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Stable Isotopes for Groundwater Assessment of the Quaternary Aquifer of the Western Part of Chad: A Case Study of Bahr El Gazel, Hadjer Lamis, Kanem and Lac Regions

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Abstract Environmental isotopes were used to decipher sources of groundwater and recharge of the Quaternary aquifer in 4 regions namely, Bahr El Gazel, Hadjer Lamis, Lac and Kanem located in the North and East of the Lake Chad Basin. Four field campaigns were conducted under the IAEA/ RAF/7/011 project for a total of 89 sampling points. Samples were collected during wet and dry seasons from 2013 to 2015. Physico-chemical and isotopes analyses were performed for groundwater and rainfall data. Stable isotopes of rainfall indicated a continental or close-sea moisture origins and evaporation as the main fractionation processes occuring in the study area, as attested by the excess values and seasonal variations. The most enriched values of stable isotopes are observed in the Lac Region in the South-East (SW) and the depleted ones are seen in the Hadjer Lamis Region in the South-East (SE). On one hand, evaporation affects groundwater during rainfalls and the recharge lead to the accumulation heavy isotopes in the unsaturated zone. On another hand, mixing and diffusion processes and conservative ions indicate successive recharge events. The decrease of tritium in precipitation is consistent with the decrease of tritium contents in groundwater, showing recharge events particularly for post and recharge.

Keywords: *environmental isotopes, groundwater, recharge, Quaternary aquifer, Lake Chad Basin*

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1. Introduction

Isotope tools are essential and mostly used as additionnal information coming from chemical and hydrogeological data in hydrosciences. They improve not only comprehension, knowedge and water tracing but also recharge processes and quantitative estimation of transport parameters and water fow [1]. They are also essential in physical process studies such as evaporation or geothermics that could affect water in different stages of the water cycle, leading to a variation of isotope initial composition. According to groundwater hydrology studies, the variation of isotopes ratios are always used as tracers for groundwater flow. By this, they are efficient tools for hydrological systems functioning. In arid and semi-arid regions, the scarcity of rainfall and quality surface water gradually lead to use of groundwater as the main resource for human activities (domestic, industrial and agricultural). Groundwaters in those geographical zones constitute the main sources for water supply. Several studies have been conducted in Chad particularly in the Lake Chad Basin for the management of water resources in terms of quantity, quality for agricultural, livestock and for domestical uses [2,3,4,5,6]. The study area is located in the saharian zone characterized by high potential evapotranspiration, small amount of rainfall and less recharge. The demand groundwater resources increases over the last decade and hence exploration, management and protection of these resource remain crucial.

This study aims to assess the source and quality of groundwater, and to characterize the recharge and mixing processes in the aquifer system of the study area (Bahr El Gazel, Hadjer Lamis, Lac and Kanem) using chemical and isotopic tools. Ultimately, it will contribute to the sustainable and efficient management of groundwater of Lake Chad Basin.

2. General Settings of the Study Area

2.1. Localization, Demography, Surface Area

The study area is located in the Lake Chad basin precisely in the western part of Chad and is composed of Kanem, Hadjer Lamis, Bahr El Gazel and Lac Regions. The surface area is around 176,845 km^2 with a total population of 1,629,794 inhabitants and 9.21 inhabitants/km^2. The study area is in the saharian zone characterized by an annual rainfall ranging from 100 to 200 mm and 29°C of temperature.

The Digital Elevation Model (DEM) of the Lake Chad basin exhibits high altitudes made of sand dunes ranging from 3,300 m in the North (Tibesti massif), 3,000 m in the NW (Hoggar Massif), 3,300 m in the SW (Adamaoua Plateau) ; to 180 m in the Centre of the basin (Pays-Bas) characterized by the piezometric depressions. However, low altitudes ranging from 20 to 40 m are observed in the Kanem Region in the vicinity of the study area; characterized by the scarcity of surface water.

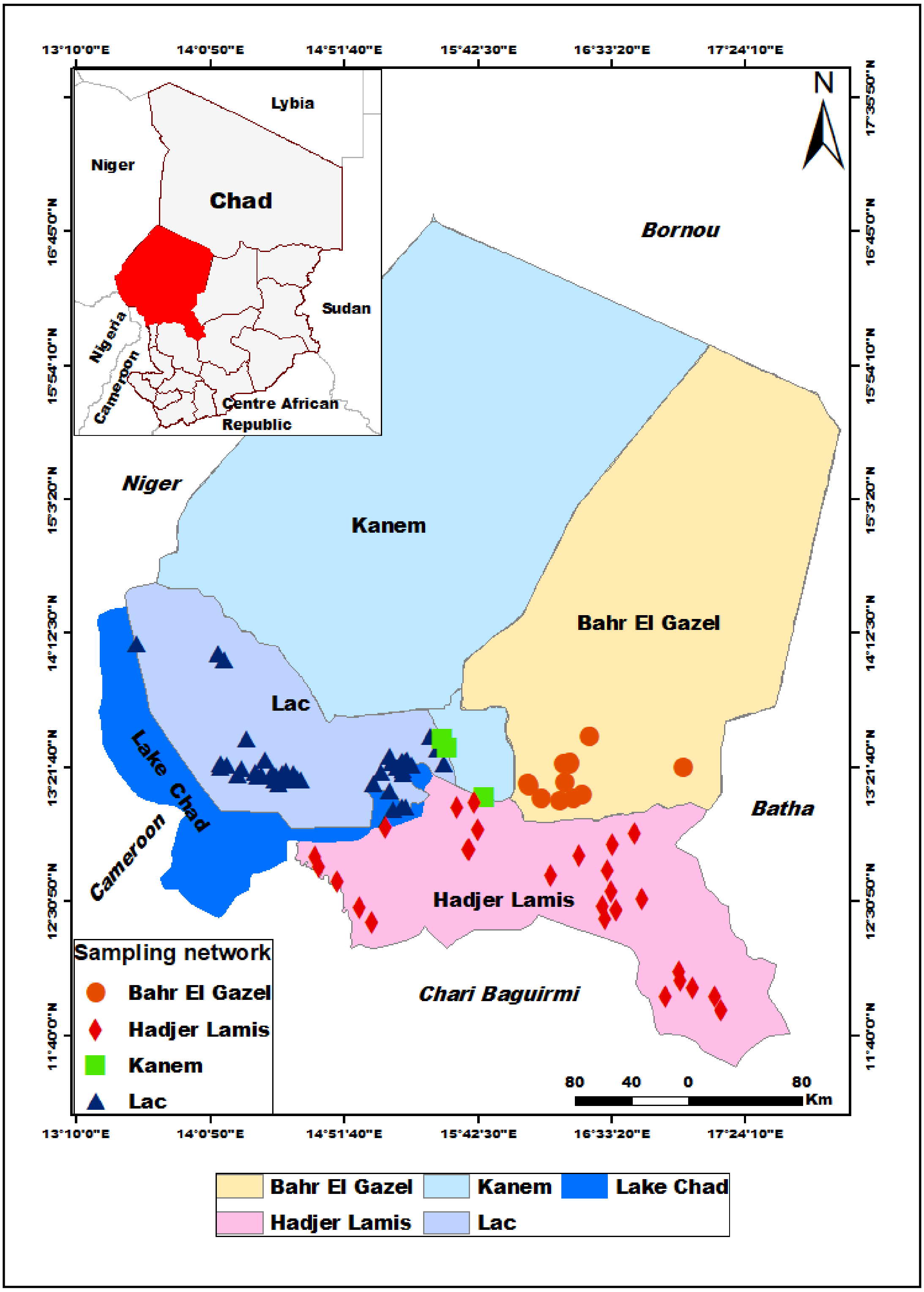

Figure 1. Localization of the study area

2.2. Geology

The geodynamics of African sedimentary basin is characterized by the panafrican orogenese. In the Lake Chad basin and precisely in the study area, several hydroclimatic conditions during the Quaternary period (from Upper Pleistocene to lower Holocene) led to three lithostratigraphic packages [7,8] namely series of:

- Moji (46 000 - 20 000 years) also named "serie of Egueï and of Padelanga" [7] or "Ghazalien" [9]. The Formations outcrop in the North of Kanem, East of Egueï and at the vicinity of Bahr El Gazal and are essentially made of shales with layers of gypsum, diatomites and sandy levels ranging from 8 to 9 m of depth. The serie continues in the central and western part of Kanem under an important sandy cover, exhibiting in the North of Lake Chad (Bol, Rig Rig) and at Hadjer Lamis (Goz Dibeck) through several surveys.

- Ogolian-Kanemian (20 000 - 12 000 years) characterized by an arid climate with a very low sea level. In the Saharan area, rock outcrops undergo intense erosion leading the erg extending the whole actual saharan zone. Some important dune formations are found in the centre part of Chad and more developped in Kanem Region, and directed NW-SE and NNW-SSE especially in the western part. The Eolian sand thickness is around 80 m at the East of Manga and is locally named Kanemian Formations [9]. These latters are very homogenous and composed of fine to medium sands, well sorted with rounded grains rich in tourmaline and ilmenite.

- Labdé (12 000 - 10 000 years) corresponding to lacustrine deposits range from 10 to 15 m of thickness and linear interdunar depressions of the erg of Kanem. The Labdé Formations are composed of silty to shale sequences at the bottom, upper layers are characterized by more shale than diatomites and limestone depending on depressions. [10] described two lake sedimentation sequences separated by a regression step leading to a dewatering time of some interdune in the western part of Kanem. Hadjer Lamis Region is particularly characterized by tardi-tectonic granite points in the SE (Ngoura, Moïto). Figure 2 highlights in details the geology of the study area.

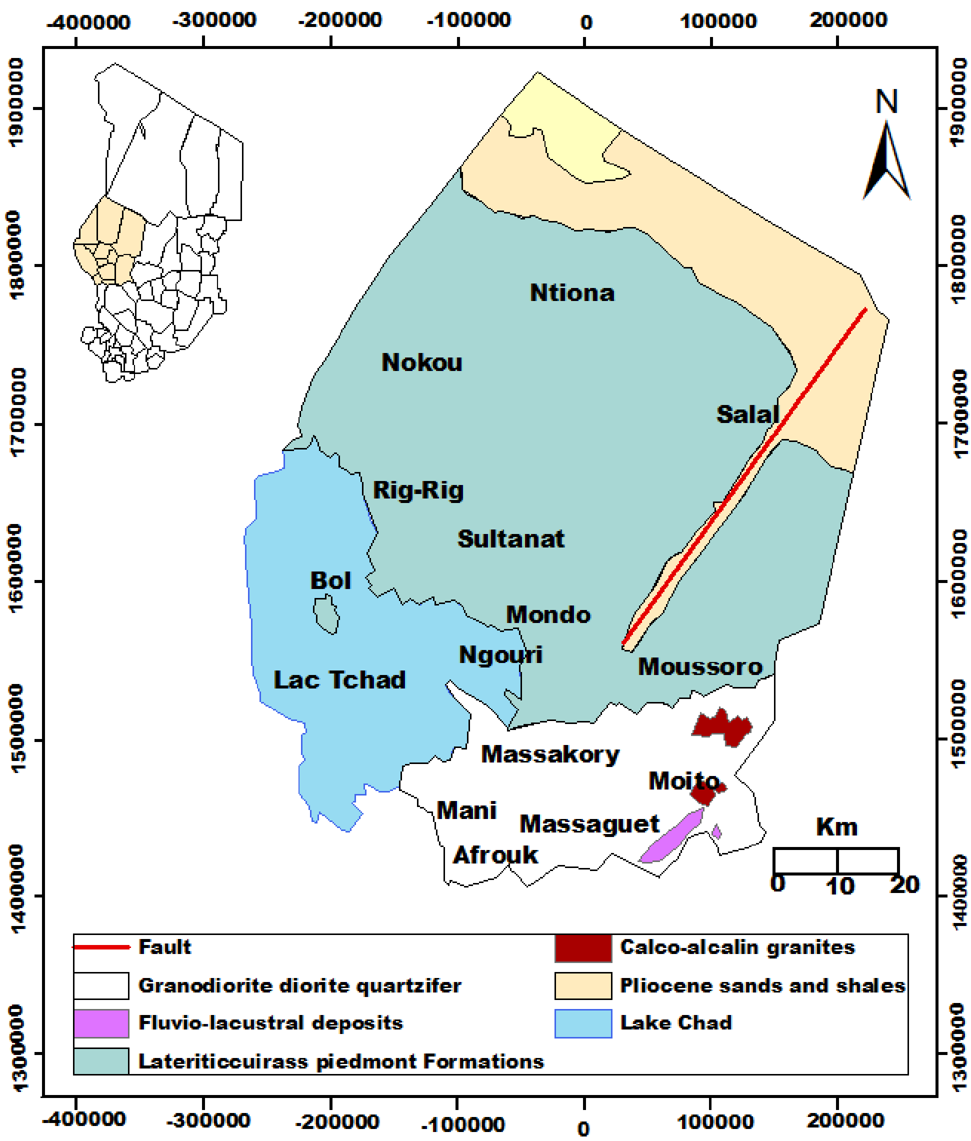

Figure 2. Geological context of the study area [8]

2.3. Hydrogeological Context

Groundwater resources in Chad Republic are located mainly in the Continental Terminal, Primary sandstone, Nubie sandstone, Plio-Quaternary aquifer system of Chad cuvette and discontinuous aquifers of bedrock reservoirs [11]. In the study area, groundwater resources belong mostly to the Quaternary aquifer system and concern predominantly Pleistocene aquifer, Ogolian sands, serie of Moji sands, Continental Terminal and Lake Chad (Figure 3). By this, aquifers of Quaternary, lower Pliocene and Continental Terminal are preferentially used for water supply. The Quaternary aquifer with a depth ranging between 60 to 100 m is composed of clastic deposits with intercalations of shales, sands limestones of fluviatil and lacustrial deposits [12]. The lower part of this aquifer is made of grey or green shales with some diatomites benches and can reach to a depth of 50 to 180 m in the North area [13] under the Lake Chad; while the South is mostly composed of Eolian sands [5]. In contrast, the boundary of the top of this aquifer corresponds with the ground surface [14]. The Quaternary aquifer covers around 500 000 km^2 with total volume ranging from 80 to 140 million m^3/year and is characterized by various facies such as sands and shales, leading to a heterogeneity in hydraulic and chemical characteristics [15]. This aquifer is mostly tapped by hand dug-wells and has good water quality with moderated mineralization [16].

The general flow is directed from South to North East towards Pays Bas, in the depression zones. The groundwater flow of the Quaternary aquifer system shows three major depressions in some regions namely Chari-Baguirmi near the South East of the Lake Chad, Komadugu-Yobé at the East of Niger and Nigeria, and Pays Bas in Chad [17] as shown in Figure 4. The Lake Chad seems to be an elevated zone according to the general hydrogeological system. In the Southern part of the Lake Chad basin, the discharge occurs towards the lake and Komadugu-Yobé depression. The North of the basin is characterized by the depression of Pays Bas which receives groundwater from the East (Chad) and West (Niger). The main flow axes follow temporarily stream beds [17]. Hydraulic gradients are low (1 to 5.10^{-4}) with a piezometric level ranging up to 100 m according to the system scale [5].

The water table (Figure 4) of the shallow aquifer of the Eolian Formations show two dividing lines [18] namely:

- the line of Chitati, generally parallel to the shorline of the Lake Chad and corresponding to the piezometric dome located in the western part of Mao (Kanem). The dome elevation is up +313 m at Kimi Kimi and it is locally called dome of Kimi Kimi with an elevation about 30 m above the level of Lake Chad;

- the line directed W-E crossing the Harr characterized by an elevation up to +290 m while it is +260 m in the North of Bahr El Gazal ; and +230 m in the South of the piezometric depression of Kouka.

Amplitudes of daily piezometric fluctuations range between 2 to 7 cm and are directly link to sunlight and evapotranspiration of plants [19]. Annual piezometric variations are sensitive along the Chari River going as far as 2.5 to 3 m in some observed points located 400 m to the River; and of 1 m for one of the sampling point located at 500 m of Chari River during 1996-1997 [20]. In contrast interannual variations observed during fifteen years show continuous decline of static water levels around 6 cm/year particularly in the center of Chari-Baguirmi depression [19]. The aquifer is very sensitive to the pumping due to water supply. Compared to the operating water flow rate of 8.2 million m^3/year in Chari Baguirmi, the static water level decrease globally from 5 to 10 m each year in the vicinity of sampled boreholes [21].

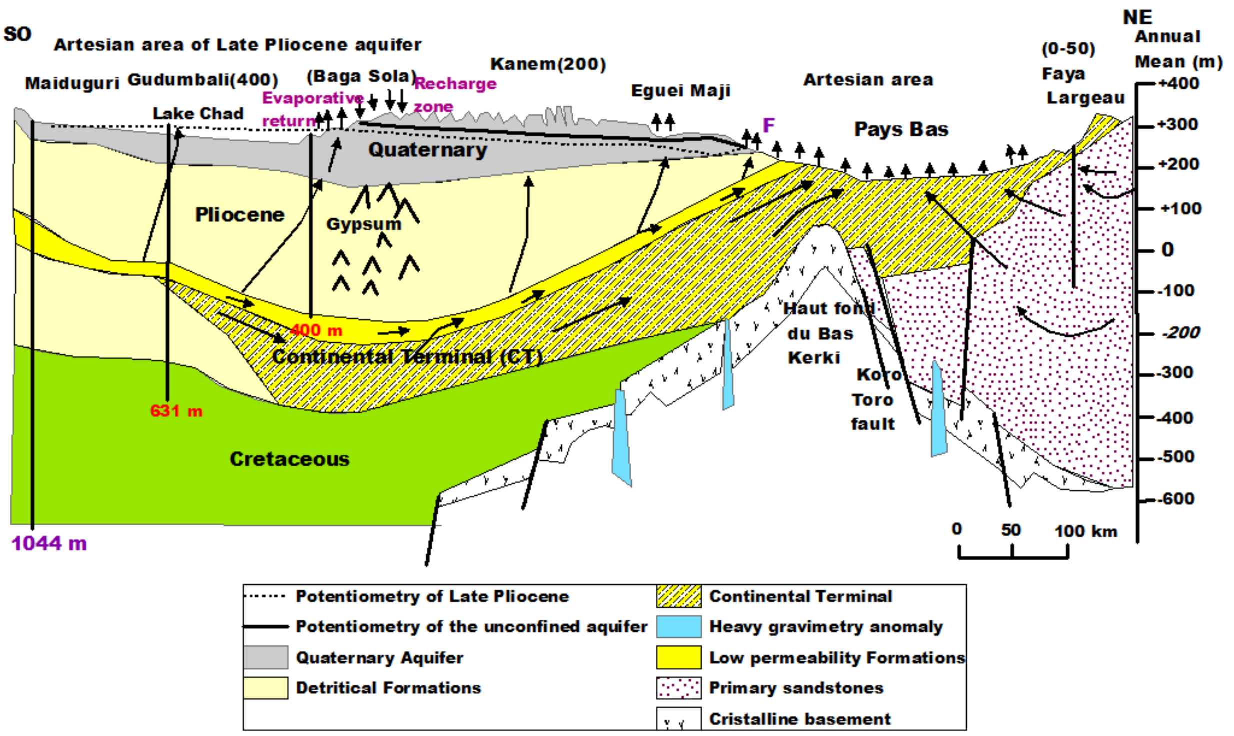

Figure 3. Cross section of the Lake Chad from Maïduguri to Faya [15]

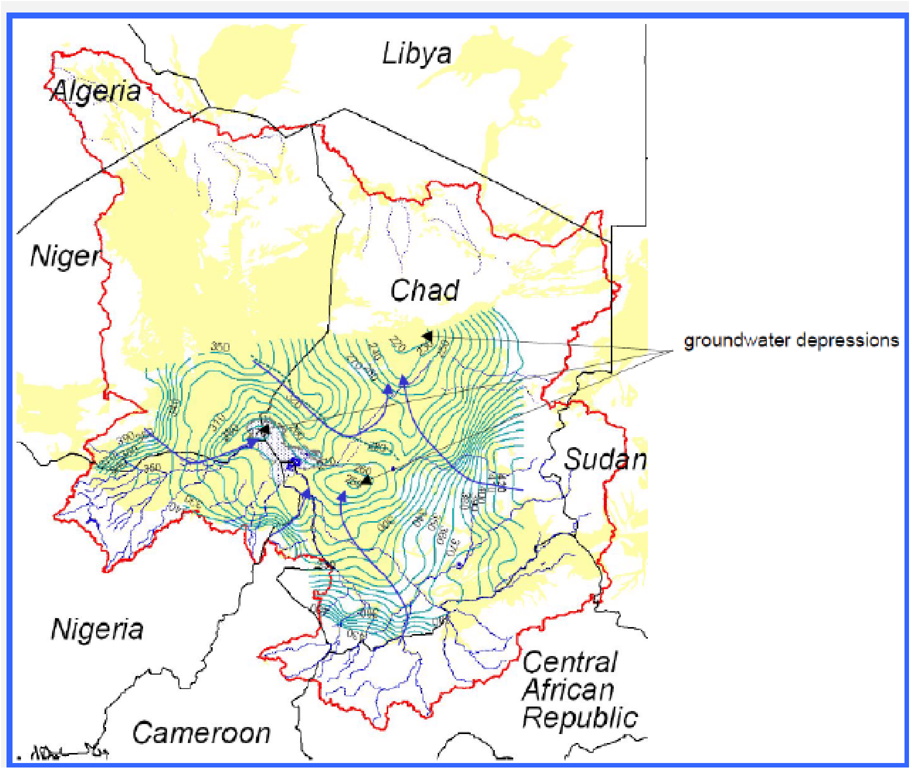

Figure 4. Piezometric map of the Quaternary aquifer [17]

The Quaternary aquifer indicates mean values of transmissivity of 6.2 10^{-3} m^2/s. Pumping tests data from 8 boreholes located in Chari-Baguirmi plain and 6 others in Ndjamena [15,16,22] exhibit values of transmissivity range from 3.2 10^{-3} to 6.6 10^{-3} m^2/s and the storage coefficient between 4.10^{-4} et 10^{-3}. In contrast, [23] estimate the mean values transmissivity at 1.6 to 2.2 10^{-2} m^2/s for the Middle Pleistocene; and at 2.5 and 3.5 10^{-2} m^2/s for the Ogolian aquifer. However, pumping tests done in Chari-Baguirmi indicate a mean value of hydraulic conductivity of 2.10^{-4} m/s [15].

3. Materials and Methods

3.1. Groundwater Sampling and in Situ Measurement

Four field campaigns were conducted within the RAF/7/011 project of IAEA in the Lake Chad basin for a sampling network of 247 dug-wells and 57 boreholes. Physico-chemical parameters such as pH, electrical conductivity, temperature and salinity are measured through the WTW multi-parameter and anither set of samples were collected for chemical and isotopic analyses (δ^2H, ^{3}H, δ^{18}O). The GPS Garmin 62 was used to geolocalized each sampling point. A total of 89 groundwater points were sampled in July 2013 during the wet season (Hadjer Lamis), October 2013 in the dry season (Kanem), February 2014 during the dry season (Lac) and April 2015 in dry season (Bahr El Gazel). Filtreted samples (0.45µm) were in well-rinsed and tightly sealed in 20 ml (for stables isotopes) and 0.5 ml (for tritium) bottles and preserved at 4°C. Rainwater samples were obtained from the Ndjamena station of the IAEA/GNIP website (http://www naweb. iaea.org/napc/ih/IHS_resources_isohis.html#wiser). The database (N=16) concerns three years precisely 1995, 2015 and 2016.

Table 1. Number of samples according to each region

Regions	^{18}O & ^{2}H		^{3}H
Kanem	03	× 03	02
Bahr El Gazel	12	× 12	10
Hadjer Lamis	26	× 26	06
Lac	42	× 42	33
Total	164		51

3.2. Laboratory Analyses Methods

Stable isotopes ratios of water (^{18}O/^{16}O and ^{2}H/^{1}H) were analyzed at the Hydrosys Labor Ltd laboratory of Budapest using the general standard procedures. The CO_2 equilibration method [24] for the ^{18}O and the reduction of water in chrome by the Pyroh method [25] or the ^{2}H were used, calibrated using Vienna-Standard Mean Ocean Water (V-SMOW) and reported in δ notation representing ‰ deviations [26]. Analytical uncertainty was equal to ±0.1 ‰ and ±1.0 ‰ for δ ^{18}O and δ ^{2}H respectively. In contrast, the samples for tritium contents were analyzed using electrolytical enrichment and liquid scintillation spectrometry [27] and expressed in Tritium Units (TU).

4. Results and Discussions

4.1. Stable Isotopes of Rainfall

The values of precipitation range from -7.5‰ to 3.5‰ with mean and median values of -1.6‰ and -2.3‰ respectively for δ^{18}O, and from -48.30‰ to 38.70‰ with mean and median values of -4.81‰ and -7.15‰ respectively for δ^2H (Table 2). This shows a wide range of precipitation δ-values probably due to the meteorological conditions during rainfall and moisture source [28] in the study area. Rainfall data (N = 16) were then plotted on the conventional bivariate diagram $\delta^{18}O$ versus δ^2H (Figure 5) and exhibit a wide distribution relative to the Global Water Meteoric Line (GWML) and the local meteoric lines. The Precipitation Weighted Least Square Regression (PWLSR) [29] and the Ordinary Least Square Regression (OLSR) [30] indicate PWLSR: $(5.98 \pm 0.33)^{18}O + (3.24 \pm 1.18)$ with $r^2 = 0.96$ and OLSR: $(6.79 \pm 0.44)^{18}O + (6.21 \pm 0.28)$ with $r^2 = 0.94$ respectively, with a weighted mean value of -2.3‰ for $\delta^{18}O$ and -11.07‰ for δ^2H. These local meteoric lines are closed to those of [31]: $\delta^2H = 6.31^{18}O + 4.19$ ($r^2 = 0.6$); [32]: $\delta^2H = 6.3\delta^{18}O + 4.64$ and of [5]: $\delta^2H = 6.33\ \delta^{18}O + 9.9$ ($r^2 = 0.92$); and values of slopes and intercepts are less than those of the GWML suggesting the occurrence of some fractionation processes and indicate evaporation effects. The weighted average point relative to values of the record precipitation data is -2.4‰ for $\delta^{18}O$ and -11.07‰ for δ^2H respectively.

In the semi-arid and arid areas, evaporation is predominant so that raindrops are usually under a high evaporation process during their fall [5,31,32,33,34]. However, important continental moisture recycling could be observed, some samples slightly deviate above the GWML and some others fall along a straight line on the GWML. The latter has an impact on the d-excess range values and shows a mean value of 11.75‰; suggesting a continental or closed sea moisture origins [34]. However, the values of d-excess for the concerned period range from -5.50‰ to 19.10‰ with a mean of 8.17‰.

Table 2. Statistics descriptives of stables isotopes (^{18}O & ^2H) of rainfall – GNIP station of N'djamena (1995, 2015 & 2016)

Variables	^{18}O (‰ V-SMOW)	^2H (‰ V-SMOW)
Mean	-1.6	-4.81
Median	-2.3	-7.15
Minimum	-7.5	-48.3
Maximum	3.5	38.7
SD	3.3	23.55
N	16	16

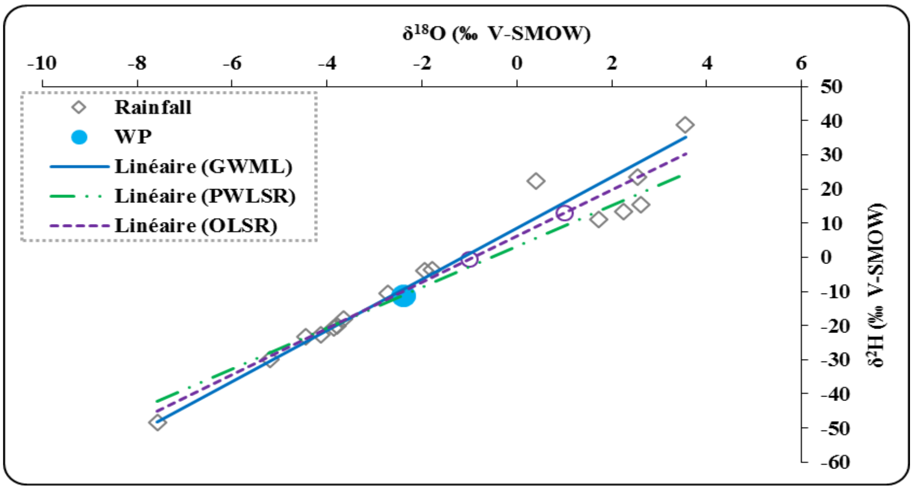

Figure 5. Relationship between δ^2H and $\delta^{18}O$ of rainfall (GNIP station of N'djamena 1995, 2015 & 2016)

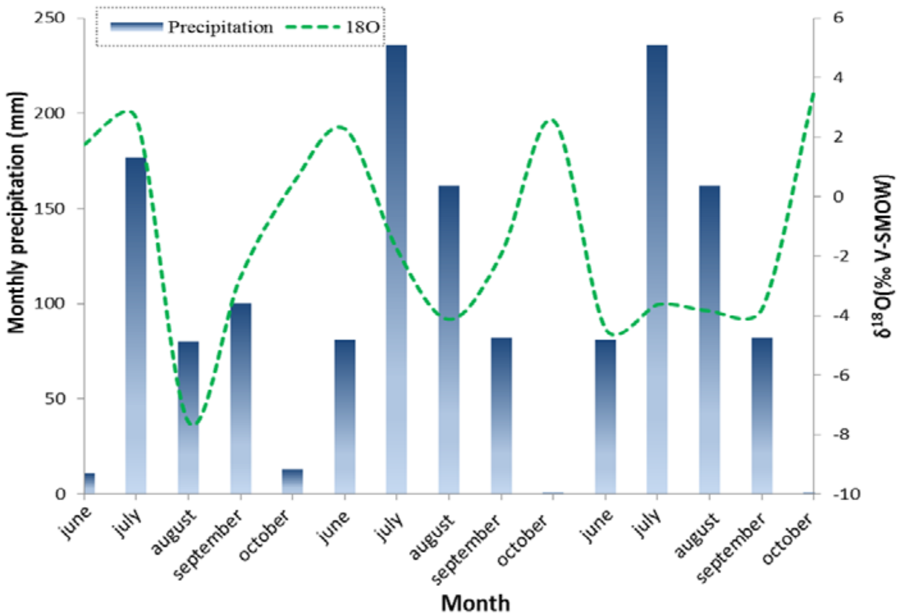

Figure 6 a. Variation of stable isotope ($\delta^{18}O$) at the GNIP station of N'Djamena (1995, 2015 & 2016)

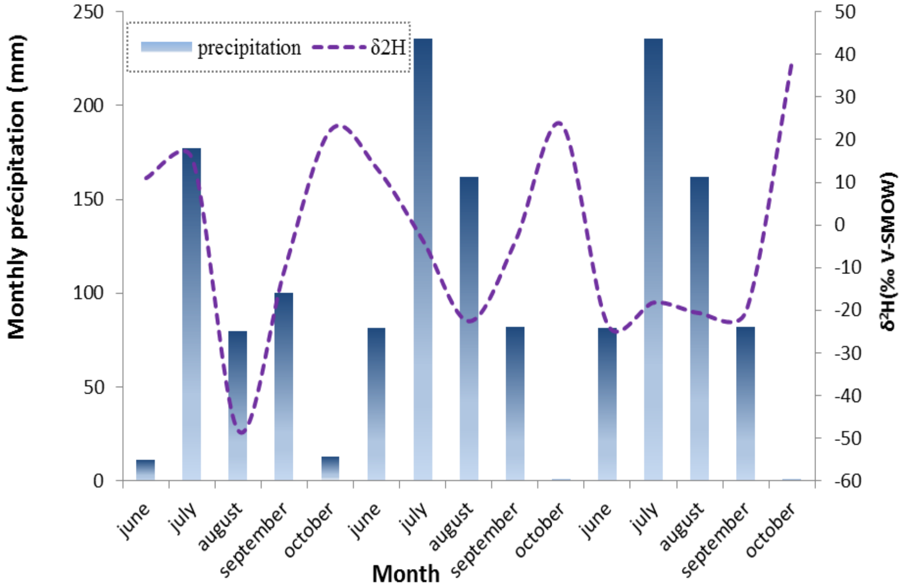

Figure 6 b. Variation of stable isotope (δ^2H) at the GNIP station of N'Djamena (1995, 2015 & 2016)

Precipitations in the study area are characterized by an important variability in δ-values. Negative values occur during the high amount of rainfall from July to August (Figure 6a & Figure 6-b). The most depleted values are observed at the peak of the rainy season from July to September. This is consistent in countries where moonson effects are high [35,36] such as Mali, Niger, Burkina Faso, and Chad where moonson winds lead to rainstorms with depleted δ-values. Evaporation processes occur generally during the pre-moonson period from April to June and during the post-moonson period on October with enriched δ-values under evaporation. This is consistent with [37] results in sahelian dry and humid areas where less amount of rainfall usually comes from local atmospheric moistures.

4.2. Stable Isotopes of Surface Water

Three samples of the two main rivers crossing the study area namely Chari, Logone were collected and analyzed for stable isotopes. Values range from -1.63‰ to -0.4‰ with a mean of -0.98‰ for $\delta^{18}O$; and from -8.00‰ to -1.60‰ with a mean of -4.60‰ for δ^2H. These mean values are more enriched than the mean values of precipitation (-1.6‰ for $\delta^{18}O$‰ and -4.81‰ for δ^2H) and the weighted point of precipitation (-2.3‰ for $\delta^{18}O$ and -11.07‰ for δ^2H). The Ordinary Least Square Regression (OLSR) [30] shows $\delta^2H = (5.41 \pm 0.53)\ \delta^{18}O + (0.70 \pm 1.30)$ with $r^2 = 0.99$ and $n = 3$. The OLSR is under the GWML and samples fall on the local meteoric line, suggesting the evaporation of surface water (Figure 7) in the study area. Furthermore, δ-values of surface water are closed to those of precipitation on one hand and their weighted averages indicate that the Chari River feeds the aquifer and controls the recharge on another hand. By this, several weighted means are given to estimate the input signature in previous studies. [15] have defined -4,5‰ for $\delta^{18}O$ while. [38] indicate that on the shorelines of the Chari River, mean values of $\delta^{18}O$ range from -3,1‰ (1967) to -2,1‰ (1969).

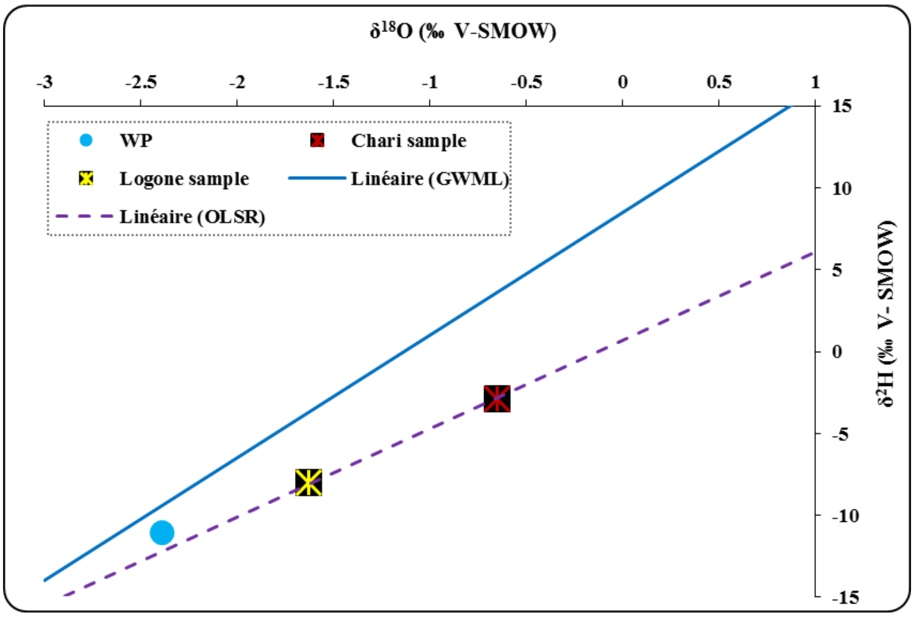

Figure 7. Relationship between δ^2H and $\delta^{18}O$ of surface water

4.3. Variability of Stable Isotopes in Groundwater

Stable isotopes of groundwater samples exhibit values ranging from -5.2‰ to 8.4‰ with a mean of -1.6‰ for $\delta^{18}O$; and from -35.30‰ to 39.90‰ with a mean value of -15.14‰ for $\delta^{2}H$ (Table 3). Standard deviation values 3.6‰ and 20.48‰ respectively for $\delta^{18}O$ and $\delta^{2}H$, indicate a wide distribution of δ-values as confirmed in the histograms (Figure 8-a & 8-b) of δ-values with a random variation. However, Hadjer Lamis Region presents the most enriched δ-values (-4.59‰ for the $\delta^{2}H$ and 0.14‰ for the $\delta^{18}O$). Depleted values are observed in the SW of the study area (Hadjer Lamis) characterized by irrigation while δ-values are closed to the others regions.

Table 3. Stable isotopes and d-excess values of groundwater in the study area

	^{2}H	^{18}O	d-excess
Minimum	-35.3	-5.25	-29.71
Maximum	-39	-8.45	8.14
Mean	-15.14	-1.6	-2.32
Median	-26.57	-3.35	1.61
Standard deviation	20.48	3.66	9.23
N	83	83	76

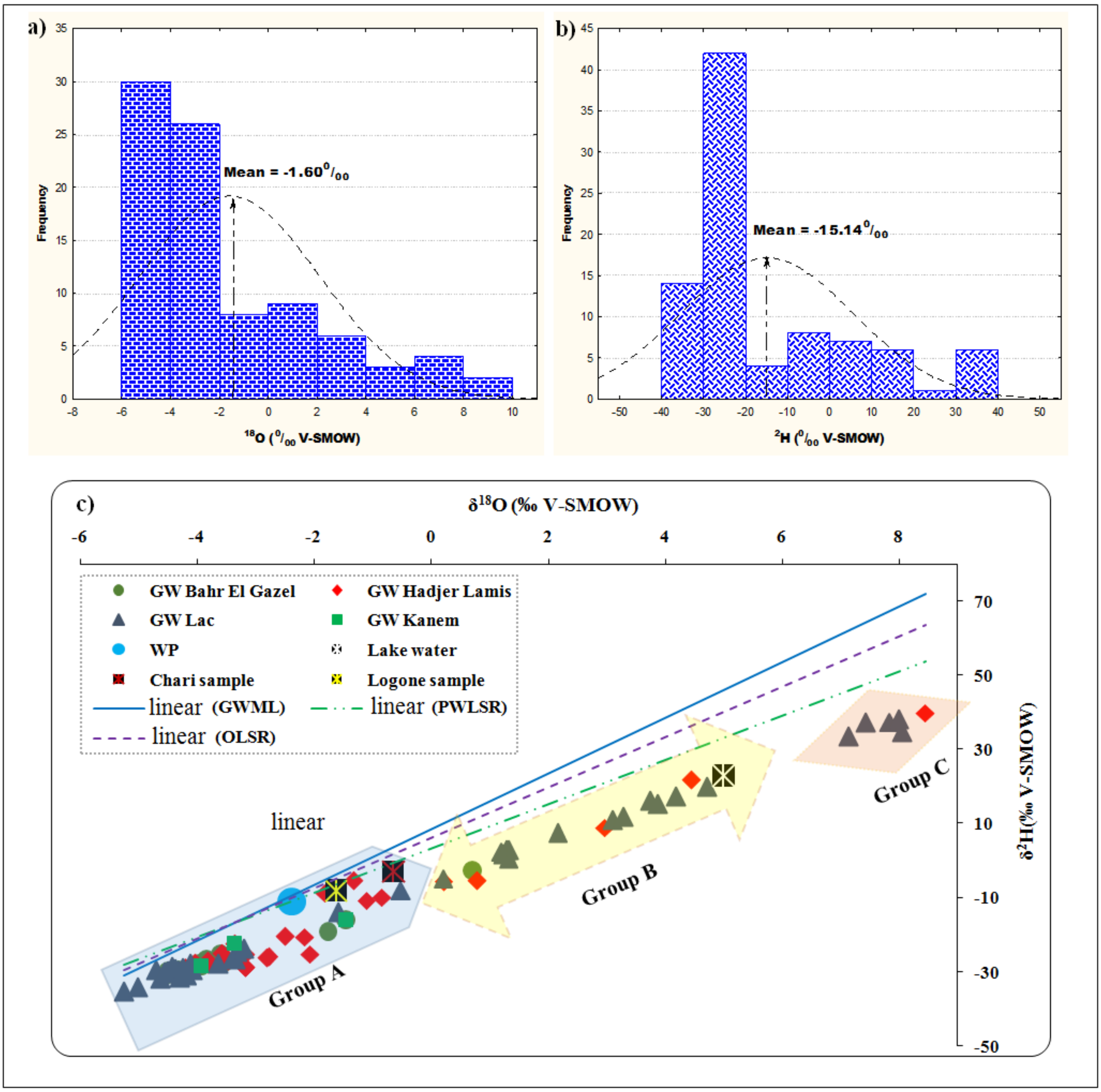

Figure 8. Bivariate diagram of $\delta^{2}H$ *vs* $\delta^{18}O$ in the study area

A plot of $\delta^{2}H$ versus $\delta^{18}O$, the weighted point (WP: $\delta^{2}H$ = -11.07‰ and $\delta^{18}O$ = -2.3‰) and the lake water ($\delta^{2}H$ = 23.00‰ and $\delta^{18}O$ = 5.0‰) contents is shown on the conventional diagram (Figure 8-c). Samples are under and scatter parallel to the meteoric lines suggesting that samples had undergone some degree of evaporation as a result of non-equilibrium kinetic process fractionation. Nevertheless, it should be noticed that the mean value of $\delta^{2}H$ is more closed to the weighted average value the mean value of $\delta^{18}O$. The deviation of those samples exhibit evaporation as the main process and it is consistent with the fact that groundwater is coming from the Quaternary system which is under the high evaporation. The latter occurs either before the recharge during the passage of raindrops in the atmosphere with least moisture, either after the recharge when accumulated heavy isotopes are leached in the unsaturated zone during the dry period [39]. Evaporation is very important in arid and semi-arid areas and marked by fractionation and residual enrichment of δ-values as shown in the isotope profiles of the unsaturated zone [40]. This increases salts and heavy isotopes as shown in Louga, Saloum and North littoral in Senegal [41,42], in Mauritania [43,44], Chari Baguirmi, Diffa, Bornou and Ndjamena in Chad [5,31,32,34].

4.3.1. Recharge and Mixing Processes

The spatial distribution of δ-values on the bivariate diagram led to identify three groundwater groups (Figure 8-c) namely:

- Group A mostly composed of a set depleted samples from Hadjer Lamis and Bahr El Gazel and Lac regions. Values of stable isotopes vary between 7.1‰ and 8.4 ‰ for $\delta^{18}O$; and from 33.60‰ to 39.90‰ for $\delta^{2}H$. The mean values of 7.8‰ and 36.83‰ respectively for $\delta^{18}O$ and $\delta^{2}H$ in one hand are far from the values of the weighted average point (-2.39‰ for $\delta^{18}O$ and -11.07‰ for $\delta^{2}H$) and from the lake water (5‰ for $\delta^{18}O$ and 23‰ for $\delta^{2}H$). In another hand, the scatter plot is much closed to the meteoric lines, indicate recent recharge coming from precipitation at the end of the wet period from November to December as mentionned by Djoret [31]. However, some samples are more depleted and could match with some recharge events occurring under cold and humid climatic conditions prevailing recently in the study area [45,46]. The homogeneity of the δ-values contents relative to this group could attest of an extended residence time without mixing, or other sources allowing mixing and diffusion processes [47]. This help to mitigate eventual variations from successive recharge events [48], as seen in some semi-arid areas like in Egypt, Lybia, Saoudite Arabia, Sudan and Australia [49,50]. In addition, a few spatial and temporal scale coupled to particular geomorphologic configurations (alterite layer on a cristalline aquifer) could increase the input signature of isotopes in precipitation before recharge [51]. This has been confirmed in the study area by [52] where some similarities were found between mean pluriannual precipitation contents and δ-values in groundwaters.

- Group B is constituted of heterogenous enriched values which range between 0.2‰ to 5.4‰ for $\delta^{18}O$ and 1.33‰ to 2.80‰ for $\delta^{2}H$ with mean values of 0.75‰ and -2.41‰ for $\delta^{18}O$ and $\delta^{2}H$ respectively. Moreover, these latters are closed to the mean value of lake water and of the values of the weighted average point. Samples deviate significantly from the meteoric lines and are more enriched compare to those of group A, indicating more evaporation effect. Some of the samples present values closed to the Chari River value probably indicating leakage processes between surface water and groundwater. This justifies either direct recharge where isotope recharge events are not marked by mixing and diffusion processes with very short residence time, either by a spatial and temporal variability of precipitation leading to weak lateral flow and runoff characterizing heterogeneous δ-values [53], or hydraulic discontinuities promote mixing processes. However, lake water isotope content could indicate a hydraulic connection between formations of Lac, Hadjer Lamis and water of the Lake [31,54,55].

- Group C presents the most enriched δ-values and deviated samples. These latters belong predominantly to the Lac Region and show values ranging between 7.1‰ à 8.4 ‰ with a mean value of 7.8‰ for $\delta^{18}O$ and 33.60‰ to 39.90‰ with a mean value of 36.83‰ for $\delta^{2}H$. Values are homogeneous suggesting an extended residence time without mixing and diffusion processes, also deleting eventual variation due to successive recharge events as in the other groups.

The variability of the isotopic signature observed between the aquifer and precipitation could be explained through several processes such as condensation or evaporation, which occur before the recharge [56]. Obviously in the semi-arid areas, evaporation is the main process [57,58]. During the peak of rainfall characterized by weak δ-values contents, recharge occurs normally [59,60]. However, from June to September, δ-values contents are more depleted and correspond in one hand to the high period of recharge and lead to mixing groundwater; and in another hand to exhibit the seasonal contrasted composition of stable isotope [60].

The spatial variation of δ-values show the large dispersion and the variability of isotope contents in groundwaters and can explain several origins and recharge events in the aquifer system of the study area. At the regional scale, isotope signature of surface water change temporally [31,61,62]. During flooding periods, the Chari River feeds the Quaternary aquifer. This recharge could contribute to the δ-values contents dispersion which could be linked to the depth of some dug-wells and boreholes where δ-values decrease with depth [31].

However, the relationship between $\delta^{18}O$ and chloride shows a large range of variation and the heterogeneity of $\delta^{18}O$ values indicate the occurrence of several sources of groundwater in the study area (Figure 9-a). By this, low chloride contents (mg/l) match with depleted values of $\delta^{18}O$ which are closed to the weighted point and probably show that groundwater contribute to the recharge. In addition, high chloride contents and depleted values of $\delta^{18}O$ in some groundwater samples are noted in Bahr El Gazel and Hadjer Lamis, indicating that the mineralization in this areas is controlled by dissolution processes. Overall, high chloride contents with enriched $\delta^{18}O$ values are also observed for the lake samples, Hadjer Lamis and Bahr El Gazel. This could be explain through the non-equilibrium kinetic process fractionation precisely evaporation [63]. Also, electrical conductivity values correspond with depleted $\delta^{18}O$ values mostly in Lac, Kanem and Hadjer Lamis Regions (not shown here). By this, low mineralized groundwater could be linked to depleted δ-values and indicate recharge without or less evaporation processes. Similarly, nitrates low values match more with depleted $\delta^{18}O$ values (Figure 9-b) showing rapid recharge of groundwater in the study area before the occurrence of fractionation processes.

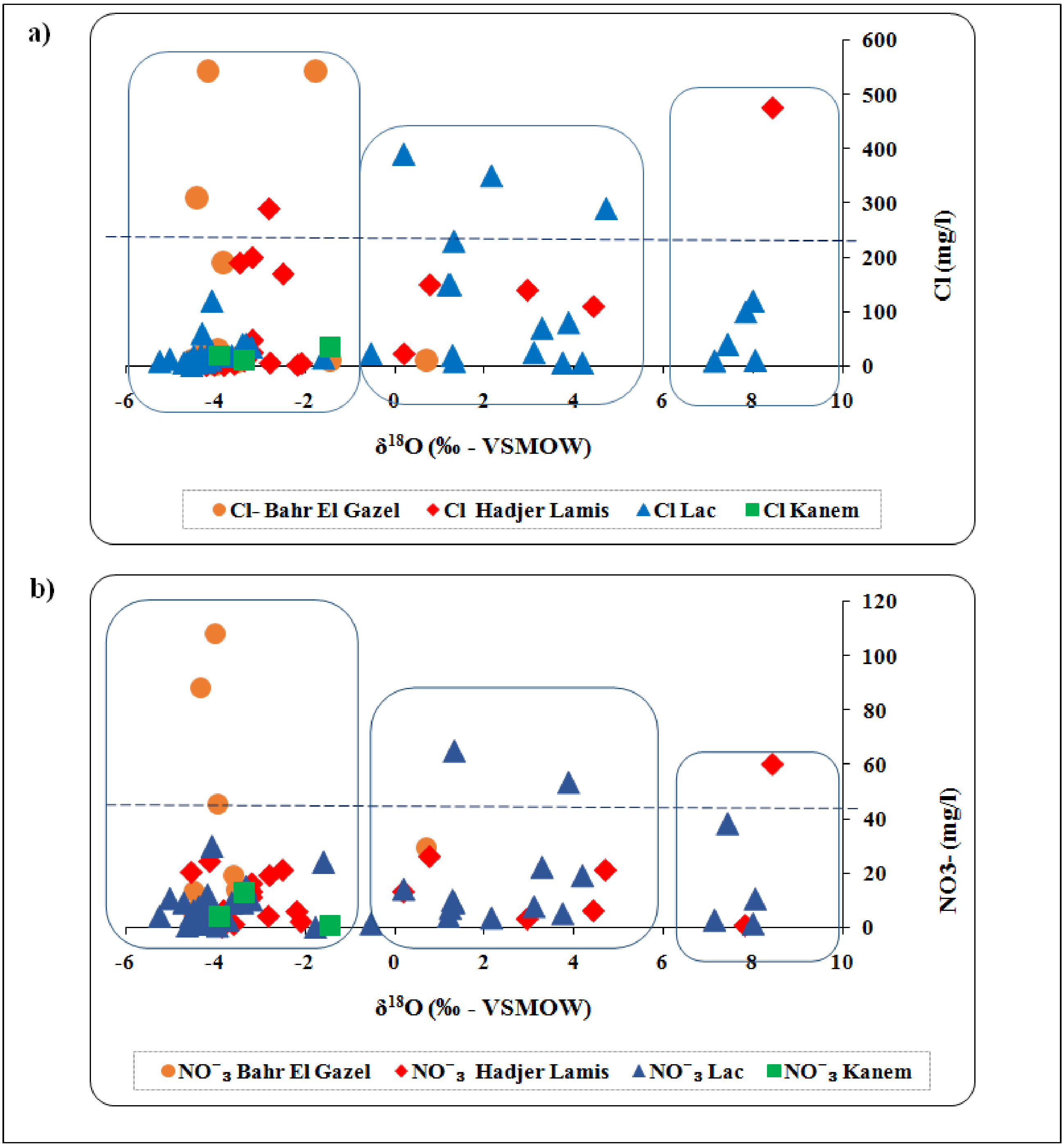

Figure 9. Relationship between $\delta^{18}O$, chloride and nitrate

4.4. Tritium Variation

Environmental tritium has a period of 12.32 years ± 0.02 [64] and corresonds to 1 atom for 10^8 atoms of hydrogene. Tritium is produced naturally through neutronic component from atmospheric azote. The natural content of tritium in atmosphere is around 5 TU [65]. Thermonuclear tests released abundant tritium in atmosphere since 1950s. The most important tests held from 1951 to 1952, led to considerably increase tritium contents in precipitations since 1963 and an important peak was observed since then. The produced tritium oxides, incorporates moisture and participates into water cycle, characterizing rainfall before falling [35]. Over time, tritium contents decrease gradually and reach natural concentrations due to the stopped thermonuclear tests. Environmental tritium impacts in water flow as an important tracer and can provide informations on residence time in groundwater up to 60 years.

4.4.1. Tritium Contents in Rainfall

The data record from the GNIP website of the station of Ndjamena (1963-1978) was used in this study. Values range from 30 TU to 1371 TU with a mean and a median values of 156.53 TU and 112 TU, respectively. The standard deviation (206.75 TU) indicate a wide distribution. Moreover, [20] used weighted values from the GNIP station of Ndjamena to stand out the gradually decrease of environmental tritium in rainfall during the same period (Figure 10-a). Since 1972, tritium contents of precipitation decrease below 1000 TU and reach a limit of 30 TU in 1978 in the study area.

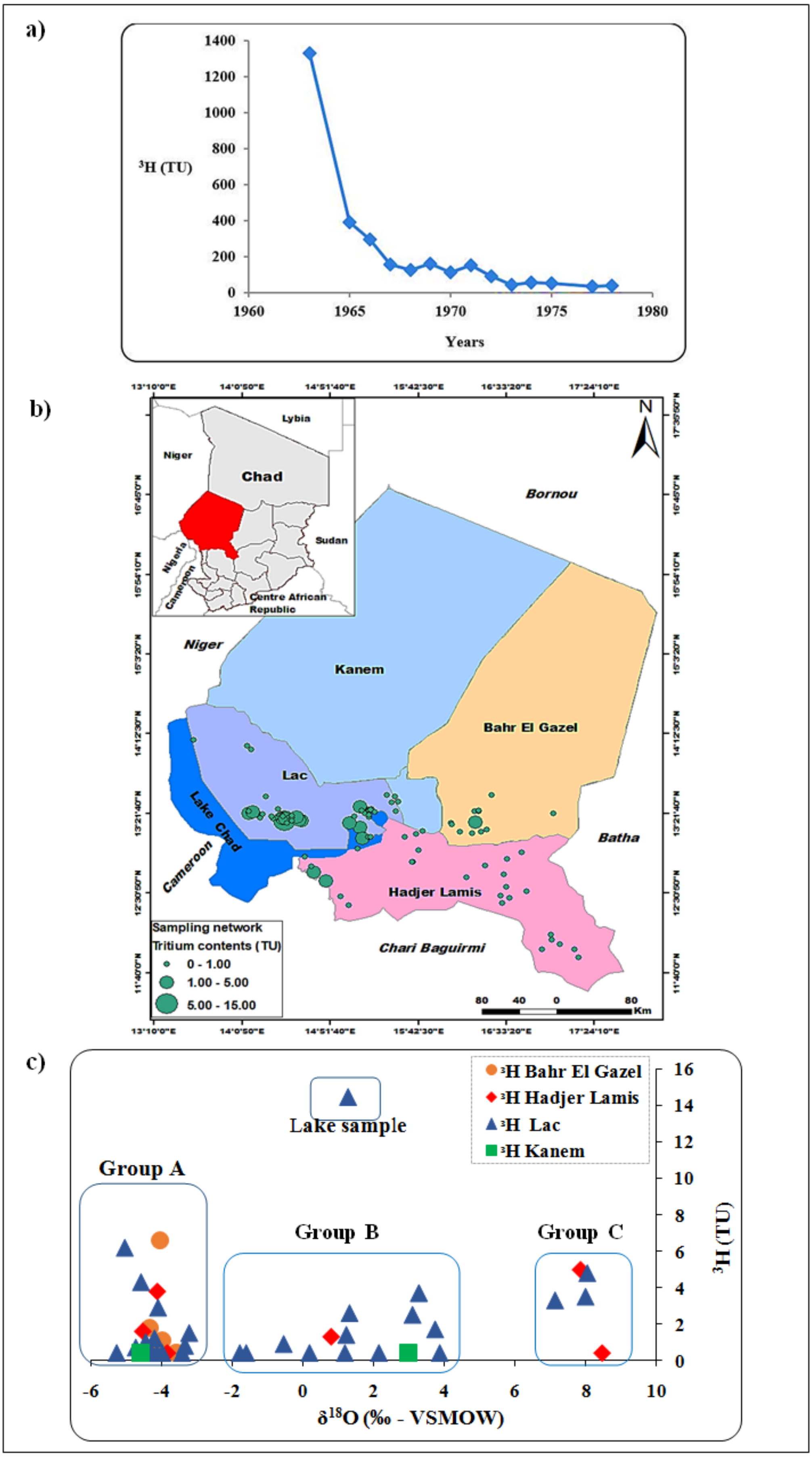

Figure 10. Relationship between $\delta^{18}O$ and ^{3}H

4.4.2. Tritium Variation in Groundwater

Environmental tritium of groundwater presents a range values of 0.4 TU to 14.5 TU with a mean and a median values of 1.73 TU and 0.75 TU, respectively. The spatial variation of tritium contents shows lower values in Hadjer Lamis, Bahr El Gazel and Kanem while values remain constant in the Lake region. Futhermore, the range of tritium values is constituted of three predominant levels (Figure 10-b): (i) values ranging between 0 to 1 TU, represent 73.07% and could indicate old groundwaters infiltrate before themonuclear tests. This suggests that the Quaternary system could contain groundwaters old up to 60 years, evaporated previously or mixed with evaporated groundwaters. (ii) Tritium contents comprised between 1 TU and 5 TU, represent spatially 17.30% and could be considered as previous and recent groundwaters. These latters are frequently encountered in aquifers [66] and could be the result of the water rising through geological discontinuities or a defective casing. (iii) Values ranging from 5 TU to 15 TU represent 9.61%, could characterize modern recharge with a mean residence time varying from 5 to 10 years. Those groundwaters should correspond to post-nuclear period and evolves gradually to a low dynamic hydrogeological environment as mentioned by [31].

The relationship between $\delta^{18}O$ and ^{3}H (Figure 10-c) indicate three main groups in which tritium contents globally range from 0 to 7 TU and where $\delta^{18}O$ values are between 5‰ to 8.5‰. However, the scatter plot of group (A) show depleted δ-values (-5‰ to -3‰) with low tritium contents (0 to 8 TU) and represent around 51.28%. These latters suggest either old infiltration during the abundant rainfall period (1940-1950), either very old water characterized by less evaporation and rainout [67]; and could be considered as pre-nuclear groundwater. These groundwater present a low renewal rate, thus a long residence time. In contrast, group (B) is made of mixing of old and recent evaporated groundwater for around 11.30% of all samples but with enriched δ-values (6.5‰ to 8.5‰) and low tritium contents (0 to 6 TU). There are thus mixing processes through vertical infiltration (hydraulic connection) and represent post-nuclear groundwater. While group (C) is composed predominantly of recent evaporated groundwater for about 3.42% with medium δ-values (-2‰ to 4‰) with low tritium contents (0 to 6.20 TU). There are recent groundwater which fluctuate relative to seasonal variations and represent recent recharge.

4.5. Radiocarbon in Groundwater

4.5.1. Apparent Age of Groundwater

The database of radiocarbon used for this study comes from the [31] Thesis. Their study was conducted in the same area especially in Hadjer Lamis and collected 14 samples from the Quaternary system. The results of $A^{14}C$ are scattered. The values of boreholes range from 7.76% pMC at Bisney (FD11) to 97.71% pMC at N'djamena Fara (FD7) with a mean value of 71.31% pMC. In contrast, the values of dug-wells range from 67.22% pMC at Mahagar (PD21) to 110% pMC at Karmé (PD20') with a mean value of 89.11% pMC. Samples of some dug-wells such as PD18, PD19 and PD20' present $A^{14}C$ values up to 100% pMC and could indicate recent water infiltration (after 1950s). Moreover, 71.42% of boreholes present notable $A^{14}C$ with values ranging from 63.20% to 97.71% pMC while dug-wells show increased values of $A^{14}C$ ranging 67.22% pmc.

Furthermore, the values of $\delta^{13}C$ for boreholes fluctuate from -17.30‰ V-PDB at Ngoura (FD24) to -6.53‰ V-PDB at Massaguet (FD6) with a mean value of -9.91‰ V-PDB. Those of dug-wells in contrast range from -13.90‰ V-PDB at Karmé (PD20') to -6.60‰ V-PDB at Bisney (PD25") with a mean value of -8.94‰ V-PDB. The most enriched values of boreholes and dug-wells could be explained by the partial interaction of carbonates between water and rocks when there is a long residence time with the mineralogical matrix [68]. FD11 seems to represent old groundwater with enriched value of $\delta^{13}C$, attesting of exchanges between water and aquifer rocks [69]. In contrast, depleted values indicate isotopic reactions exchanges with carbonate sources such as soil CO_2 or organic matter and the occurrence of dissolution of carbonates.

4.5.2. Residence Time Estimation

The correction model of Fontes and Garnier eq was adopted relative to the geochemical context of the Quaternary aquifer of the study area. This model indicate on one hand, actual age for borehole FD4 at Djermaya and the dug-well PD23 at Dogo characterized by very low tritium contents (below the detection limit). On another hand, this model gives old ages, attesting of old groundwater which has evolved in a closed system; and characterized by high residence time of several hundred or thousand years. By this, the model indicates particularly ages ranging from actual to 25 805 years, corresponding to Upper Pleistocene to actual periods. Moreover, [20] show stepped apparent ages going from present period to a few thousands years relative to 1950 of our era for the superficial aquifer system. These apparent ages do not match with the assumed superficial recharge aquifer and this could indicate mixing processes between various groundwater proportions and recent water coming from precipitations; leading to a stratification ages groundwater in the system.

5. Conclusion

Stable isotopes of rainfall characterize the input signature relative to the Quaternary aquifer in the study area. The main fractioning process of groundwaters seems to be the physical evaporation processes as attested by the scatter plot of the meteoric lines and the low slope. This evidences the unconfined character of this aquifer and the arid conditions climate in the study area. Stable isotopes contents show a wide range of values, attesting of their homogeneity and heterogeneity according to the spatial repartition. By this, δ-values show different origins of groundwater. Tritium contents indicate a variability in residence times through the Quaternary aquifer attesting several and distinct recharge events with some old groundwater (pre-nuclear). In addition, groundwater ages range from Upper Pleistocene to actual periods. However, mixing processes lead to a stratification water ages in the system.

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