6.6	6.7	26.0	2.3	10.1	25.6	252	2%	-21.49	-3.57
F50	54.0	6.4	126.9	31.7	61.0	2.0	6.1	1.9	8.0	4.2	4.8	8.0	96	2%	-24.3	-4.33
F51	53.7	6.1	163	31.8	103.7	1.3	2.9	0.3	11.1	4.1	6.3	12.0	142	-3%	-24.8	-4.45
F52	-	6.8	320	29.4	109.8	19.0	44.4	8.2	33.0	1.2	10.1	17.6	243	1%	-19.49	-3.3
F53	32.0	6.9	206	32.8	115.9	3.0	6.1	2.2	16.4	2.3	6.7	16.0	169	0%	-23	-3.94
F54	34.0	6.5	165.7	29.4	48.8	8.0	22.6	5.8	9.0	3.1	3.8	16.0	117	2%	-22.01	-3.64
F55	61.5	6.7	341	31.2	207.4	4.2	15.3	2.7	32.7	3.7	11.0	28.9	306	1%	-20.6	-3.53
F56	66.0	7.1	349	31.1	183.0	5.0	26.6	3.7	25.0	1.5	13.0	28.0	286	1%	-21.3	-3.7
F57	50.0	6.2	275	29.6	97.6	10.0	40.1	8.3	24.0	3.8	8.2	18.4	210	1%	-23.98	-4.34
F58	60.5	7.3	437	28.9	256.2	15.0	2.7	8.2	25.0	0.6	22.1	37.6	367	0%	-23.49	-4.07
F59	42.2 55.4	7.7	335	32.5	231.8	3.0	3.6	4.7	22.4	1.3	13.4	33.6	314	4%	-22.04	-3.63
F60	55.1	6.1	159	31.7	91.5	4.0	1.2	<1	13.0	3.1	6.2	9.6	129	0%	-24.0	-4.36
F01	55.8	6.4	211	31.9	101.3	5.4	27.2	1.2	14.2	4.5	8.7	15.9	1/8	1%	-22.4	-4.00
F62	58.0	0.0 C 2	121	31.1	142.7	9.9	24.9	4.2	21.3	1.6	2.5	24.3	240	0%	-22.2	-3.82
F03	-	0.Z	142	31.2	05.4	1.2	9.5	0.4	9.9	4.0 2 0	2.5	9.1 10 E	101	-3%	-23.1	-4.10
F04	49.3 79.7	0.1 6 2	143	32.0	95.Z	2.0	3.Z	0.5	12.9	3.8 2.0	4.2	10.5	152	-4%	-22.5	-3.92
F65	49.3	6.6	220	20.9	122.0	2.0	15.2	0.0	Э.0 15 Л	1.0	9.0 9.0	20.8	196	2%	-22.5	-4.14
F67	88 5	0.0 7 1	220	30.8	122.0	3.0 26 Q	11.2	8.8	21.6	1.5	18.2	20.8	250	1%	-21.5	-3.80
F68	-	7.1	487	30.4	305.0	5.0	65	49	45.5	2.5	17.7	36.0	423	0%	-22.7	-4 01
F69	39.5	6.7	655	31.0	268.4	37.0	74.4	 19.8	28.0	7.6	31.7	61.6	528	0%	-19.2	-3,30
F70	16.3	6.8	121	29.7	42.8	5.0	12.1	3.3	2.0	2.8	4.8	12.0	85	2%	-19.4	-3.73
F71	- 0.0	6.9	365	32.7	244.0	3.8	9.1	2.9	23.1	2.4	19.9	33.1	338	1%	-23.2	-4.06
F72	91.9	8.6	1670	29.0	884.5	7.0	<0.5	52.4	376.0	7.9	12.9	12.0	1425	0%	-31.7	-5.24
F73	-	7.0	289	26.2	170.8	2.0	12.0	2.9	25.0	1.5	7.2	28.0	249	0%	-15.2	-2.95



Figure 5: Spatial distribution of TDS

In order to determine water types, chemical compositions of the analyzed water samples were plotted on the Piper trilinear equivalence diagrams (Piper, 1944) shown in **Figure 6**.

The Piper diagram shows that surface water samples are mainly bicarbonates associated with mixed cations, which gives them a hydrofacies of Ca-Mg-HCO₃. The study area is made up of two lithologic units: in the North the Birrimian basement and in the South the Volta basin which consists of consolidated sedimentary rocks. In these consolidated sedimentary rocks, groundwater flow is dominated by secondary permeability from fractures. In the anion triangle, almost all the samples (69 out of 73) are from the bicarbonate pole and the rest from the mixed pole. However, in the cation triangle, most of the samples are mixed with a clear evolution towards the sodium pole for the Volta basin samples. It appears that for the Birrimian basement samples, three hydrofacies have been identified: Ca-Mg-HCO₃ facies (71%) followed by the Ca-HCO₃ facies (26%) and finally the Na-HCO₃ facies (3%). The predominance of the Ca-Mg-HCO₃ facies in the basement area is consistent with the results of several other studies (Savadogo, (1984); Faillat, (1986); Ousmane, (1988)). Thus, the water samples of the Volta basin are divided into 5 hydrofacies dominated by the Ca-HCO₃ (40%) and Na-

HCO₃ (26%) facies. The least represented facies are the Ca-Mg-HCO₃ (14%), Na-K-HCO₃ (14%) and finally Na-Cl (8%) facies. For these waters, a natural evolution from the calco-magnesian facies to the sodium facies is observed probably due to the bases exchange. These results clearly reflect those obtained by Zoulgami, (2018) in the Kara region in the same lithological formations.



Figure 6: Piper Diagram showing chemical compositions of surface water and groundwater.

3.1.2. Application of the Water Quality Index

The Water Quality Index (Table 5) of the groundwater samples analyzed ranges from 14 to 84 with an average of 34 ± 12.5 . Based on the results obtained, 93.15% of the water samples have a WQI of less than 50 and therefore are of excellent quality and a proportion of 6.85% have a WQI between 50 and 100 and therefore are of good quality. Almost all samples collected in the study area are at least of good quality and fit for human consumption.

WQI range	Water type	Number of water samples	% of samples		
< 50	Excellent water	68	93.15		
50 - 100	Good water	5	6.85		
100 - 200	Poor water	0	0.00		
200 - 300	Very poor water	0	0.00		
> 300	Unfit for drinking	0	0.00		

Table 5: Classification of sampled points according to WQI

3.1.3. Principal Component Analysis

Principal component analysis showed (Figure 7) that the first 3 factors explaining mineralization account for 69.06% of the total variance (Table 6). The factor F1 accounts for 36.40% of the total inertia and is correlated with electrical conductivity, HCO_3^- and Na^+ (Table 6). It is linked to the

mineralization process by acid weathering of silicate minerals. The regrouping of HCO_3^- and Na^+ lets believe that these ions come from a process other than pollution through infiltration water. In the crystalline basement of West Africa, this phenomenon of silicate weathering is always expressed by the factor F1 (Faillat, (1986) ; Biémi, (1992)). This proves that acquisition of water mineralization in this zone is very complex (Abdoubabaye, (2012)). However, the factor F2 contributes for 19.24% of the variance, represented by Ca^{2+} and Mg^{2+} and therefore can be initially attributed to "natural mineralization" processes arising from water-rock interaction. Finally, the factor F3 related to NO_3^- , Cl^- and SO_4^{2-} accounts for 13.41% of the variance. This factor opposes nitrate with the rest of the major elements and reflects the result of anthropogenic processes, including nitrate contamination linked to the excessive application of chemical fertilizers.



Figure 7: Plot of the variables on the plan F1-F2 (A) and plan F1-F3 (B) summarizing correlation between variables and factors.

	F1	F2	F3
pН	0.644	-0.102	-0.282
Cond	0.982	-0.021	0.064
HCO ₃ -	0.884	0.251	-0.304
Cl ⁻	0.412	-0.220	0.667
NO ₃ -	-0.234	0.299	0.661
SO4 ²⁻	0.476	-0.423	0.494
Na^+	0.907	-0.324	-0.029
\mathbf{K}^+	0.012	0.370	0.150
Mg^{2+}	0.317	0.838	0.110
Ca^{2+}	0.325	0.769	0.065
Eigenvalue	3.640	1.924	1.341
Variability %	36.400	19.245	13.413
Cumulative %	36.400	55.645	69.058

Table 6: Factor loadings after varimax rotation

3.1.4. Mineralization processes of groundwater

To discuss the different processes contributing to water mineralization, binary diagrams were used. Figure 8a shows that almost of the groundwater samples in the study area fall below the Y=X equation line due to the excess bicarbonates. It indicates that silicate weathering is the main source of sodium and bicarbonates and that it exerts a major control over groundwater chemistry in this area (Lakshmanan *et al.* (2003); Rajmohan and Elango, (2004)). This result is in agreement with the conclusions of Loh *et al.*, (2012) for the entire basement aquifer of northern Ghana. This finding is also supported by the graph of Na⁺ versus Cl⁻ (Figure 8b) showing that most of the groundwater samples lie above the line of equation Y=X indicating that Na⁺ does not result of halite dissolution. According to Stallard and Edmond, (1983), excess of Na⁺ can be attributed to the alteration of silicate minerals such as feldspars or to human activities. Rogers (1989) found that if silicate alteration is the source of sodium, HCO_3^- would be the dominant anion as is the case in this study. This is probably the dissolution of albite to kaolinite leading to a subsequent increase in Na⁺ and HCO_3^- (Figure 8c):

$$2NaAlSi_{3}O_{8} + 9H_{2}O + 2H_{2}CO_{3} \Leftrightarrow Al_{2}Si_{2}O_{5}(OH)_{4} + 2Na^{+} + 2HCO_{3}^{-} + 4H_{4}SiO_{4}$$

Albite Kaolinite

Figure 8d which is the bivariate graph $(Ca^{2+} + Mg^{2+})$ vs HCO_3^- shows a simultaneous increase in the HCO_3^- and $(Ca^{2+} + Mg^{2+})$ concentration. The increase in $Ca^{2+} + Mg^{2+}$ concentrations is the result of the hydrolysis of silicate minerals such as pyroxenes and amphiboles, which are very abundant in the study area, especially in the samples from the Birrimian basement. The main weathering processes are illustrated by the following reactions:

$$\begin{aligned} CaMg(Si_{2}O_{6}) + 4CO_{2} + 6H_{2}O &\Leftrightarrow Ca^{2+} + Mg^{2+} + 4HCO_{3}^{-} + 2H_{4}SiO_{4} \\ \end{aligned}$$
Pyroxene
$$\begin{aligned} Ca_{2}Mg_{5}Si_{8}O_{22}(OH)_{2} + 14CO_{2} + 22H_{2}O &\Leftrightarrow 2Ca^{2+} + 5Mg^{2+} + 14HCO_{3}^{-} + 8H_{4}SiO_{4} \\ \end{aligned}$$
Amphibole

These results indicate that lithological composition of aquifers strongly influence the geochemistry. Groundwater geochemistry is also influenced by the degree of confinement of aquifer and the transmissivity. The study area consists of 2 types of lithology: in the North, the Birrimian basement formed mainly of granitoids (mainly granites and granito-gneiss), granodiorites, migmatites and amphibolites; to the South, the Volta basin formed mainly by consolidated sandstones (feldspar and mica rich sandstone) and shales. This basement is therefore predominantly acidic (saturated with silica). As a result, the groundwater of these environments is generally not very mineralized. Most granitoids are made up of plagioclase (oligoclase), amphibole, and biotite. Hydrolysis is the dominant process in the weathering of granite, leading to the dissolution of ions resulting from this phenomenon. The alteration of silicate minerals in granites gives rise to new silicate minerals, often from the clay family such as montmorillonite (smectite family) and kaolinite with the liberation of Ca^{2+} , Mg^{2+} , Na^+ and K^+ .

The hydrolysis of plagioclases is illustrated by the following formula (Boubakar Hassane, (2010)): (Equation1): $NaCaAlSi_2O_8 + CO_2 + H_2O \Rightarrow Al_2Si_4O_{10}(OH)_2 + Ca^{2+} + Na^+ + H_4SiO_4 + HCO_3^-$ Montmorillonite Or

 $(Equation 2) NaCaAlSi_2O_8 + CO_2 + H_2O \Longrightarrow Al_2Si_2O_5(OH)_2 + Ca^{2+} + Na^+ + H_4SiO_4 + HCO_3^-$ Kaolinite



Figure 8: Relationships between major elements in the analyzed water samples: $(Ca^{2+} + Mg^{2+})/(SO_4^{2-} + HCO_3^{-})$ (a); Na^+/Cl^- (b); HCO_3^-/Na^+ (c), $(Ca^{2+} + Mg^{2+})/HCO_3^{-}$ (d);

The hydrolysis of silicates is facilitated by infiltration of water rich in dissolved CO₂. The contact of these aggressive waters with silicate minerals will lead to the release of the most mobile cations (Na⁺, K⁺, Ca²⁺, Mg²⁺), silica and aluminum following the hydrolysis process. The destruction of primary minerals by incongruous dissolution (plagioclases, ferromagnesian minerals, etc.) generally generates the appearance of a sequence of neoformation clays such as montmorillonite, kaolinite, illite or gibbsite depending on their content in bases and degree of rainfall (Dekayir and El-Mataaoui, (2001); Nguetnkam *et al.* (2008)).

The saturation index results from the comparison of the ionic solubility product Ks of minerals with the corresponding ionic activity products in groundwater. Therefore, the saturation index assesses the balance between minerals and groundwater. The calculation of saturation indices concerned only calcite, aragonite (CaCO₃), dolomite (CaMg(CO₃)₂), and gypsum (CaSO₄, 2H₂O). Groundwater in the study area shows negative saturation index values (IS <0) with respect to gypsum (Figure. 9). These indices reflect a state of under-saturation with respect to this mineral. Compared to calcite, aragonite and dolomite, the saturation index values are also less than 0 for most samples. However, a few samples show saturation index values with respect to these minerals which are between 0 and 1, indicating a state of equilibrium of the groundwater studied with respect to these minerals. The analysis of saturation indices does not allow us to understand the geochemical mechanism of water mineralization from the precipitation of carbonate minerals (calcite) generally absent in granitic basement rocks. It is clear that the dissolution of calcium and sodium aluminosilicates minerals under the action of CO₂ dissolved in water is the dominant process in the acquisition.



Figure 9: Groundwater saturation indices with respect to some minerals

The presence of clays has been demonstrated and formed from level of sandy clays which may be the seat of ion exchange process. In addition, cation exchange processes are evaluated using the graph of $(Na^+ + K^+ - Cl^-)$ vs $(Ca^{2+} + Mg^{2+} - HCO^{3-} - SO_4^{2-})$ (Wanda *et al.* 2011). It shows an increase

Boguido et al., J. Mater. Environ. Sci., 2024, 15(5), pp. 648-673

in the Na+ content especially in the samples from the Volta basin scattered along a line with a slope of -1 (Figure 10). In this figure, the samples are shifted just below the origin, probably indicating the phenomenon of base exchanges with clay minerals, relatively abundant in the aquifer levels of the study system. During this process, existing Ca²⁺ and Mg²⁺ in the groundwater were exchanged by the Na+ previously adsorbed on the surface of clay minerals. Cationic exchanges take place according to the following global mass balance equation (Guo and Wang, 2005; Ben Moussa *et al.* 2010):



Na-argiles +
$$Ca^{2+}$$
 =======> Ca-argiles + $2Na^{+}$

Figure 10: Highlighting of basic exchanges for the aquifer system of the study area.

Groundwater was plotted on Gibbs' diagram for cations and anions (Figure 11). The Gibbs (1970) diagram for cations plots the total dissolved solids (TDS) on a logarithmic axis against the ratio of sodium and the sum of sodium and calcium on a linear axis.



Figure 11: Gibbs' diagrams for cations (a) and anions (b) indicating rock-water interaction.

The diagram for anions plots the total dissolved solids (TDS) on a logarithmic axis against the ratio of chloride and the sum of chloride and bicarbonate on a linear axis. The diagrams show that all the samples plot in the rock–water-interaction dominance field. This observation confirms that the chemistry of groundwater in the Northern Togo is dominated by the interaction between water and aquifer material. This is consistent with observations about the general hydrochemistry of groundwater from the major hydrogeological terrains in the country, binary relationship and principal component analysis. This result also corroborates the bases exchange and silicate weathering found as dominant processes controlling groundwater mineralization. Some authors in Ghana, using the Gibbs diagram, Banoeng-Yakubo *et al.* (2009); Yidana, (2009); Ganyaglo *et al.* (2011); Kaka *et al.* (2011); Yidana *et al.* (2012); Salifu *et al.* (2013) and Boateng *et al.* (2016) concluded that rock-water interactions are the most important processes that control the hydrochemistry of groundwater in different areas underlain by various geological formation such as the Birimian Supergroup, the Voltaian Super Group, the Cape Coast granite complex, the Lower Birimian and the Buem (Koffi, 2017).

In addition to these chemical analyses, stable isotopes analyses are performed, to better understand the dynamics of aquifer systems in the Savannah region which should help with better apprehending the mineralization of groundwater.

3.2. Stable isotopes hydrology

The isotopic approach is of crucial importance in modern studies of groundwater. This approach provides important information to help identify the origin of water and the history of their movement on the surface and subsurface. These techniques contribute to the understanding of recharge mechanisms, or to the characterization of the dynamics of aquifers by providing indications on the continuity and/or the hydraulic discontinuity of aquifer systems (Njitchoua *et al.* (1997); Kwang & Yongje, 2007; Cronin *et al.* (2005)). Despite the widespread use of environmental tracers in isotopic hydrology, the application of these methods is still exploratory in Togo in general and in the Savannah region in particular.

In this study, several isotopic results were used, of which 73 groundwater samples and 11 surface water samples were analyzed. These isotopic results are compared against to Global Meteoric Water Line (GMWL) of Craig and the Local Meteoric Water Line (LMWL) of the study area obtained by Boguido, 2020 (Equation: δ^2 H=7,81 δ^{18} O + 11,46).

Surface water samples show a wide variation in stable isotopic contents, -4.68 to -1.13% VSMOW with a mean of -2.54% VSMOW for δ^{18} O, and -26.9 to -7.9% VSMOW with a mean of -17.80% VSMOW for δ^{2} H. The groundwater shows a variation from -5.62 to -2.95% VSMOW with the mean of -4.35% VSMOW for δ^{18} O and of -34.95 and -15.17% VSMOW with a mean of -25.32% VSMOW for δ^{2} H. Histogram of oxygen 18 data is shown in Figure 12.

The stable isotopes contents are for the most part relatively depleted, with about 70% of the δ^{18} O values lower than -4.0‰ VSMOW therefore lower than the weighted average of rainwater which is - 3.91‰ VSMOW for Oxygen 18 and -19.11‰ VSMOW for Deuterium (Boguido, 2020). The most enriched values represent 5.5% of the samples with isotopic contents of δ^{18} O greater than -3.5‰ VSMOW.



Figure 12: Histogram of δ 18O values for groundwater samples.

A plot of δ^2 H versus δ^{18} O, for groundwater samples, reveals three distinct groups, based on the GMWL and LMWL (Figure 13).

-The first group is composed of samples located on or in the immediate vicinity of the GMWL. These samples, relatively depleted in heavy isotopes, have a δ^{18} O content between -5.0 and -3.5 ‰ VSMOW, which suggest fast recharge from infiltrated rainwater with no evaporation. This could be linked to the process of episodic recharge of these aquifers following short and intense floods, according to the usual pattern of arid and semi-arid zones. Water samples that fall in the first group constitute the largest part and are located in the Volta basin.

-The second group comprise samples located the points located under the GMWL and the LMWL, with enriched stable isotope contents (> -3.5 % VSMOW). This enrichment is due in part to evaporation at the surface, highlighting the influence of indirect recharge from surface water. These water samples follow the evaporation line of surface water ($\delta^2 H = 4.5016\delta^{18}O - 5.3464$; R²=0.925) indicating their contribution to the recharge of aquifer. This is the case for borehole F48 located near the Boadé dam where agricultural activities are practiced, explaining the high nitrate concentration (50.2 mg/l). It is the same for borehole F69 with a nitrate concentration of 74.4 mg/l, showing the connection between surface water and groundwater in this zone of high agricultural activity. These samples enriched in stable isotopes are located in the Birrimian basement and in the Southwest of the Volta basin (Figure 14).

- The third group, consisting of samples with depleted oxygen 18 content (<-5.0‰ VSMOW), is mainly located in the Volta basin, especially in sandstone and shales units where infiltration is slow. The depleted character of these borehole samples shows that these aquifers are either recharged by the significant precipitation at the peak of the rainy season, or it is relatively old water. This suggests that groundwater could come from a recharge during previous wetter periods. This poses the hypothesis of an old recharge that can be confirmed by research of radioactive isotopes.



Figure 13: Relation δ^2 H versus δ^{18} O of the analyzed water samples.



Figure 14: Spatial distribution of oxygen 18

The correlation between Oxygen 18 and NO₃⁻ (Figure 15a) shows the samples with high nitrate contents (> 30 mg/l) are more enriched in δ^{18} O. The fact that nitrates have a surface origin indicates the contribution of contaminated surface water to groundwater recharge. This anthropogenic origin of nitrates is confirmed by Figure 15b which shows that high concentrations are found in boreholes with

a depth of less than 60 m. As is the case for borehole F48 with 50.2 mg/l of nitrates content at a depth of 43.2 m and borehole F69 with 74.4 mg/l at a depth of 39.5 m.



Figure 15: Relationship between δ^{18} O versus NO₃⁻ (a) and Depth versus NO₃⁻ (b).

The relationship established between chlorides and oxygen-18 content has shown that (Figure 16) two trends:



Figure 16: Diagram ¹⁸O/Cl⁻ of groundwater in Savannas region

- The groundwater of the Volta basin has oxygen 18 content between -5.5 and -4‰ VSMOW with chloride concentrations increasing exponentially. Most of the groundwater in the Birrimian basement has δ^{18} O contents of -4.5 to -3‰ VSMOW with chloride content also increasing exponentially. These findings show that the mineralization of groundwater in the study area is acquired by the dissolution of minerals contained in aquifer formations by contact effect (dissolution of silicate minerals). The acquisition of the salt charge by dissolution effect has already been indicated previously.

- However, homogeneous waters with chloride contents between 2 and 5 mg/l, and oxygen 18 values between -5.5 and -4‰ VSMOW were observed. This type of water presenting geochemical

signature with a relatively soft and little evaporated, corresponds to the average composition of the precipitation which contributed to its recharge.

Conclusion

The present study combines of hydrogeochemical and isotopic analyses for the characterization of groundwater in the Savannah region of northern Togo. These analyses were in order to determine processes responsible for groundwater mineralization. Results from this study indicate that groundwater is weakly to moderately mineralized with TDS not exceeding 1400 mg/l. According to the Water Quality Index, groundwater has of good to excellent quality. The predominant hydrochemical facies in the Birrimian basement is the Ca-Mg-HCO₃ facies and the dominant one in the Volta basin is the Ca-HCO₃ facies. Principal Component Analysis and binary diagrams allowed to determine the processes that control groundwater mineralization. The main processes that influence groundwater mineralization are weathering of silicate minerals, and water-rock interaction due to the residence time of water and bases exchange. Some groundwater samples, however have high levels of nitrates showing pollution linked to human activities. Based on the isotopic signature of groundwater samples, three types are recognized. Water with depleted stable isotopes content, located around the meteoric lines, is interpreted as recharge by non-evaporated rainfall. However, water with relatively enriched stable isotopes content is thought to be reflecting evaporation from surface water. But the existence of depleted water compared to current precipitation in the Volta basin would highlight the presence of old water.

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