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Contribution of Piezometry and Hydro-Geochemistry to a Better Understanding of the Adamawa-Yadé Hard Rock Aquifer System in Ngaoundéré

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Abstract The hard rock-aquifer system in the urban context of Ngaoundere was investigated using piezometric measurements and hydro-chemistry to enhance understanding of its functioning and assess groundwater suitability for drinking and domestic purposes. Seasonal and intra-seasonal piezometric monitoring was conducted in different localities, along with chemical analysis of thirty-five ground and surface water samples. The chemical composition was determined for major elements using ion chromatography, and water facies and mineralization processes were assessed using Piper and Gibbs diagrams. The water quality index (WQI) was calculated to evaluate groundwater suitability for human consumption. The findings revealed diverse piezometric behaviors depending on well/borehole geomorphological positions and seasons. Wells situated on hilltops exhibited high piezometric fluctuations, while those in valleys near rivers showed low fluctuations due to support from river water levels. Recharge occurred during the rainy season through direct infiltration from hilltops, with stream water levels influencing piezometric levels in surrounding wells and boreholes. The surface and ground waters exhibited low mineralization, characterized by calcium-magnesium bicarbonate and sodic-potassic bicarbonate facies. Water-rock interactions and dilution with rainwater were identified as the main processes controlling water mineralization. According to the WQI, all groundwater samples were classified as "excellent quality water" for human consumption. However, the microbiological quality of groundwater in and around Ngaoundere was influenced by human activities, making it unsuitable for drinking without treatment.

Keywords: *hard-rock aquifer, hydrodynamic, water-mineralization, water-quality, Ngaoundere*

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1. Introduction

Access to drinking water is a fundamental human right recognized by the general assembly of the United Nations in 2010, which is working to ensure that this vital human need is met in all parts of the globe. To satisfy this right, groundwater in Africa as in other parts of the world is highly sought, as it is assumed to be relatively more protected from anthropogenic pollution [1]. It is well known that a major part of the African population (over 75%) relies on groundwater as their primary source of drinking water [2,3,4,5,6,7,8,9]. In fact, the growing population, tourism industry, and social advancement have all contributed to a rise in the quantity and quality of water needed in recent years [10,11,12]. This justifies the significant pressure exerted on this natural resource, bringing it to the forefront of scientific research for its sustainable management in recent decades.

Groundwater mainly located in the hard rock terrain which were intensively fractured owing to various tectonic events [13,14,15] and / or have been subjected to the process of supergene alteration [16,17,18,19]. These hard rock aquifers are of major importance, as they cover a significant proportion of the African continent, accounting for more than 50% of its surface area [7], over 80% in Cameroon [20] and can be close to 100% in the Adamawa region. They are generally known as hold good groundwater potential using as a source of water for populations residing in hard rock terrains [21]. However, their chemical characteristics generally depend on the diversity of geological formations and their alteration products through which the groundwater has flowed [22,23,24,25,26,27,28], as well as on the many human activities that have a greater impact in urban than in rural contexts [12,25,29,30,31].

Geologically, the Adamawa region in Cameroon belongs to the Central African Fold Belt (CAFB), specifically called Adamawa-Yadé domain located between the Sanaga Fault and Tchollíré-Banyo shear-zone and well known for its petro - structural diversity [32,33,34,35,36,37,38]. The relationship between the geological formations of Adamawa-Yade domain and groundwater was recently characterized in the SW part of the Adamawa region, precisely in the Mbakaou-Tibati area by [26,27]. These studies revealed that: (1) the large variability of the geological structure of the aquifer consists of several productive layers between 2 and 74 m depth; and (2) the water-rock interaction is the main process of groundwater mineralization, which mainly produces calcium-magnesium bicarbonate and sodium-potassium bicarbonates facies. Moreover, this geological and structural diversity relative to the different magmatic episodes has recently enabled the presentation of complex alteration sequences that highlight the existence of paleosols [39], whose impact on groundwater dynamics and chemistry cannot be ignored. In view of the above, it becomes crucial to examine the hydrodynamic and hydrochemical functioning of this hard rock aquifer in a urban context of developing country. Thus, the main objective of this study is to improve understanding of the aquifer's functioning, and its hydrochemical behaviours for sustainable management of a hard rock aquifer system (saprolite aquifer / fractured aquifer) in the context of Ngaoundéré and to test the groundwater suitability for human consumption.

2. General Setting

Geography

The study area is located in and around Ngaoundéré, regional headquarter of the Adamawa region in Cameroon (Figure 1a). It extends between the parallels 7.15 and 7.60 degrees of North latitude and the meridians 13.30 and 14.0 degrees of East longitude, with rivers Bini and Vina as the main water courses in the area (Figure 1b). The climate is humid tropical or Sudanese [40,41,42], with two seasons characterized by: (1) a dry season (from October to March) and a rainy season (from April to September); (2) average annual rainfall of 1500 mm [42] and (3) average annual temperature of 21.4°C. The geomorphology is dominated by plateau reliefs [39,43] with an average altitude of 1100m separated by accidental features such as the “cliff of Ngaoundéré” or the waterfalls of Bini.

Geology and Hydrogeology

The Adamawa plateau is located in the Central Domain of Cameroon (Figure 1a) in the Central pan-African Fault Belt [37,44,45]. Also called the Adamawa-Yadé domain, it corresponds to a Paleo-Proterozoic to Archean basement complex, remobilized during the Pan-African orogeny by polyphase deformations, and the emplacement of several generations of granitoids, including the Ngaoundere pluton [44]. The Adamawa plateau consists of a granito-gneissic basement represented by metamorphic rocks (Gneiss, amphibolites, schists) and pre-Neoproterozoic granitic rocks [37,46]. The study area is characterized by the presence of two major rock groups, namely plutonic rocks (calco-alkaline granites) and volcanic rocks (basalts) (Figure 1b). The granites vary from fine grain, medium grain to porphyroïd granites and outcrop in slabs and blocks of some centimeters to tens of meters size. They are alkaline and calco-alkaline and have as mains minerals quartz, plagioclase, feldspars with biotite and secondary minerals oxides, muscovite [32,37]. On the other hand, volcanism represented by the NE branch of the Cameroon Volcanic Line with volcanic rocks such as basanite , basalt, in northern Ngaoundere and Tchabal Mbabo [47,48]. The various rocks are traversed by fractures whose main direction is E-W or ENE-WSW and which can contribute enormously to the circulation of groundwater [44,49]. The said rocks are mostly covered by lateritic soils with thickness ranging from few centimeters to several tens of meters [50,51]. The lateritic soils are rich in clay minerals such as kaolinite goethite, hematite, halloysite, illite, smectite and can be indurated or not and are sometimes associated with hydromorphic soils [52,53].

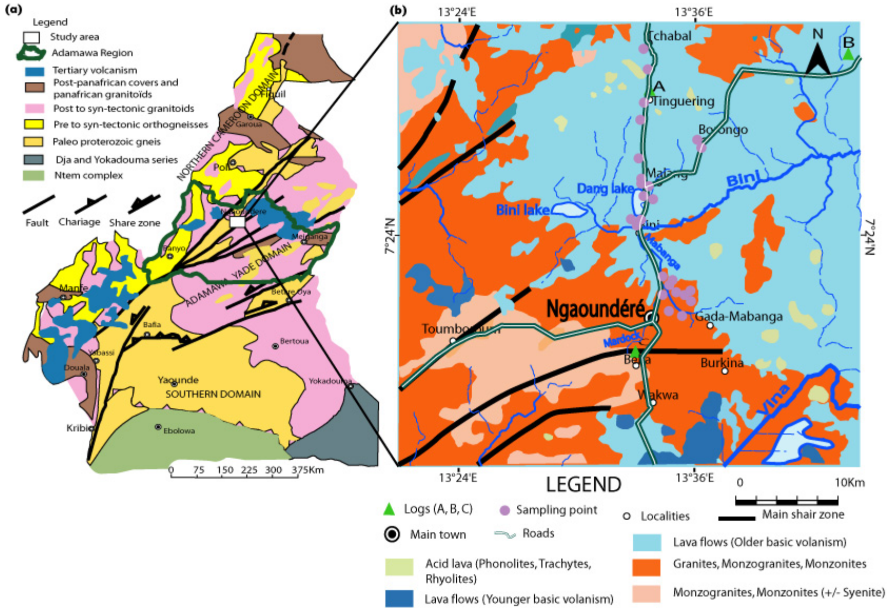

Figure 1a. Adamawa Region in Cameroon with main geological units, **b**. Location map of the study area comprising the geological map, the sampling and seasonal monitoring points

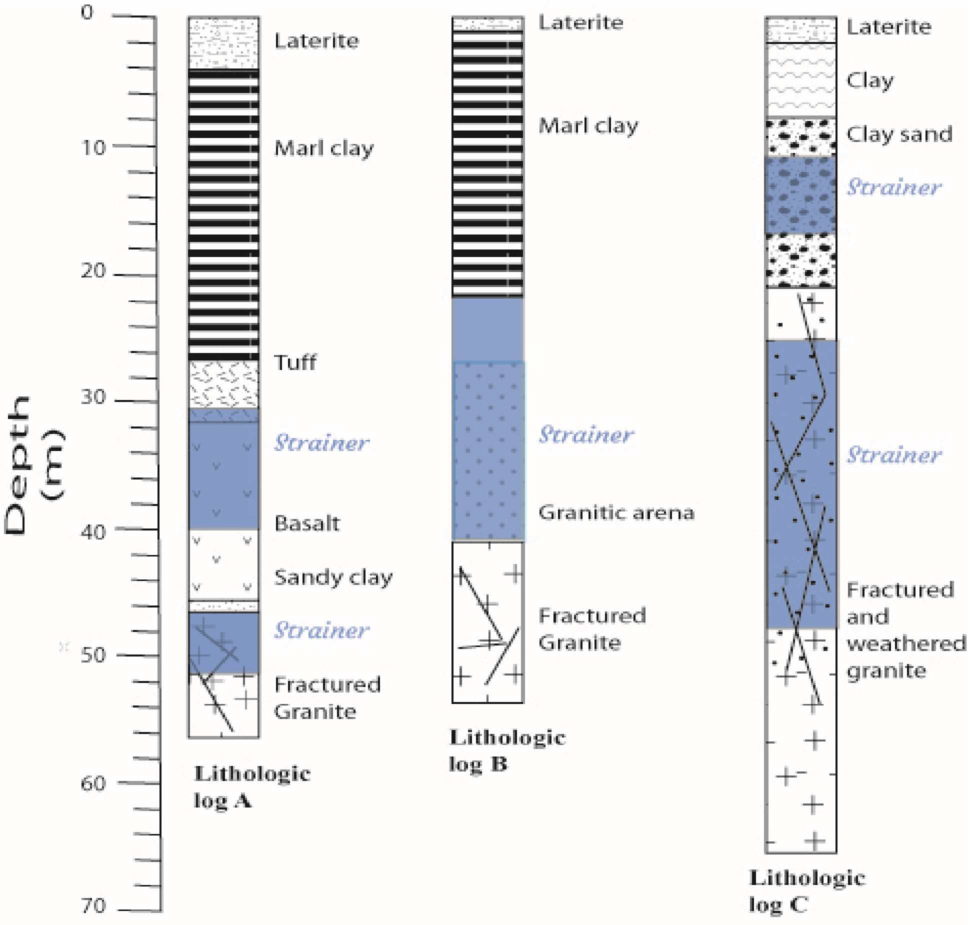

Figure 2. Typical lithological log description of boreholes in the study area

Hard rocks zones are generally characterized by the presence of two types of aquifers: superficial aquifers in alterites and deep aquifers in fractures [54,55]. Adamawa is no exception to this rule and shows that the superficial aquifers are located between 2 and 17 m deep and deeper fractured aquifers between 11 and 74 m [26,56]. In the study area, lithological logs of productive boreholes (Figure 2) allow to identify the two aquifer levels: (1) a superficial level located between 1 and 22 m below the ground surface in the alterites; (2) a deep level located below 25m deep in the fractured rocks. The two aquifer levels are separated by a semi-permeable to impermeable layer of clayey textures on basaltic profiles and clayey-sandy on granitic profiles (Figure 2). The superficial aquifer is captured mainly by shallow wells (traditional or modern) but also by some boreholes and the deep level is captured only by boreholes whose depth is between 25 and 90m. These hard rock aquifers constitute an important groundwater reservoir in the area. [57] showed that more than 70% of the population depends on groundwater for their various water needs: each compound has either a traditional or modern well, or a borehole and some local companies exploit this water for commercial purposes.

Water sampling and chemical analysis

A HACH multi-parameter probe was used to measure the physicochemical characteristics (pH, EC and temperature) of water samples in situ. This was done once in May for Tchabal-Malang (1 river, 7 wells and 3 boreholes), October for Dang (3 rivers, 7 wells and 3 boreholes), and November for Gada-Mabanga (2 rivers, 7 wells and 3 boreholes). In Mardock watershed, electric conductivities were simultaneously with the piezometric monitoring on the same points (Figure 3).

A total of thirty five ground/surface samples were also collected from three different localities for chemical analysis. Thus, 01 surface and 10 ground water samples were collected in May 2022 for Tchabal-Malang, 03 surface and 09 ground water samples in October 2019 for Dang, and 02 surface and 10 ground water samples in November 2019 for Gada Mabanga. The samples were analyzed to determine their chemical composition in major ions (**Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, SO_2^{3-}, NO_3-, Cl^{-}** and **HCO_3^{-}**) using ion chromatography at the Geochemical Water Analysis Laboratory (LAGE) of Yaoundé in Cameroon. TDS was calculated using the formula given by [58] 1mg/l = 1.56 µS/cm).

Groundwater and surface water data were plotted in the Piper diagram [59] using the software "Diagrammes (6.48 version)" which is an empirical way of determining the water type and for establishing correlations between some chemical elements. The CAI 1 and CAI 2 were also calculated for the various samples as followed

$$CAI\ 1 = Cl^{-} - \left(Na^{+} + K^{+}\right) / Cl^{-} \tag{1}$$

$$CAI\ 2 = Cl^{-} - \left(Na^{+} + K^{+}\right) / \left(SO_4^{-} + HCO_3^{-} + NO_3^{-}\right) \tag{2}$$

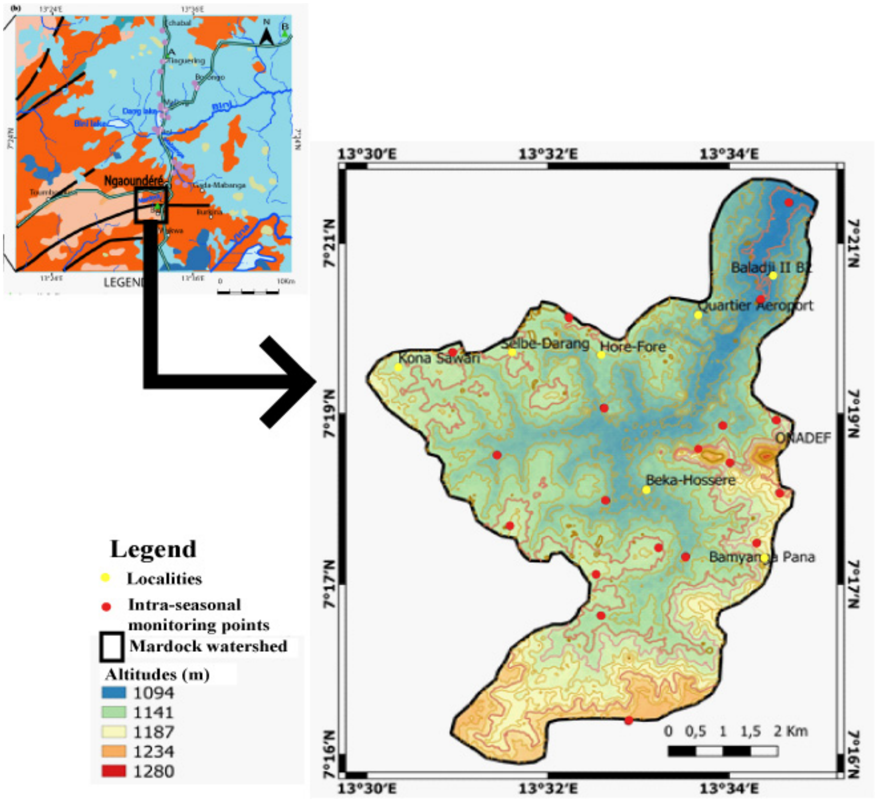

Figure 3. Map intra-seasonal monitoring points

Calculation of Water quality Index (WQI)

Obviously, water is only considered potable if it meets certain conditions. To assess the suitability of the study area's groundwater for human consumption and general domestic use from the chemical point of view, the Water Quality Index (WQI) described by [60,61,62], was used. It assesses the composite influence of different parameters taken individually on the overall quality of water [63] intended for human consumption.

The WQI calculation method consists of three steps as summarized by [63]:

The first step, involves assigning each of the parameters i (HCO_3, Cl, SO_4, NO_3, Ca, Mg, Na and K) a weight (w_i) whose value varies between 1 and 5, depending on its relative impact in the overall quality of drinking water. The weights assigned here are those proposed by [63], where great importance is given to parameters whose presence above certain critical concentration limits could limit the resource's ease of use for domestic and drinking purposes [65].

The second step consists in calculating the relative weight (Wi) of each parameter according to the equation:

$$\mathrm{Wi} = wi / \sum_{i=1}^{n} wi \qquad (3)$$

where Wi is the relative weight, wi is the weight of each parameter and n is the number of parameters.

The third step is to assign each parameter a quality rating scale (qi) by dividing its concentration in each water sample by its respective standard. The standards used here is that of the [64]:

$$qi = \left(Ci / Si\right) * 100 \qquad (4)$$

where qi is the quality rating, Ci is the concentration of each chemical parameter in each water sample (in mg/l).

To calculate the WQI, the sub-index (SI) is first determined for each chemical parameter, and then used to determine the WQI according to the following equations:

$$SIi = Wi * qi \qquad (5)$$

$$WQI = \sum SIi \qquad (6)$$

3. Results

Piezometric fluctuations

Different types of behaviors are observed in relation to the periods of the piezometric measurement in well or borehole. Seasonal piezometric fluctuations in the locations studied show different amplitudes, ranging from 0.2 to 7m at Tchabal with an average of 2.41 ±1.75m (Figure 4a), from 1.43 to 2.6m, at Dang with an average of 0.57±0.61m (Figure 4b), from 0.3m to 7.4m at Gada-Mabanga with an average of 1.8 ±1.31m (Figure 4c). Seasonal piezometric monitoring shows that piezometric head is deeper in the dry season than in the wet season. Figure 4a, 4c and 4d show a recharge (between May and November), figure 4b shows a discharge of the aquifer (between august and December). However, some wells (DgP127, DgP182, DgP202, GMP62) and boreholes (TMf6, TMf7) show an opposite hydrodynamic behavior to that described above.

Intra-seasonal piezometric monitoring carried out every two weeks during the rainy season in the Mardock locality has shown that piezometric levels rise towards the ground surface as the rainy season progresses (Figure 4d). This confirms that groundwater recharge is mainly due to precipitation, as already seen with seasonal fluctuations. The recharge period starts at the beginning of the rainy season in May and end at the beginning of the dry season (end September or October for most of wells). The discharge period begins with the dry season in October and certainly ends in May. This hydrodynamic behavior is generally observed in wells located near main water course of Mardock river. These wells are generally shallow depth and have low piezometric fluctuations (0.3 to 1m), demonstrating that the watercourse supports the groundwater in its immediate vicinity during the observation period. However the wells located far away from main river course and deeper than 10m (MK-P43, MK-P14, MK-P50, MK-P45, MK-P23) record high piezometric fluctuations (between 4 and 7.6m) and show that recharge period can extend beyond end of October. This hydrodynamic behavior is generally observed in wells located on mountain tops and slopes. Based on the results obtained here, it can be concluded that the unsaturated zone of the alterite aquifer which is heterogeneous, leads to high variable permeabilities.

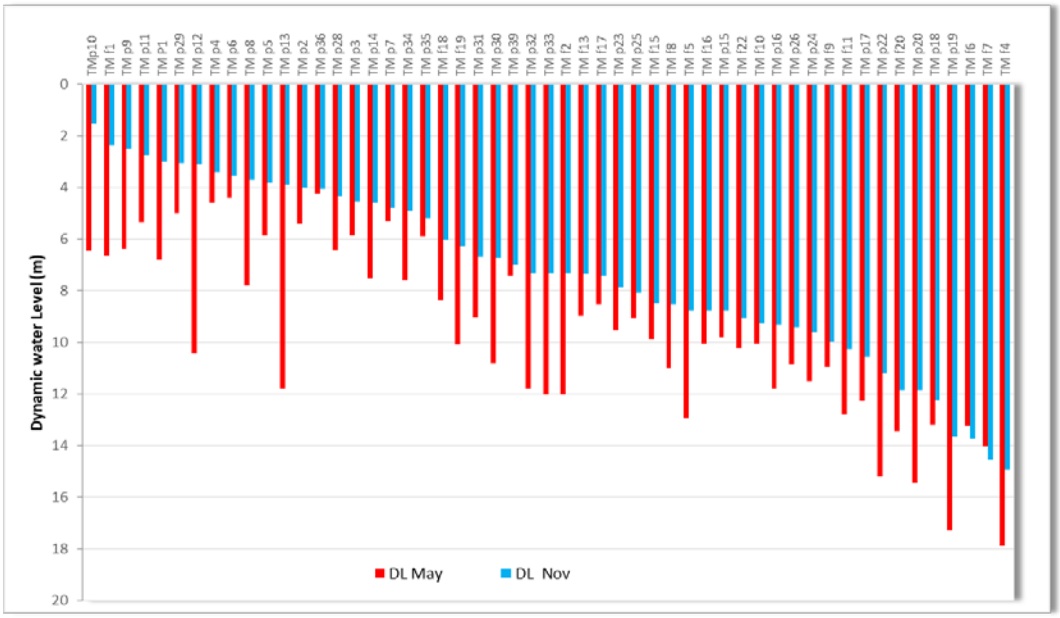

Figure 4a. Dynamic Water Levels in wells and boreholes for the months of May and November in Tchabal-Malang

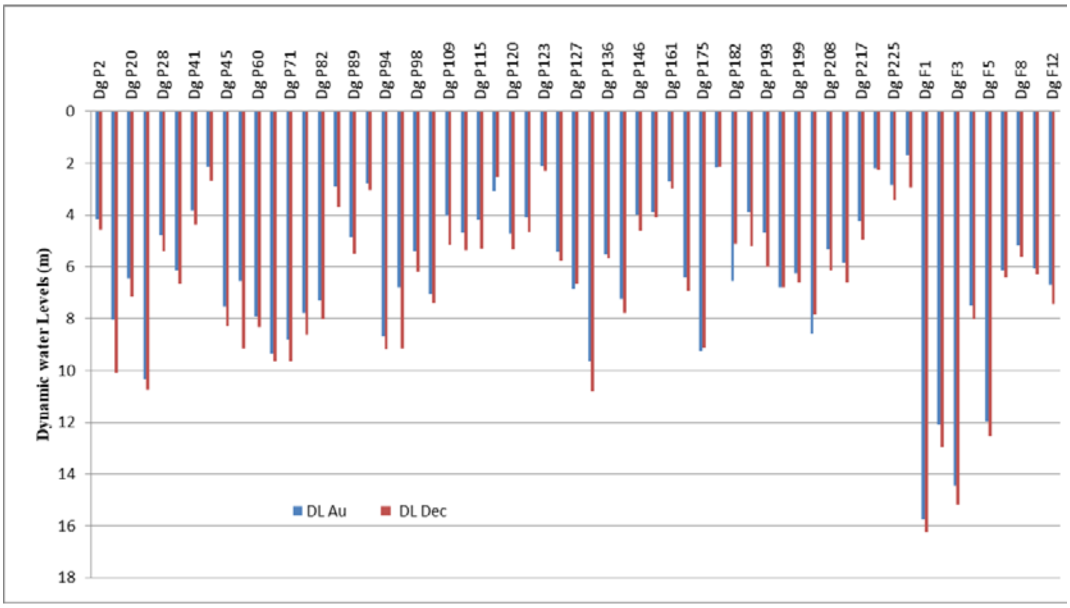

Figure 4b. Dynamic Water Levels in wells and boreholes for the months of August and December in Dang

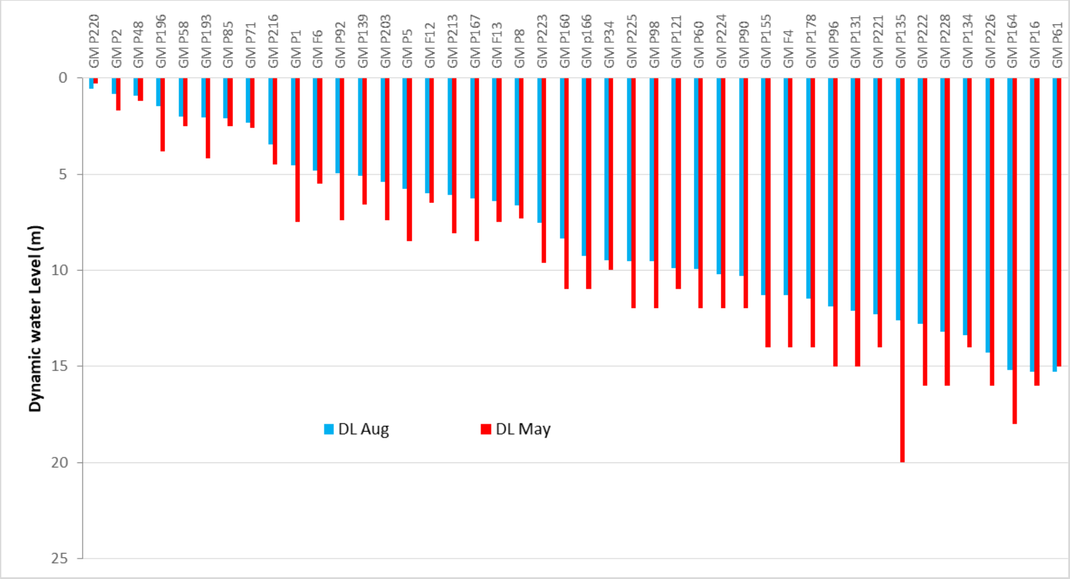

Figure 4c. Dynamic Water Levels in wells for the months of May and August in Gada Mabanga

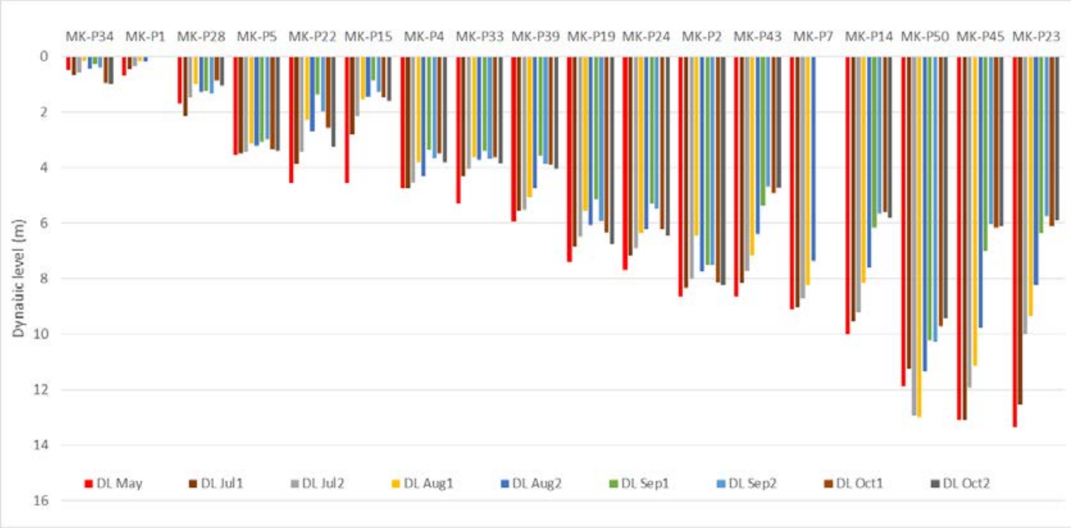

Figure 4d. Dynamic Water Levels in wells for the months of May, July, August and September in Mardock watersh

General Hydrochemistry

Chemical analyses of water samples from the study area produced the results that are presented in Table 2 below. The results are presented for each of the localities per type of water sample (groundwater from well and from borehole) as far as groundwaters are concerned.

With a mean of 24.8°C, the temperature swings between 24 and 27°C for surface waters. Concerning groundwaters (wells and boreholes), temperatures vary between 24 and 25°C. The environment at the time of measurement has a considerable impact on the temperature, which is typically in equilibrium with that of the atmosphere (about 25°C) at that period of the year. Both the surface water and the groundwater were found to be acidic and/or close to neutral. However, it's important to note that there is a decrease of pH values from surface to groundwater. The EC remain averagely low for all the samples, surface and groundwater from the various localities. It is evident that EC increases slightly while shifting from surface water to well water and then to borehole water, with the exception of a few (DgS3, DgP3 DgP4, GMP131, GMP213, TMF1, DgF4, GMF4). Intra-seasonal monitoring shows that the EC varies widely from a well to another (Figure 5). It's worth noting that in some wells (MKP4, MKP28, MKP33, MKPP34, MKP39) the EC remains very low (less than 50µS/cm) during all the period of observation. Some wells (MKP7, MKP14, MKP19, MKP22, MKP23, MKP24 and MKP45) recorded an increase of their EC and others (MKP2, MKP43 and MKP50) had a decrease. Considering mean concentrations in Table 1 below, it appears that the concentration of most of the cations and anions increases from surface to underground with some exceptions Cl-, NO_3- whose concentrations decrease and K^+ that remains relatively stable.

Chemical data of major ions were to calculate the CAI 1 and CAI 2and plotted on the diagram below (Figure 6). The tri-linear diagram of Piper [59] was used to determine the types of waters in the study area, as well as their geochemical characteristics. The diamond shaped field on the diagram which is divided into six major groups representing each a water type (Figure 7), shows that the waters in the study area are of two main types: calcium-magnesium bicarbonate (Ca-Mg-HCO_3) and sodium and potassium bicarbonate (K-Na-HCO_3). It can also be seen that in the sodium and potassium bicarbonate field, only samples from Gada Mabanga are found.

The plot of water samples in the Piper diagram (Figure 7) shows that: in the cations triangle, the samples of both surface and ground waters are scattered. However, some water samples (GMP135, GMP16, DgP3) are closer to the **Ca^{2+}** pole, while others (GMP131, GMP213, GMF4) are closer to the **K^++ Na^+** pole. In the anions triangle, all the samples of both surface and ground waters are grouped around the bicarbonate pole. This shows that HCO_3- is the lone dominant anion in all the water samples.

Water Quality Index (WQI)

The results of the WQI calculated for the groundwater samples are presented in the Table 2 below. They range from 7.9 to 39.8, thus all classified as of excellent quality according to the classification given by [65].

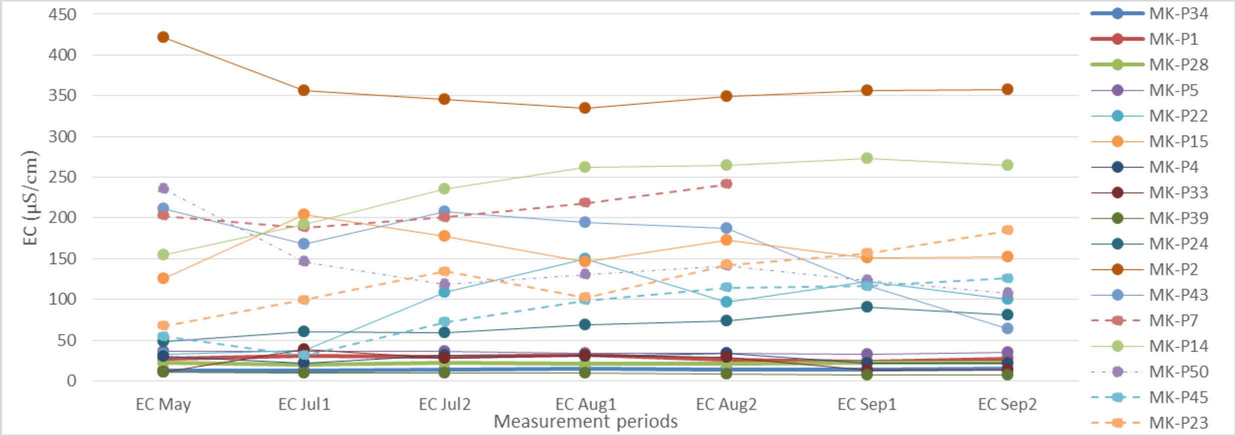

Figure 5. Temporal evolution of EC between May and October in 18 wells

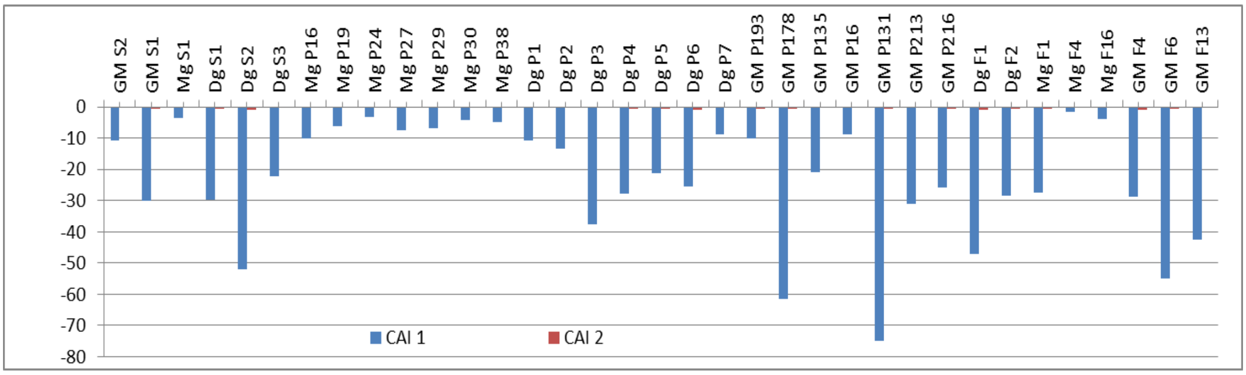

Figure 6. CAI 1 and CAI 2 values for the water samples in the study area

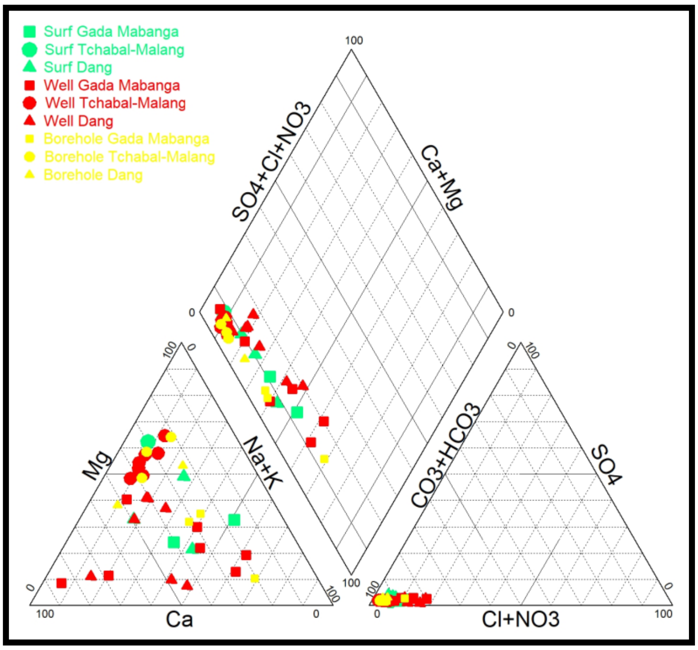

Figure 7. Plot of surface and groundwater (well and borehole) samples from different localities of the study area in the Piper diagram

Table 1. Physico-chemical composition of surface and ground-water samples in Ngaoundere town and surroundings

Sample		T°C	pH	EC (µS/cm)	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	Na^{+} (mg/l)	K^{+} (mg/l)	SO_4^{2-} (mg/l)	NO_3- (mg/l)	Cl- (mg/l)	HCO_3- (mg/l)
Surface water	Max	27	6.2	151.3	6.0	3.6	4.5	4.1	0.5	2	0.7	27.9
	Min	24	5.7	24.3	1	1.2	2.0	0.2	0.4	0.5	0.2	16.2
	Mean	24.8	6.0	66.1	4.0	2.2	3.2	2.0	0.5	1.2	0.3	19.5
	SD	1.3	0.2	50.1	2.0	0.9	1.0	1.6	0.1	0.6	0.2	4.8
Wells Groundwater Malang	Max	25.8	6.8	58.7	6.4	5.5	1.5	2.3	0.8	1.1	0.6	47.8
	Min	25.4	5.2	9.5	2.9	4.2	0.4	1.6	0.4	0.1	0.3	23.6
	Mean	25.6	5.7	27.0	5.1	4.9	0.8	1.8	0.6	0.5	0.5	34.4
	SD	0.1	0.6	20.4	1.3	0.5	0.4	0.2	0.2	0.3	0.1	9.7
Wells Groundwater Dang	Max	24.8	6.4	167.9	20.1	6.1	5.2	3.9	0.4	6.5	0.5	37.2
	Min	24	4.4	21.4	5.0	0.6	2.3	0.5	0.3	1.03	0.2	15.2
	Mean	24.4	5.3	85.8	8.6	2.7	3.7	1.6	0.4	2.9	0.4	25.3
	SD	0.3	0.6	59.5	5.5	1.9	1.1	1.2	0.0	1.9	0.1	10.3
Wells Groundwater Gada Mabanga	Max	25.7	6.9	180	30.1	13.4	4.5	6.8	0.5	3. 9	0.1	37.2
	Min	24	4.9	10	1	0.6	2.4	0.2	0.4	1.1	0.1	18.6
	Mean	24.9	5.8	77.5	10.5	3.1	3.5	2.9	0.5	1.7	0.3	25.6
	SD	0.2	0.7	56.0	11.4	4.3	0.7	2.5	0.0	0.9	0.2	6.6
Borehole Groundwater Malang	TMF1	25.6	5.6	20.46	2.33	4.26	0.45	2.35	0.14	0.07	0.1	8.73
	TMF4	25.8	6.9	317	3.12	3.43	0.33	1.21	1.26	0.49	0.99	76.86
	TMF16	25.7	7.8	87.9	5.4	4.12	0.57	2.49	0.83	0.32	0.76	50.45
Borehole Groundwater Dang	Dg F1	24.3	6.53	30.6	23.06	10.33	3.8	2.1	0.43	0.54	0.161	16.3
	Dg F2	24.2	5.8	67.4	3.01	4.25	2.02	2.7	0.43	0.26	0.19	17.86
Borehole Groundwater Gada Mabang	GM F4	26	5.6	40	2.01	0.61	4.7	5.1	0.46	1.58	0.4	18.61
	GM F13	24	5.6	60	3.01	2.43	4.8	0.5	0.46	1.5	0.18	37.21

Table 2. WQI for each groundwater sample analyzed and classification

Sample	Code	WQI	Water quality according to [66]
Well Tchabal-Malang	TMP16	14.2	Excellent water quality
Well Tchabal-Malang	TMP19	14.4	Excellent water quality
Well Tchabal-Malang	TMP24	16.1	Excellent water quality
Well Tchabal-Malang	TMP27	14.1	Excellent water quality
Well Tchabal-Malang	TMP29	18.1	Excellent water quality
Well Tchabal-Malang	TMP30	13.6	Excellent water quality
Well Tchabal-Malang	TMP38	16.5	Excellent water quality
Well Dang	Dg P1	39.8	Excellent water quality
Well Dang	Dg P2	29.0	Excellent water quality
Well Dang	Dg P3	28.1	Excellent water quality
Well Dang	Dg P4	18.7	Excellent water quality
Well Dang	Dg P5	21.8	Excellent water quality
Well Dang	Dg P6	23.5	Excellent water quality
Well Dang	Dg P7	13.2	Excellent water quality
Well Gada Mabanga	GM P193	15.8	Excellent water quality
Well Gada Mabanga	GM P178	38.8	Excellent water quality
Well Gada Mabanga	GM P135	28.4	Excellent water quality
Well Gada Mabanga	GM P16	19.1	Excellent water quality
Well Gada Mabanga	GM P131	15.7	Excellent water quality
Well Gada Mabanga	GM P213	20.5	Excellent water quality
Well Gada Mabanga	GM P216	20.8	Excellent water quality
Borehole Dang	Dg F1	28.5	Excellent water quality
Borehole Dang	Dg F2	11.8	Excellent water quality
Borehole Tchabal-Malang	TMF1	7.9	Excellent water quality
Borehole Tchabal-Malang	TMF4	19.1	Excellent water quality
Borehole Malang Mabanga	TMF16	17.2	Excellent water quality
Borehole Gada Mabanga	GM F4	17.3	Excellent water quality
Borehole Gada Mabanga	GM F6	19.9	Excellent water quality
Borehole Gada Mabanga	GM F13	12.7	Excellent water quality

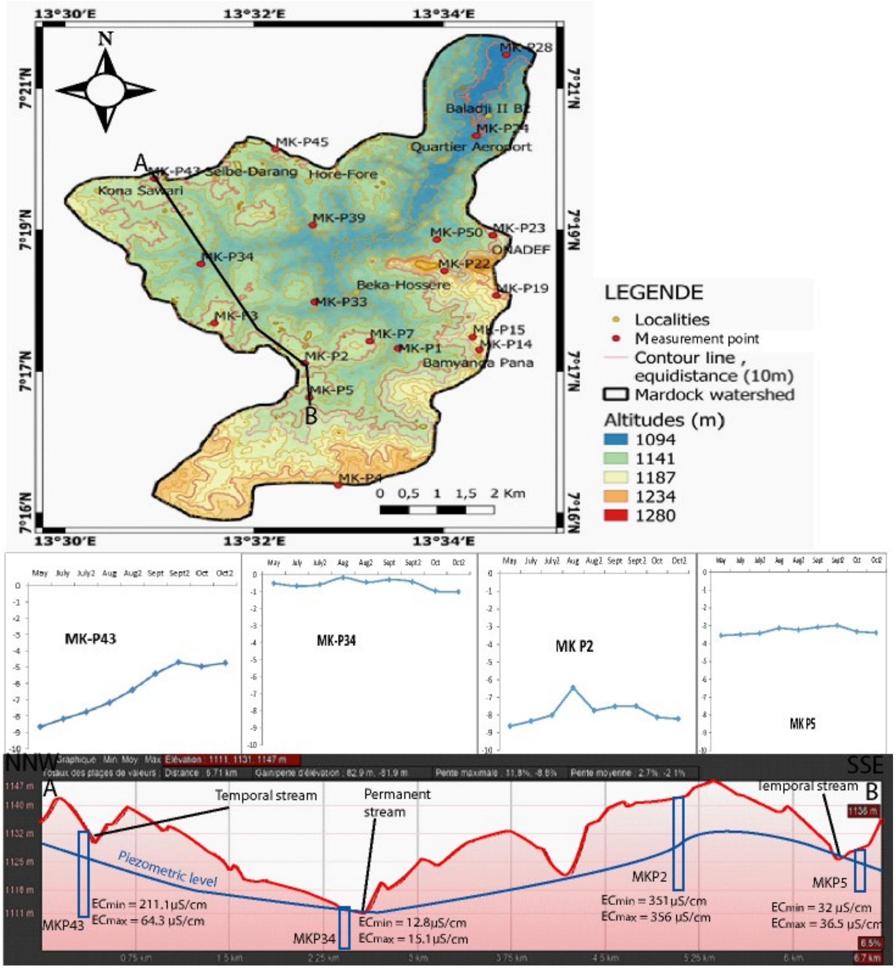

Figure 8. Piezometric evolution of wells MK P39, MK P33, MK P2 and MK P5 during the monitoring period in Mordock and sketch of the relationship between ground and surface waters

4. Discussions

Hydrodynamic functioning of the aquifer system

Seasonal piezometric monitoring in Tchabal, Dang and Gada-Mabanga and Mardock reveal that during rainy period, the water table rises towards the surface showing a recharge of the aquifer; inversely, during dry period the water table falls dipper showing the aquifer discharges. The scenario is similar in both wells and boreholes, suggesting that the aquifer exploited through the boreholes and wells is recharged with rain water through direct infiltration. Therefore the recharge of the aquifer should takes place in the month of April (beginning of the rainy season). The five months biweekly piezometric monitoring in Mardock area combined with low EC observed (Figure 4d), confirm this recharge through direct infiltration of rain water. These findings corroborate other studies which have shown that the shallow hard rock aquifers are principally recharged through direct infiltration of rain water [16] [66,67,68,69,70]. Indeed, the more we advance in the rainy season, the more piezometric heads rise towards the surface. However, it's worth noting that infiltrated water doesn't arrive in the saturated zone of the aquifer at the same time in all the monitored wells. It can be explained principally by the variation of permeability of the saprolite which also exhibits the vertical and lateral heterogeneity of saprolite formations that would delay recharge [17,22,39,71]. Other authors like [72] in Sanon granitic aquifer (Burkina Faso), mention as reason that boreholes and wells tap groundwater from different aquifer parts (weathered aquifer above or fissured aquifer below) that may be poorly connected or disconnected [72]. The disconnection in the study area is not clearly observed in lithological-logs from drilling technical report (not details in this paper), and allow to demonstrate that boreholes / wells tap in both weathered and fissured fractured zone..

On the other hand, some wells (DgP127; DgP182 and DgP202, GMP62) show a decrease of piezometric head during the recharge period. The impact of small daily withdrawals which locally drawdown piezometric heads can be accentuated by the long distance to be covered between the wells / boreholes monitored during the various field campaigns; As a result, in the dry season, piezometric heads are closer to the Earth's surface, while in the rainy season, they become deeper.

For a better understanding of the relationship between ground and surface waters a cross-section (AB) passing through some monitored wells and rivers in Mardock watershed was presented in figure 8. This figure clairly shows different piezometric behaviors depending on the geomorphological position of the well/borehole. Indeed, at the study area scale, the wells situated on a hilltop (MK P39, MK P2, TMP12, TMP13, DgP53, DgP96 and

GMP135) show a high piezometric fluctuation (≥ 2m); and those situated in the valley, near river (MKP1, MKP5, MKP34, TMP6, TMP7, TMP35, TMP36, DgP28, DgP43, DgP92, DgP180, GMP8, GMP48, GMP71, GMP83, and GMP220) show low fluctuation (≤ 2m). These high amplitudes of piezometric variation at the top of the hills are interpreted as zones of direct recharge by infiltration of precipitation. The low amplitudes in the valley bottoms (close to rivers) suggest that, in addition to direct recharge, the aquifer's piezometric heads are supported by river water. Although punctual withdrawal by population impacted the piezometric heads during seasonal monitoring in some wells, the same observations were made in the groundwater of other localities in the study area (Dang, Gada-Mabanga and Tchabal-Malang).

Overall piezometric physico/chemical monitoring and waters' chemical compositions suggest that the aquifer in the study area behaves as an unconfined one.

Groundwater mineralization

The general hydrochemistry results displayed above showed that both surface and ground waters are poorly mineralized and dominated by calcium-magnesium bicarbonate (Ca-Mg-HCO_3) facies associated to less dominant sodic-potassic bicarbonate (Na-K-HCO_3) facies. The presence of these facies underlines a complex mineralization process within the aquifer. On the Gibbs diagram (Figure 9), the groundwater samples fall in the domains of dilution and water-rock interactions. The dilution process occurs as rain water passes into the aquifer through direct infiltration (for wells and boreholes situated at the hilltops) or due to mixing of groundwater with the surface water flowing in the streams (for wells and boreholes situated in valleys near streams). Chemical composition of surface and ground waters are principally governed by water-rock interactions. In fact, from a geological point of view, the study area consists of a granito-gneissic basement overlain by basaltic formations whose alteration is likely to release these elements. According to [46,73,74] granites and basaltic series contain respectively minerals of calcic and sodic plagioclases and alkali feldspars, whose alteration brings Ca and Na into solution. Alteration of ferromagnesian minerals such as biotite and olivine in granites [37,75] and basalts [46] respectively, releases predominantly Mg. However, the coexistence of different rock types in the same environment makes the relationship between water chemistry and geology complex. This complexity is underlined by the work of [39], which presents the existence of paleosols developed on basaltic series of different ages in a granitic environment. These elements are therefore in favor of the existence of a majority of calcium bicarbonate facies associated with a sodium bicarbonate facies. The chemical trends expected according to geological formations therefore remain difficult to highlight from the concentrations of major elements because of the polyphase soil developed on different geological formations precised by [39] and relatively good lateral flow of groundwater in the heterogeneous weathered formations already pointed out by many authors in the hard rock aquifer context (eg: [17,76,77].

Calculation of CAI, equations (1) and (2) shows negative values, in favor of a normal exchange of Ca and Mg ions from the water by Na and K ions from the solid matrix. The most negative values (GMS1, GMP121, GM112 and GMF4) recorded at Gada Mabanga underline the dominance of this process in the acquisition of mineralization and are consistent with the sodic bicarbonate facies obtained on the Piper diagram. This idea is supported by the increase in sodium concentrations from surface water to the groundwater observed in samples GMS1, GMP121, GM112 and GMF4. This shows that groundwater gradually acquires its mineralization as it flows from the recharge area to the sampled site. [79] explained similar process in the granite-carbonate coastal aquifer of Bonifacio (Corsica, France).

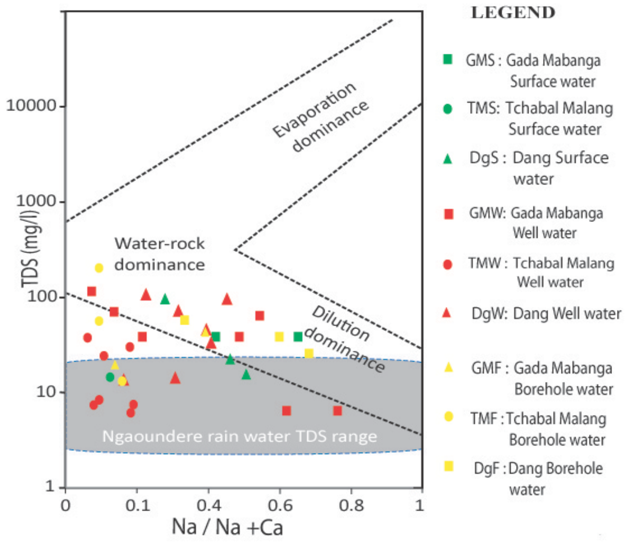

Figure 9. Gibbs diagram: TDS vs. Na/(Na + Ca) on which is materialized the range of TDS of Mbalang-Djalingo rain water from [87]

In groundwater from boreholes, there is a good correlation between alkalinity and conductivity which testifies of the hydrolysis of silicates. Indeed, according to [79] the weathering of silicate minerals (feldspars, micas, quartz, etc.) is the main cause of water alkalinity in basement aquifers. The evolution of groundwater mineralization can also be influenced by it residence time in the aquifer and by human activities [80,81]. The Gibbs diagram (Figure 7) shows that the great majority of samples have a TDS lower than 100mg/l, with two main processes governing water mineralization: water-rock interactions and dilution. The water-rock interactions process takes place over the entire aquifer, while the dilution by rain water is perceptible in areas of preferential recharge (hilltop) and spreads progressively into the water table, attenuating in the direction of underground flow. However, it should be kept in mind that these mineralization processes can be locally disturbed by lateral and vertical variations of petrographic and/or pedological types, and by anthropogenic contaminants [25]. As a result, groundwater is poorly mineralized, as it is highly diluted by recharge water from rainfall. A similar process has already been observed in hard rock aquifer on tropical humid climat in Cameroon such as at the Mbakaou-Tibati area [26] in Yaoundé area [69] and in other part of the world [82,83,84,85].

On the other hand, temporal evolution of conductivity within the recharge period (see Figure 4) show that in the hilltop, the downward conductivity trend (MKP2, MKP15, MKP43, and MKP50) underlines a dilution through direct infiltration of low mineralized rainwater as measured by [26] and [86]. Meanwhile, the upward conductivity trend observed on hillsides (MKP23, MKP7, MKP14, MKP22, MKP45 …) reflects the arrival of more mineralized water from the redistribution of groundwater from recharge areas by piston flow effect in the saturated layers [17,68,87]. However, this trend could also be due to infiltration of rainwater strongly impacted by anthropogenic activities such as agriculture (MKP24). Otherwise, the stable conductivity trend observed in the valley near stream (MKP1, MKP5, MKP34, MKP33, MKP4, MKP28) seems to reflect recharge by rainwater infiltration combined with a short residence time in the groundwater table before discharge into the streams.

Punctual measurements of EC in the localities of Dang, Gada-Mabanga and Tchabal-Malang in both surface and groundwaters give low values (except the borehole TMF4), underlining that these waters are all young deriving principally from rainwater.

Suitability of groundwater for drinking purposes and domestic usages

Several studies have shown that unconfined aquifers are more vulnerable to pollution [88,89,90,91,92,93,94,95,96].

Although pH does not usually have a direct impact on consumers [64], it is a parameter that has an important impact on other chemical elements present in water. In the study area, the pH of groundwater ranged from 4.4 to 7.8, with an average of 5.76±0.4. The pH values are generally below the upper limit (pH = 9.2) set by [64], but several samples have pH values below the lower limit (pH = 6.5). These results show that low pH levels are associated to increased biological activity. According to [98], the generally low pH values obtained in the grounder water might be due to the high levels of free CO_2, which may be due to the presence of organotrophic microorganisms like fungal and coliforms. Therefore, it is advisable to treat the water in order to destroy it microbiological content before for consumption.

Electrical conductivity expresses the ability of water to conduct or transmit heat, electricity or noise. All samples have an electrical conductivity of between 9.5 and 317 µS/cm, below the maximum limit (500 - 1400µS/cm) set by the WHO. These conductivity values suggest a low solubilization or exchange rate between the groundwater and its surrounding aquifer materials.

Calculated WQI values range from 7.9 to 39.8. These results show that all samples are classified as "excellent quality water" for human consumption regarding the WQI. These results corroborate those of [26] who found groundwater in Tibati to be of good quality when compared to the WHO standards of water content in major ions. Also, sulfate and nitrate which indicate an anthropogenic contamination [99], were generally not found in abundance in groundwater samples. Groundwater contamination through anthropogenic activities could not be perceived with these elements. [30] showed that groundwater from wells in the town of Ngaoundéré was the source of water-borne diseases such as diarrhea and typhoid. [99] as well as [100] tested the microbial quality of groundwater through heterotrophic plate counts of total coliform, fecal coliforms and enthero-pathogenic E. coli in boreholes and hand dug wells water in the Vina Division of Adamawa Region. They noticed a widespread of fecal contamination of groundwater (in both hand-dug wells and boreholes). This idea is supported by the low pHs that are associated to a microbiological activity in the waters analyzed. The problem with groundwater is thus related to its microbiological quality, which is largely influenced by human activities. Indeed [99] explained that hand dug wells are within distances of less than 10 m from potential sources of groundwater contamination. Therefore there is a possibility of inflow of leachate of effluents from the bottom of pit latrines into the nearby wells and some boreholes. Another reason is that some of the community members used the bushes and streams nearby as toilets and during rainy days, everything is swept into the streams and to the aquifer through direct infiltration causing ground water contamination.

This situation renders groundwaters not suitable for drinking unless it is treated.

5. Conclusion

The main objective of the study was to enhance the understanding the functioning of the hard rock aquifer system in Ngaoundere using piezometric and hydrochemistry data. Results obtained show that piezometric heads in wells and in boreholes have the same range of variations within the observation period. Piezometric fluctuations were high (>2m) at the hilltops (preferential recharge areas) and low (<2m) in the valleys near rivers (preferential discharge areas). In addition, seasonal (dry and rainy season) and intra-seasonal (rainy season) piezometric monitoring in boreholes and wells was carried out. And results show that piezometric heads are drawn closer to the surface in the rainy season thus allowing to conclude that the aquifer is recharged through direct infiltration of rain water. The intra-seasonal piezometric monitoring the associated to ECs variations allow to distinguish different recharge patterns: (1) direct infiltration at the hilltops, (2) piston flow on the hill-side (3) the combination of (1) and (2) in the valleys. Overall piezometric physico/chemical monitoring and waters' chemical compositions suggest that the aquifer in the study area behaves as an unconfined one. Looking at the suitability of groundwater for drinking purposes in the study area, the chemical composition (physic-chemical parameters and major ions) doesn't allow perceiving any contamination. Regarding the suitability of groundwater for domestic purposes, WQI was calculated. And it revealed that groundwater in the said area is of excellent chemical quality. However, some authors have shown that in the study area, wells and boreholes waters have a high load of microorganisms that cause water borne diseases. So the quality problems noted with groundwater in this area is due to other parameters like their bacteriological load as shown by the said authors and this is due to hygienic conditions that are not respected.

Declaration of Competing Interest

The authors declare that they have not known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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