

Physico-Chemical and Isotopic (^{18}O , ^2H and ^3H) Characterization of the Upper Dallol Maouri Watershed (Niger)

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Abstract

Dallol Maouri is one of the fossil valleys on the left bank of the Niger River. Its watershed drains water from valleys in the Tahoua and Dosso regions of Niger. The watercourse is not continuous and has areas of surface water accumulation (ponds) and areas of spreading and infiltration. The surface water potential in this area is limited, with most of the ponds having a temporary to the semi-permanent regime. Groundwater resources are, therefore, the main sources of withdrawal for human food, agriculture, and livestock. Climate change through the variation in rainfall, the often-anarchic multiplication of catchment works (wells and boreholes) and agricultural activities can have impacts on the qualitative and quantitative evolution of surface and groundwater. The objective of this study is to characterize the surface and underground water of the upper dallol Maouri through the physicochemical parameters of the water and the use of the isotopes of the water molecule (^{18}O , ^2H and ^3H). A total of 53 water samples were analyzed at the laboratory of the Regional Directorate of Hydraulics and Sanitation of Tillabéri (Niger) for chemical parameters and 73 samples were analyzed at the Radio Analysis and Environment Laboratory (LRAE) of the National School of Engineers of Sfax (ENIS) of Tunis for isotopy. The water of the ponds is characterized by three types of facies: calcium bicarbonate, calcium and magnesium bicarbonate, and calcium nitrate chloride. The groundwater is 75% of the chloride-nitrate-calcium facies and the CT3/CT2 groundwater is calcium and magnesium bicarbonate. The results of the stable isotopes made it possible to highlight the presence of four distinct water groups: ponds characterized by highly evaporated water, the sheets of Continental Terminal 1 and 2 (CT1 and CT2) with an isotopic cachet of old water, the water table consisting of a two-layer system in the

southwestern part of the area. The water is not very mineralized (40 μS to 600 μS) and is slightly acidic (pH = 6.4). The analysis of the radioactive isotope (^3H) content of the water from the water table has made it possible to identify the areas of recharge of the water table. These results also highlight: the presence of an upward drainage zone, and the contribution of lowland ponds to the recharge of alluvial aquifers ranging from 24% to 84%. No structure in this zone reaches the Continental Intercalaire and the Continental Hamadien, the depth of which is estimated at an average of 600 m. The relationship between the ^{18}O and ^3H contents of groundwater water shows two types of water with tritium contents higher than 2 TU for alluvial aquifers and tritium contents lower than 2 TU for groundwater (CT3). The analysis of the radioactive isotope (^3H) contents of the groundwater has made it possible to identify recent recharges at the level of the alluvial aquifers and in the outcrop zone of CT3. There is no hydraulic continuity between the plateau ponds and groundwater.

Keywords

Dallol Maouri, Physicochemistry, Isotopy, Ponds, Groundwater, Continental Terminal

1. Introduction

Climate variability and change have a direct effect on the hydrological cycle, modifying it considerably [1]. Climate change is one of the emerging factors in West Africa and is noticeable in the problems of agricultural development [2]. The drought of the 1980s was characterized in the Sahel not only by a drop in rainfall but also aggravated its already irregular poor distribution in space [3]. This situation also acts on the recharge of the water table dependent on rain. Water supply is therefore a fundamental problem for the population. Niger, with increased sensitivity to extreme situations (floods, droughts) due to its economic, social, and demographic structure, is one of the countries most impacted by the consequences of climate change and variability.

Faced with the marked aridity of its climate, Niger's national agricultural policy sought, from 1960, new agricultural strategies capable of improving productivity wherever conditions seemed favorable [4]. Today, because of these catastrophic droughts, a dynamic of accumulation arises from the irrigation and development of the lowlands. Therefore we are witnessing the construction of several boreholes and market gardening wells. In the Dallol Maouri, in addition to the temporary ponds, the inhabitants use wells of variable depth in the plains of the valleys where the alluvial water table is present at shallow depths for irrigation and human consumption. On the intermediate level, the shafts sink to a depth of 25 m [5]. These operations can have both quantitative and qualitative impacts on water resources. Indeed, according to the report of the Integrated Platform Program for Water Security in Niger [6], the most dominant land use

units in terms of area are the dense shrub steppes with 333,707.8 ha or 25.2% and rainfed crops with 329,882.5 ha or 24.9%. Market gardening is poorly represented in Dallol Maouri. It is noted that these crops represent only 431 ha or 0.03%. Marshy areas represent an area of 486.2 ha or 0.03%. This demonstrates the weight of farming in the study area. However, agriculture by the usage of fertilizers and pesticides leads certain chemical elements to the aquifer to modify its physicochemical nature [7]. This imbalance causes waterborne diseases which are most often caused by an excess of World Health Organization (WHO) standards for these elements in the water following their transfer.

On another level, the galloping demographic growth of the area (3.9% according to the RGPH, 2012) often pushes the population to overexploitation of water resources. This increase compromises, in the long term, extensive practices: decline in fertility, stagnation of yields. The water resources most exposed to these constraints are groundwater because they can be easily mobilized, while the interrelation between the different groundwater in the area on the one hand and between surface water and groundwater on the other hand remains. Still poorly known, unlike the downstream part of the Dallol Maouri, its upstream part has been the subject of little work. Knowing that knowledge of water resources is necessary for a rational, efficient, and sustainable management of these in arid and semi-arid zones, therefore this study was initiated. It concerns the analysis of the chemical and isotopic parameters of water to define its current state on the qualitative level and the possible relationships between the states of these resources. It concerns the analysis of the chemical and isotopic parameters of water to define its current state on the qualitative level and the possible relationships between the states of these resources in order to better prevent the risks of deterioration of the quality of the water resources.

2. Materials and Methods

2.1. Presentation of the Study Area

Dallol is a name given by the Peulhs to a valley, so etymologically “dallol Maouri” would mean the Maouri valley and “Maouri” which represents an ethnic group from Niger. It is a fossil valley located in the middle of the Sahelian zone in the center-west of Niger. It collected during the last wet climatic phase the water of the koris of the Ader Douchi. Currently, this water can no longer flow very far and infiltrate fairly quickly towards the water table of the Continental Terminal.

The Dallol Maouri is a Ramsar site. Its number is 1381, with an area of 317,520 ha. The site was registered on 26-04-2004 as a Ramsar site.

The upper Dallol Maouri belongs to the vast basin of the Iullemeden. It is located between longitude 3°46' and 5°07' East and latitude 13°53' and 14°56' North (**Figure 1**). Its watershed covers an area of 10,210 km² and is in the north of the department of Dogondoutchi straddling 2 communes and a department, namely the rural communes of Dogon kirya, Soukougoutan and the department of Bagaroua (**Figure 1**). In this area, the surface water potential is limited and

consists of semi-permanent and permanent ponds threatened by climate change and human activities. Groundwater resources are therefore the main sources of water supply for populations, livestock and withdrawals for irrigated crops.

2.1.1. Geological, Geomorphological and Hydrogeological Contexts

• Geological and geomorphological framework

The geology of the study area is characterized by crystallophyll formations and sedimentary formations (Figure 2). The filling of the sedimentary formations consists mainly of sandstone, sand and silts with clayey intercalation dating from the Silurian to the Quaternary. We observe from bottom to top [8]:

- The Continental Intercalaire (CI) and Continental Hamadien (CH) series made up of fine to coarse sandstones and medium to coarse sands.
- The series of Paleocene/Ypresian marine deposits made up of marl and limestone, the Continental Terminal 1 (CT1) series which rests on the marine formations of the Paleocene/Ypresian (the facies is essentially sandy with clay passages and soft gray green sandstones, sandstone, clayey sand).
- The Continental Terminal 2 (CT2) series consisting of two layers of gray clay with lignite and peat sandwiching a layer of sand in which thin past clay layers appear.
- The Continental Terminal 3 (CT3) series essentially made up of sand, hetero-granular sandstone, and more or less clayey silts and finally the alluvial aquifer series, essentially made up of alluvial sand.

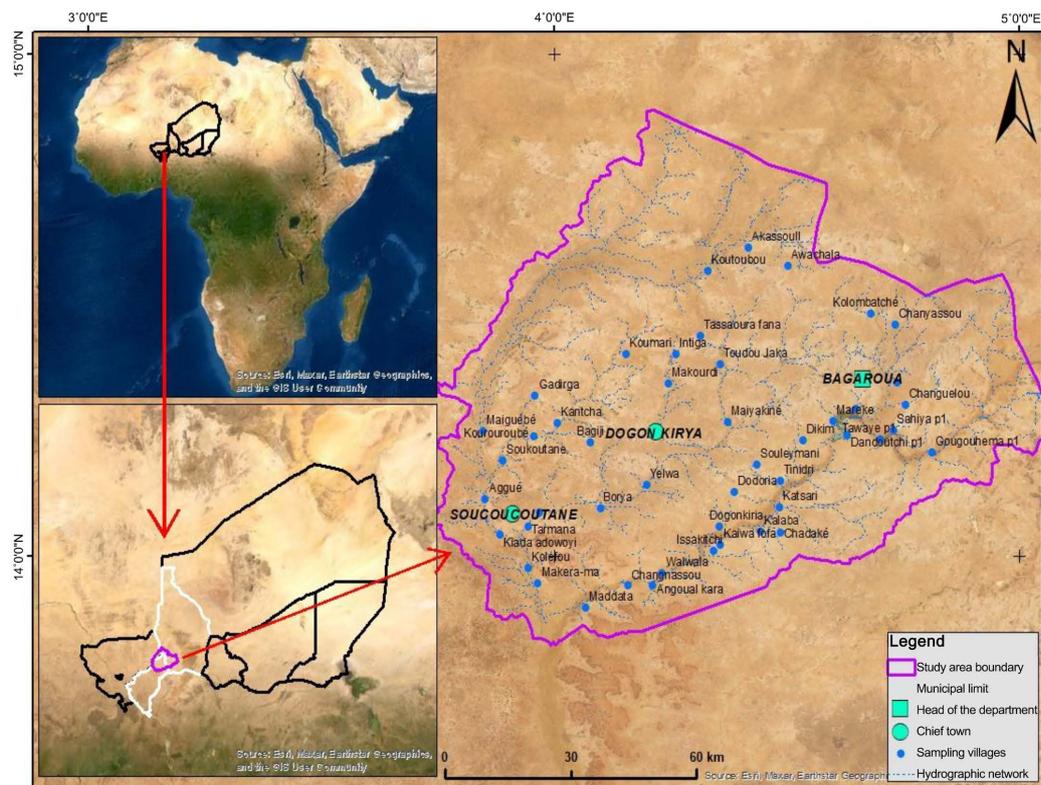


Figure 1. Location of the study area and distribution of sampling villages.

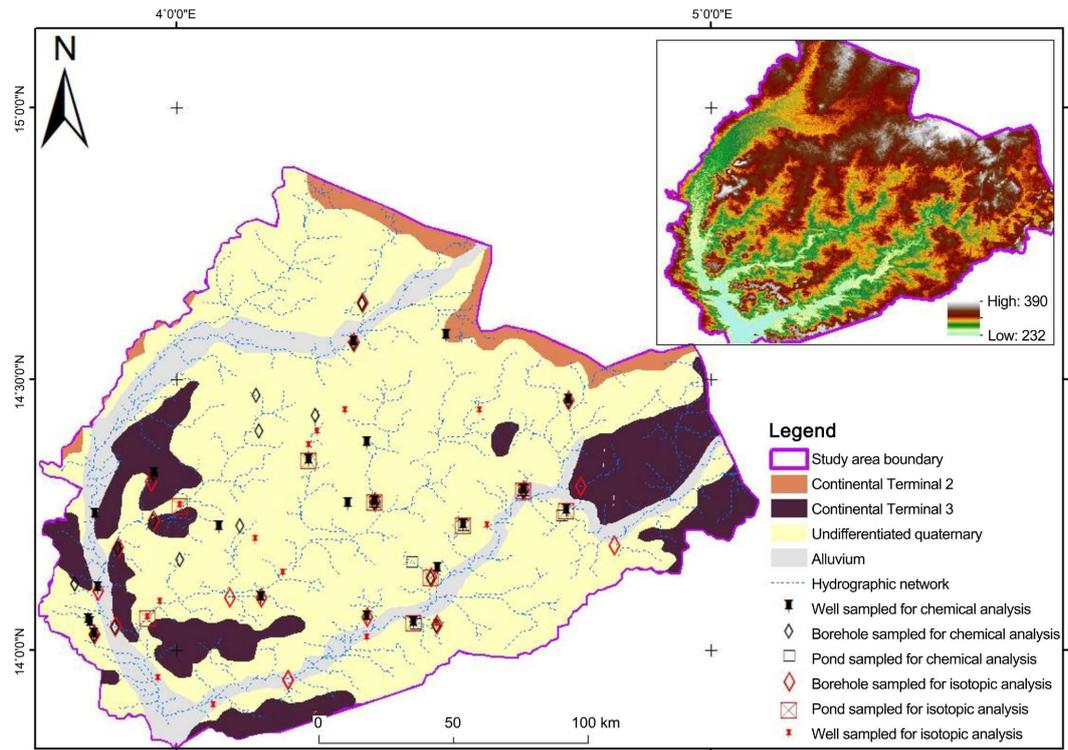


Figure 2. Geological map of the upper Dallol Maouri watershed and distribution of types of structures sampled.

The relief of the study area is made up of plateaus, intermediate zones and Dallol plains with altitudes varying from 232 to 390 m above sea level (Figure 2).

• Hydrogeological setting

The hydrogeology of the area is characterized by several superposed aquifers: alluvial aquifers, CT3, CT2, CT1 aquifers and CI/CH aquifers. The impermeable layers separating the different aquifers become sandy or thin in places, thus promoting communication between the aquifers [8]. The alluvial aquifer, the most exploited for irrigation purposes above all, is characterized by sudden variations in lithologic facies, leading to the formation of perched aquifers. According to [9] the morphology of its piezometric surface is complex. In the north of the dallol and under the plateaus, diffuse recharge is low or even non-existent. It is carried out in a localized way from the points of concentration of runoff water, permanent ponds and streams [10] [11] [12].

The Dallol Maouri is one of the valleys where the availability of water (the alluvial water table is less than 25 m deep) makes it possible to envisage a good development of irrigated crops, after the rainy season and before the arrival major periods of heat in April and May [3]. Also, on the plateaus, the impermeable ferruginous armor can support a few narrow pools of short duration, where the sandy cover is the most important.

2.1.2. Climate

The climate is dry tropical with a rainy season which conditions all life [5]. The

Dallol Maouri covers an area of more than 45,000 km² in a desert region with average temperatures varying very strongly during the year. The highest, recorded in April and May, ranges from 40°C to 47°C. This high temperature causing intense evaporation would be the basis of the early drying up of much surface water [13]. The lowest temperatures observed in December and January fluctuate between 15°C and 20°C [14]. A short rainy season of 3 to 4 months begins from June and can reach until September. The annual cumulative rainfall is around 400 mm.

2.1.3. Measuring Tools

The tools used in the context of this work are composed of field tools for *in situ* analyzes of the physical parameters of water and sampling, as well as laboratory tools used in chemical and isotopic manipulations.

The field tools consist of a Garmin-type GPS for taking geographical coordinates of the various sample collection points; a multi-parameter conductivity meter for measuring conductivity, temperature, and pH; 10 ml amber glass pillboxes, 500 ml polyethylene bottles intended for taking samples for isotopic analyzes and 1 liter bottles for chemical analyzes.

As far as laboratory tools are concerned, they are divided into two categories, the purpose of which is chemical analyzes for one and isotopic analyzes for the other. These are the DR/2000 and DR/2800 spectrophotometers, a Jenway PFP 7 flame photometer and reagents for the analysis of chemical parameters.

For isotopic analyses, a still, flasks, an LGR laser absorption spectrometer, a mass spectrometer and an oven are used.

2.2. Methodological Approach

2.2.1. Setting up the Sampling Network

This step consisted of choosing the sites for taking the water samples to be analyzed. The purpose of this choice is to cover the entire study area and to affect all the types of water present according to their environment, both from a chemical and isotopic point of view. The geospatial distribution of ponds, wells and boreholes made it possible beforehand, depending on their distribution, to choose the different water points to be analyzed.

The physical parameters (conductivity, temperature, and pH) were recorded at ninety-three water points, all categories combined, during two periods of the year 2021 in January and July (**Figure 3**). These months correspond to the periods when the water table reaches its maximum called “high water” (January) and its lowest level, “low water” (July). These measurements took place *in situ*.

Samples from six ponds, nineteen wells and twenty-eight boreholes were taken for chemical analysis against those from nine ponds, forty wells and twenty-four boreholes for isotopic analyzes (**Figure 2**).

Some of these water points were sampled for simultaneous chemical and isotopic analyzes (**Figure 3**).

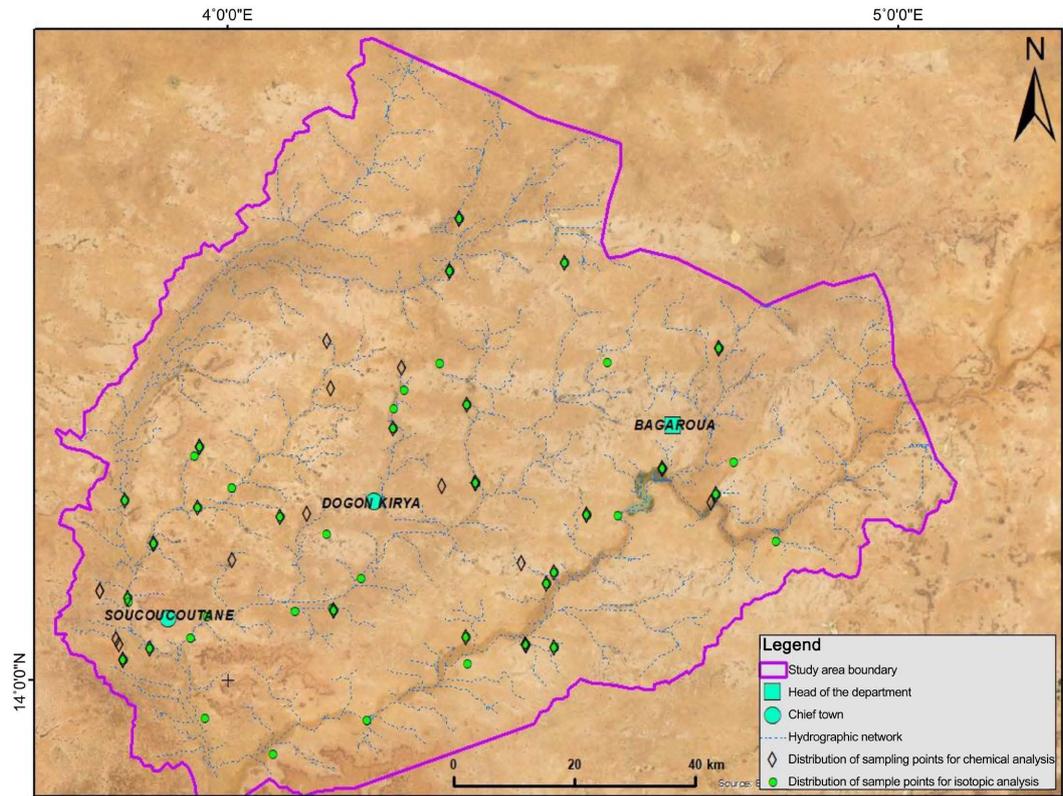


Figure 3. Distribution of sampling points.

2.2.2. Analytical Techniques

The chemical elements were determined by titration for TAC, TH, Ca^{2+} and Cl^- , by colorimetric spectrometry for NO_3^{2-} , NO_3^- , SO_4^{2-} , F^{2+} and F^- and the spectrometric method for Na^+ and K^+ .

For isotopy, tritium was analyzed by electrolytic enrichment and stable isotopes (oxygen-18 and deuterium) by laser spectrometry.

2.2.3. Data Processing

For chemistry, the calculation of ionic balances was the prelude to data processing. Its purpose is to check the reliability of the analytical results of the chemical parameters obtained in the laboratory. It is given by the formula:

$$(u)(\%) = \frac{\mathcal{E}_{\text{cations}} - \mathcal{E}_{\text{anions}}}{\mathcal{E}_{\text{cations}} + \mathcal{E}_{\text{anions}}} * 100 \leq 6\%$$

where (u) = the ionic balance, $\mathcal{E}_{\text{cations}}$ = sum of positive major ions and $\mathcal{E}_{\text{anions}}$ = sum of major negative ions.

The ion formula is used to show the general trend of ion dominance orders. The DIAGRAMME software developed by Roland Smiller from the Hydrogeology Department of the University of Avignon in France, made it possible to define and confirm the chemical facies of the water as well as the similarity of their origins through the piper and Schoeler diagrams Berkloff.

The calculation of the elementary statics consisted in determining the maximum, the minimum, the average, the median, the coefficient of variation of the

different series of data. The characteristic ratios or ionic ratio have been applied to characterize the origins and process of water mineralization.

For the processing of isotopic data, a characterization of the isotopic contents of the poles of influence (water from precipitation and ponds) of groundwater recharge is carried out. Having not done isotopic analyzes of rainwater, data from previous work carried out in Niger and neighboring countries (Mali, Chad) with similar climatic characteristics to our area were used. These are the works of [8] [15]-[20]. As well as the line of global meteoritic water

$$\delta^2\text{H} = 8\delta^{18}\text{O} + 10 \quad (1)$$

established by [21] in 1961.

The results obtained within the framework of this study were compared with the isotopic signatures (contents of oxygen-18 and deuterium (^2H)) of the precipitation resulting from the work of the authors presented above. To study the relationships between water to estimate mixing rates, the oxygen-18 isotopic balance was used.

To determine the “ages” of groundwater from the water table, tritium was used. The approach used is a simple comparison which consists of comparing the tritium contents at the system outlet and those measured in the groundwater during this work. To do this, the system output tritium contents were calculated from the contents of the precipitation reconstituted by applying a simple radioactive decay according to the piston flow model of formula

$$C_t = C_0 e^{-\lambda t} \quad (2)$$

where C_t = number of atoms at time t ; C_0 = number of atoms at the closure of the system; $\lambda = \ln 2 / T$ decay or radioactive constant; t = time elapsed since closing; T = the period or half-life of the radioactive isotope (for tritium $T = 12.43$ years).

3. Results and Discussion

3.1. Physical Parameters of Water

➤ Conductivity

Conductivity makes it possible to assess the quantity of salts dissolved in the water [22] [23]. It can also provide information on pollution, the different inter-water mixing zones and/or the infiltrability of water. The World Health Organization (WHO), 2011 standard for drinking water is between 500 and 1500 $\mu\text{S}/\text{cm}$.

The conductivity values of the first campaign range from 50 to 240 $\mu\text{S}/\text{cm}$ with an average of 121.67 $\mu\text{S}/\text{cm}$, a median of 105 $\mu\text{S}/\text{cm}$ and a standard deviation of 72 $\mu\text{S}/\text{cm}$ ($n = 6$) for the water of the ponds and those of the second campaign vary from 70 to 240 $\mu\text{S}/\text{cm}$ with an average of 150 $\mu\text{S}/\text{cm}$, a median of 140 $\mu\text{S}/\text{cm}$ and a standard deviation of 78.74 $\mu\text{S}/\text{cm}$.

For groundwater, these values are higher and range between 70 and 1770 $\mu\text{S}/\text{cm}$ with an average of 271.54 $\mu\text{S}/\text{cm}$, a median of 195 $\mu\text{S}/\text{cm}$ and a standard

deviation of 273.32 $\mu\text{S}/\text{cm}$. cm ($n = 55$) for the first campaign against values from 100 to 1260 $\mu\text{S}/\text{cm}$ with an average of 286.35 $\mu\text{S}/\text{cm}$, a median of 225 $\mu\text{S}/\text{cm}$ and a standard deviation of 208.58 $\mu\text{S}/\text{cm}$ for the second campaign.

The water of CT2/CT1 are taken in a grouped way. The conductivities of these water vary from 70 to 290 $\mu\text{S}/\text{cm}$ with an average of 148.33 $\mu\text{S}/\text{cm}$, a median of 140 $\mu\text{S}/\text{cm}$ and a standard deviation of 75.74 $\mu\text{S}/\text{cm}$ and those of the second vary from 90 at 340 $\mu\text{S}/\text{cm}$ with an average of 143.33 $\mu\text{S}/\text{cm}$, a median of 105 $\mu\text{S}/\text{cm}$ and a standard deviation of 96.88 $\mu\text{S}/\text{cm}$ for CT2/CT1 water ($n = 30$).

An increase in the conductivities from the first campaign to the second campaign is observed for the water of the ponds and the water table against a decrease in these for the water of CT2/CT1 (**Table 1**). These increases could be linked to additions of chemical elements to ponds and groundwater after the rainy season. These variations are caused by runoff water reaching the ponds for the ponds and infiltration water for the aquifer. All measured values are below the WHO standard for drinking water.

➤ pH

The pH modifies certain physio-chemical equilibrium conditions. It provides information on the aggressiveness or corrosive action of water on certain materials. The WHO, 2011 standard for drinking water is between 6.5 and 9.2 pH units.

The pH values of the first campaign vary from 6.27 to 7.60 pH units with an average of 7.11, a median of 7.18 and a standard deviation of 1.05 ($n = 6$) for the water of the ponds and those of the second campaign are between 6.67 and 7.81 with an average of 7.30, a median of 7.28 and a standard deviation of 0.49.

For groundwater, the values are between 6.02 and 7.22 with an average of 6.60, a median of 6.46 and a standard deviation of 0.49 ($n = 55$) for the first campaign and those of the second campaign vary from 5.52 to 7.61 with an average of 6.23, a median of 6.30 and a standard deviation of 0.60.

The pH values vary from 5.95 to 6.76 with an average of 6.34, a median of 6.33 and a standard deviation of 0.33 and those of the second vary from 5.66 to 6.59 with a mean of 6.01, a median of 6.01 and a standard deviation of 0.34 for CT2/CT1 water ($n = 30$).

Table 1. Statistical values of water conductivity in the area.

Designation	Middle of the water	Country	MEAN	MEDI	ECAR	MAX	MINI
Conductivity	Ponds	1 st	121.67	105	72.5	240	50
		2 nd	150	140	78.74	240	70
	Groundwater	1 st	271.54	195	273.32	1770	70
		2 nd	286.35	225	208.58	1260	100
	CT2/CT1	1 st	148.33	140	75.74	290	70
		2 nd	143.33	105	96.88	340	90

The general analysis of the different data shows that the pH of the pond water is neutral while the water of the groundwater table and CT2/CT1 are slightly acidic (**Table 2**). The pH tends to decrease between the first and the second campaign for groundwater, whereas it increases for surface water. By diluting, rainwater lowers the pH of groundwater, while for surface water; runoff water can modify the pH of pond water.

➤ Temperature

The temperature of the water acts on the solubility of gases, the dissociation of dissolved salts and the pH. It also provides information on the origin of the water and any mixtures. This must be 25°C according to the WHO standard, 2011.

The temperature values of the first campaign range from 21.40°C to 24.40°C with an average of 23.38°C, a median of 23.70°C and a standard deviation of 1.05 (n = 6) for the water of the ponds and those of the second campaign vary from 23.20°C to 28.70°C with an average of 24.62°C, a median of 23.90°C and a standard deviation of 2.05.

For groundwater, the values are between 20°C and 32.90°C with an average of 29.88°C, a median of 30.40°C and a standard deviation of 2.25 (n = 55) for the first campaign and those of the second campaign vary from 28.20°C to 33.30°C with an average of 31.23, a median of 31.50 and a standard deviation of 1.27.

The temperature values vary from 30.80°C to 33.80°C μ S with an average of 32.37°C, a median of 32.40 and a standard deviation of 1.57 and those of the second vary from 29, 30°C to 33.40°C with an average of 32.37°C, a median of 31.95°C and a standard deviation of 1.52 for CT2/CT1 water (n = 30).

The water of the ponds shows a very strong variability of temperature; this could be due to the impact of the movement of the winds on the surface water. The water of the water table gives temperatures like those ambient; this could be related to the thermal balance with the atmosphere. As for the deep water of CT2/CT1, the temperatures are much higher, which is in line with the evolution of the thermal gradient (**Table 3**).

3.2. Water Chemical Parameters

3.2.1. Order of Abundance of Ions in Water

➤ Cations

The relative importance of the major cations in the samples analyzed is as follows:

Table 2. Statistical values of the pH of the water of the area.

Designation	Middle of the water	Country	MEAN	MEDI	ECAR	MAX	MINI
pH	Ponds	1 st	7.11	7.18	0.53	7.6	6.27
		2 nd	7.3	7.28	0.49	7.81	6.67
	Groundwater	1 st	6.6	6.46	0.49	7.8	5.87
		2 nd	6.23	6.3	0.6	7.61	5.22
	CT2/CT1	1 st	6.34	6.33	0.33	6.76	5.95
		2 nd	6.01	6.01	0.34	6.59	5.66

Table 3. Statistical values of water temperature in the area.

Designation	Middle of the water	Country	MEAN	MEDI	ECAR	MAX	MINI
Temperature	Ponds	1 st	23.38	23.7	1.05	24.4	21.4
		2 nd	24.62	23.9	2.05	28.7	23.2
	Groundwater	1 st	29.88	30.4	2.25	32.9	20
		2 nd	31.23	31.5	1.27	33.3	28.1
	CT2/CT1	1 st	32.37	32.4	1.57	33.8	30.8
		2 nd	31.82	31.95	1.52	33.4	29.3

$\text{Ca}^{2+} > \text{Na}^+ > \text{Mg}^{2+} > \text{K}^+$ for pond water;

$\text{Ca}^{2+} > \text{Mg}^{2+} > \text{Na}^+ > \text{K}^+$ for groundwater samples;

$\text{Ca}^{2+} > \text{Mg}^{2+} > \text{Na}^+ > \text{K}^+$ for CT2 water samples;

$\text{Na}^+ > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+$ for CT1 water samples.

Overall, calcium ions are the most dominant (75%) at the cation pole, followed by sodium ions at 25%. Potassium ions remain the least important ions for all types of water.

➤ Anions

The relative importance of the major anions in the samples analyzed is as follows:

$\text{HCO}_3^- > \text{SO}_4^{2-} > \text{Cl}^- > \text{NO}_3^-$ for pond water;

$\text{HCO}_3^- > \text{NO}_3^- > \text{SO}_4^{2-} > \text{Cl}^-$ for groundwater samples;

$\text{HCO}_3^- > \text{SO}_4^{2-} > \text{Cl}^- > \text{NO}_3^-$ for CT2 samples;

$\text{HCO}_3^- > \text{SO}_4^{2-} > \text{NO}_3^- > \text{Cl}^-$ for CT1 samples.

At the level of the anions, in general it is the bicarbonate ions which dominate 100 % against a parity of the nitrate and chloride ions in the last position.

3.2.2. Water Facies (Piper Diagram)

The projection of the chemical elements of the water on the Piper diagram made it possible to distinguish four types of chemical facies overall (**Figure 4**), all observed at the level of the CT1 water, three types at the level of the ponds and the groundwater table and finally two types in CT2 water. Two types of facies are common to all types of water, namely the calcium and magnesium bicarbonate facies and the calcium and magnesium chloride and sulphate facies. The sodium and potassium bicarbonate facies is present in groundwater and CT1 water. The sodium and potassium chloride or sodium sulphate facies is only observed in the water of the ponds and in the water of CT1.

In general, the calcium and magnesium chloride and sulphate facies is the most dominant with 45% of the water samples. It is followed by the calcium and magnesium bicarbonate facies with 43%. Then comes the sodium and potassium bicarbonate facies up to 8% and finally the sodium and potassium chloride or sodium sulfate facies with only 4%.

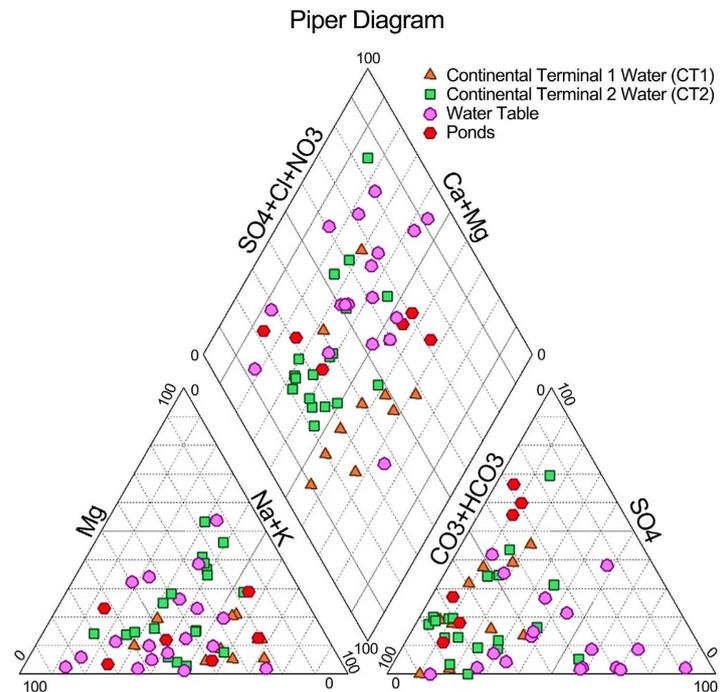


Figure 4. Piper diagram of water in the study area.

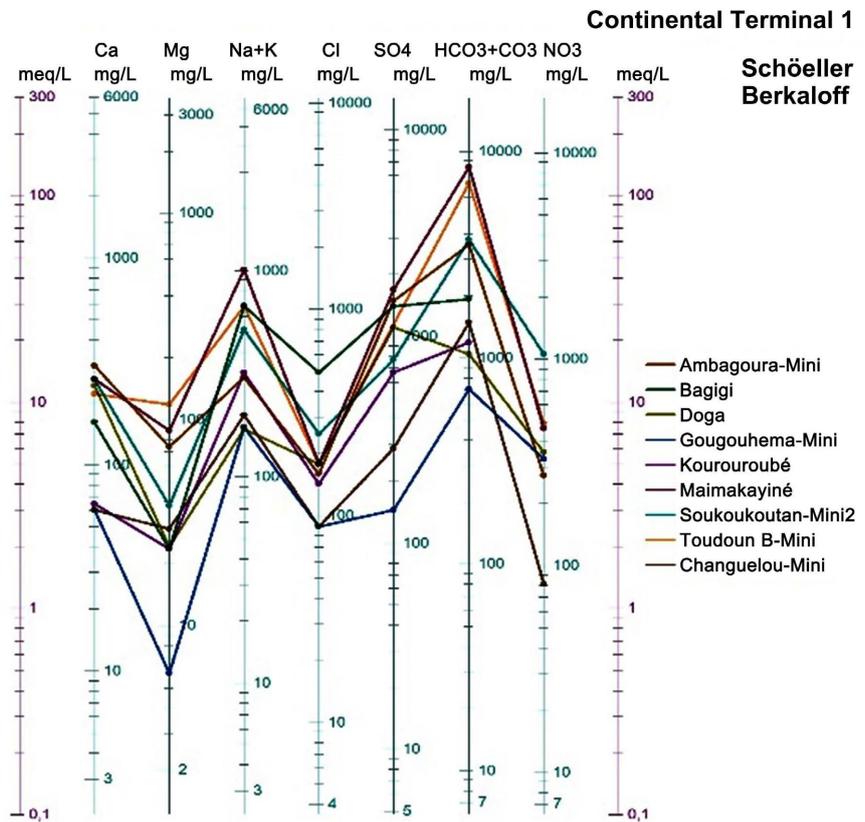
➤ Distribution of facies types according to water environments

Table 4 gives the proportions of the different types of facies encountered according to the water environment.

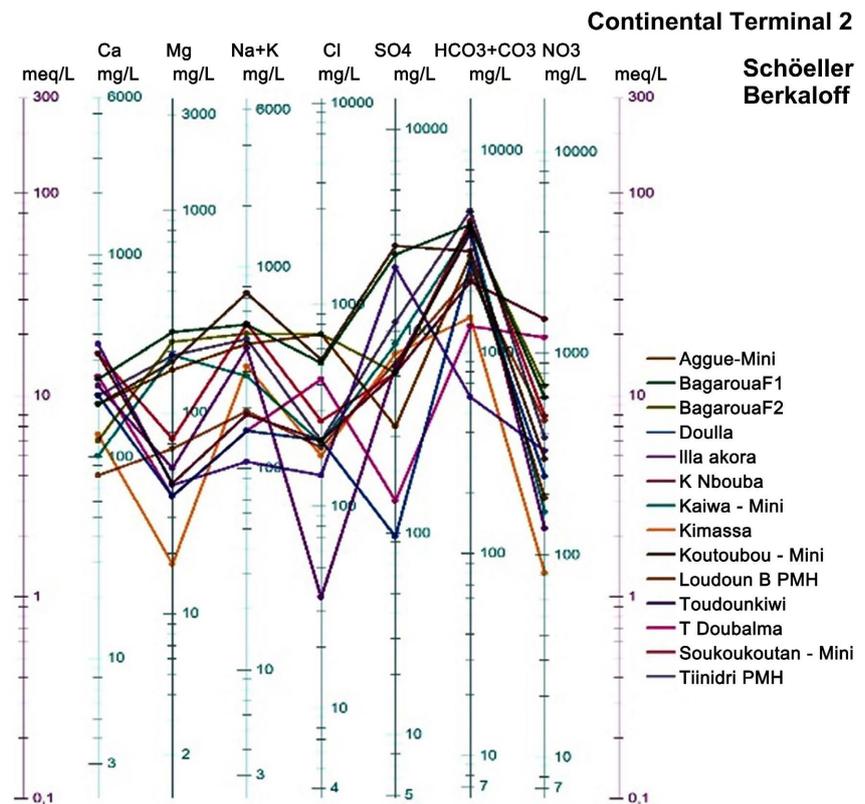
3.2.3. Diagram of Schöeler Berkaloff

The Schoeler Berkaloff diagram is a semi-logarithmic diagram which allows to graphically representing the results of chemical analyses. Depending on the geological environment of the water resource withdrawn (CT1, CT2, groundwater and pond), the Schöeler Berkaloff diagram was drawn up to highlight the origins of the water. **Figure 5(a)** demonstrates that the peaks obtained at the level of the bicarbonate and sodium and potassium poles for the water of CT1 confirm the name of the dominant facies: this is the sodium and potassium bicarbonate facies as well as for the water of CT2 demonstrated by the **Figure 5(b)**. The heterogeneous character of the different curves shows that at the water level of the water table there can be various facies at different degrees **Figure 5(c)**. The various peaks observed in **Figure 5(d)** confirm the dominant type of facies, which is calcium bicarbonate and magnesium in the case of pond water.

In addition to confirming the different types of facies, **Figure 5** gives an idea of the origin of the different types of water. The parallelism of the various curves in **Figure 5(a)** and **Figure 5(d)** show that the water of CT1 between them on the one hand and the water of the pools sampled between them on the other hand have the same origin. The almost parallel character of the curves in **Figure 5(b)** also confirms that, these water have the same origins or fair close origins. Regarding groundwater, **Figure 5(c)** through the heterogeneity of the curves confirms that these water have different origins.



(a)



(b)

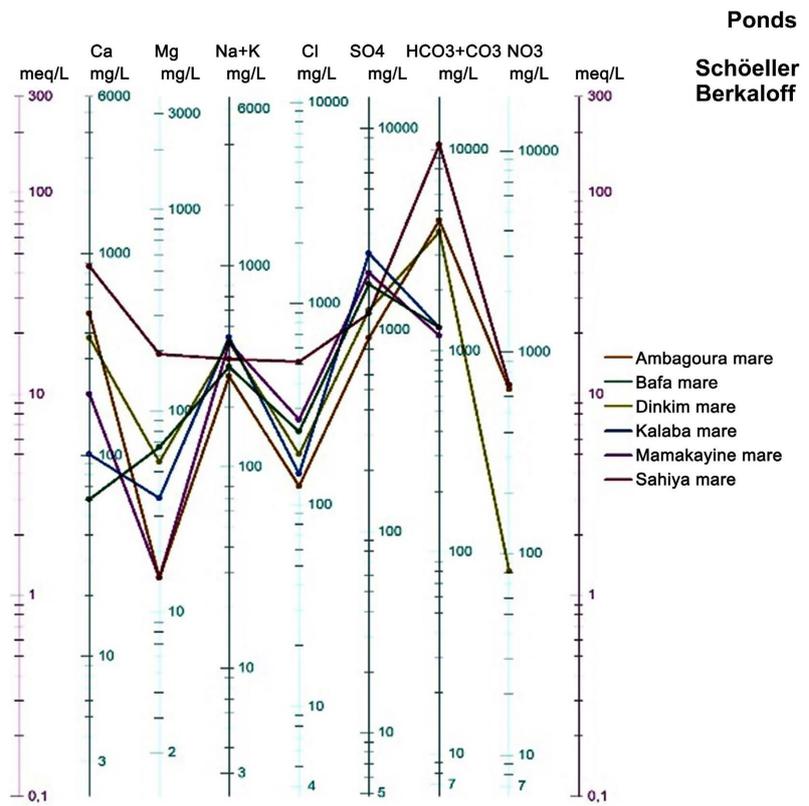
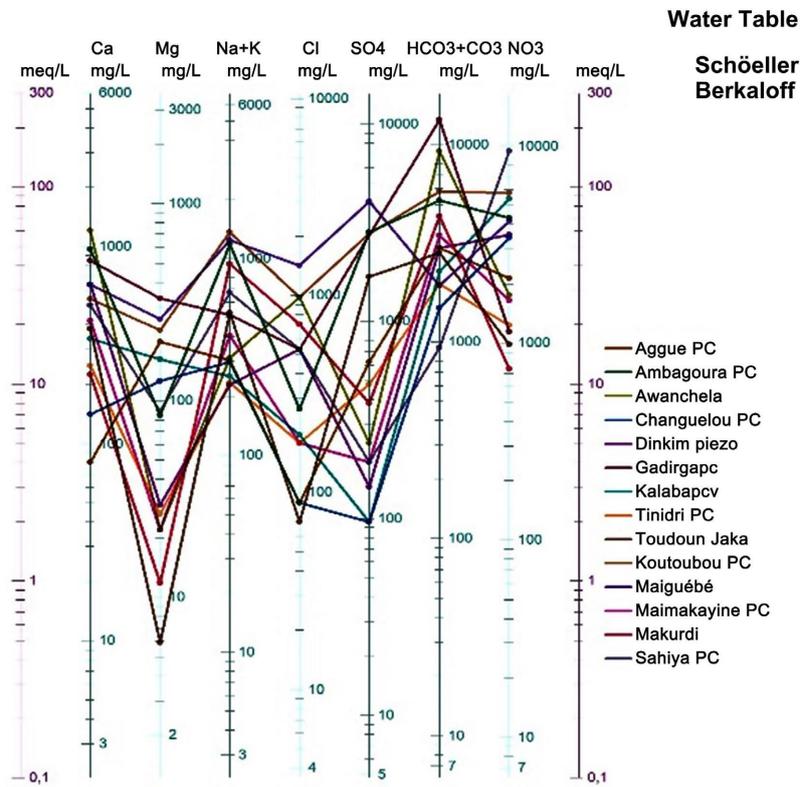


Figure 5. Schöeler Berkaloff diagrams of different types of water.

Table 4. Proportion of different facies encountered.

	Sodium and potassium bicarbonate	Calcium and magnesium bicarbonate	Chloride and sulphate calcium and magnesium	Sodium and potassium chloride or sodium sulphate
CT1	45%	33%	11%	11%
CT2	68%		32%	
Groundwater	5%	16%	79%	
Pond		50%	33%	17%

3.2.4. Analysis of Major Elements

➤ Pond water

Table 5 gives the statistical values of the major elements at surface water level. Only iron has values exceeding WHO standards. These values are observed at the level of plateau pools located on the ferruginous hardpan.

➤ Groundwater

Table 6 presents the statistical values of the major elements at groundwater level. Elements with values exceeding WHO standards are fluorine, nitrate, and iron.

Structures with values exceeding WHO standards for nitrate are structures from which animals come to drink. For iron, the value exceeding the WHO standard is observed at a single water point: this is a piezometer whose static level is less than one meter above the ground.

➤ Groundwater from CT2/CT1

Table 7 presents the statistical values of the major elements at the CT2/CT1 water level. Iron is the only element exceeding WHO standards. Since samples with exceeded values are taken from the tap, corrosion of the pipes made of galvanized material could be the probable reason.

3.2.5. Origin and Process of Mineralization

To determine the origin of the major ions and their evolution in the water of the upper Dallol Maouri basin, the binary diagrams $[\text{Na}^+]$ vs $[\text{Cl}^-]$; $[\text{K}^+]$ vs $[\text{Cl}^-]$; $[\text{Ca}^{2+} + \text{Mg}^{2+}]$ vs $[\text{HCO}_3^- + \text{SO}_4^{2-}]$ and $[(\text{Ca}^{2+} + \text{Mg}^{2+}) - (\text{HCO}_3^- + \text{SO}_4^{2-})]$ vs $[(\text{Na}^+ + \text{K}^+) - \text{Cl}^-]$ were used.

➤ Diagram $[\text{Na}^+]$ vs $[\text{Cl}^-]$ and $[\text{K}^+]$ vs $[\text{Cl}^-]$

Figure 6 presents the relationship between the sodium ions and the chloride ions of all the samples analyzed. This diagram shows that the points are highly scattered. This shows that halite dissolution is not involved in water mineralization or has been masked by other processes. The points located above the halite (NaCl) dissolution line with a slope equal to 1 reflect an excess of sodium and these points mainly concern the water of the CT2 and CT1 aquifer. This excess could be explained by the phenomenon of cationic exchange with the clays constituting the roof and/or the wall or present in lenticular form in these layers. This result agrees with that obtained by [8] in Dallol Maouri.

Table 5. Major elements of pond water.

	HCO ₃ ⁻ (mg/l)	Cl ⁻ (mg/l)	SO ₄ ²⁻ (mg/l)	F ⁻ (mg/l)	NO ₃ ⁻ (mg/l)	NO ₂ ⁻ (mg/l)	Na ⁺ (mg/l)	K ⁺ (mg/l)	Fe ²⁺ (mg/l)	Ca ²⁺ (mg/l)	Mg ²⁺ (mg/l)	Mineralization (mg/l)
Maximum	173.85	14.50	50.00	0.29	11.0	0.20	11.4	7.27	14.4	43.0	15.8	293.23
Minimum	19.52	3.50	19.00	0.00	0.00	0.00	2.57	4.50	0.02	3.00	1.22	91.10
Mean	62.22	6.83	32.50	0.13	3.81	0.09	7.30	5.11	6.27	17.5	5.22	146.98
WHO S., 2011	200-300	250	500	1.50	50	3.00	200	100	0.50	200	150	1500
Deviation	59.58	4.05	11.40	0.14	5.42	0.08	3.63	1.08	6.05	15.1	5.46	74.30
Median	42.70	5.75	30.50	0.11	0.66	0.06	7.70	4.69	5.69	14.5	3.83	124.85
Resume	0.96	0.59	0.35	1.11	1.42	0.92	0.50	0.21	0.96	0.86	1.05	0.51

Table 6. Major elements of groundwater.

	HCO ₃ ⁻ (mg/l)	Cl ⁻ (mg/l)	SO ₄ ²⁻ (mg/l)	F ⁻ (mg/l)	NO ₃ ⁻ (mg/l)	NO ₂ ⁻ (mg/l)	Na ⁺ (mg/l)	K ⁺ (mg/l)	Fe ²⁺ (mg/l)	Ca ²⁺ (mg/l)	Mg ²⁺ (mg/l)	Mineralization (mg/l)
Maximum	219.60	40.00	85.00	1.69	151.8	0.46	38.3	20.6	0.58	60.0	27.3	369.69
Minimum	15.25	2.00	0.00	0.03	4.84	0.00	1.57	1.98	0.00	4.00	0.49	87.02
Mean	65.16	12.25	19.75	0.32	50.4	0.06	12.8	7.22	0.10	24.3	8.50	200.72
WHO S., 2011	200-300	250	500	1.50	50	3.00	200	100	0.50	200	150	1500
Deviation	53.18	11.43	26.00	0.38	38.63	0.11	10.5	5.34	0.15	15.5	8.55	95.52
Median	48.80	6.50	6.50	0.20	44.66	0.02	7.30	5.13	0.04	20.1	5.41	163.01
Resume	0.82	0.93	1.32	1.21	0.77	2.00	0.82	0.74	1.54	0.64	1.01	0.48

Table 7. Major elements of CT2/CT1 water.

	HCO ₃ ⁻ (mg/l)	Cl ⁻ (mg/l)	SO ₄ ²⁻ (mg/l)	F ⁻ (mg/l)	NO ₃ ⁻ (mg/l)	NO ₂ ⁻ (mg/l)	Na ⁺ (mg/l)	K ⁺ (mg/l)	Fe ²⁺ (mg/l)	Ca ²⁺ (mg/l)	Mg ²⁺ (mg/l)	Mineralization (mg/l)
Maximum	137.25	20.00	55.00	0.66	40.9	1.88	35.7	6.75	3.10	18.0	20.7	245.87
Minimum	9.75	0.00	0.00	0.09	0.00	0.00	2.76	0.25	0.02	3.00	0.47	32.37
Mean	49.08	6.61	16.23	0.28	8.87	0.13	9.65	3.69	0.56	10.2	6.32	111.59
WHO S., 2011	200-300	250	500	1.50	50	3.00	200	100	0.50	200	150	1500
Deviation	31.16	5.36	14.40	0.13	9.48	0.39	7.33	1.96	0.91	4.25	5.76	50.02
Median	46.36	5.00	13.00	0.27	6.16	0.03	6.94	4.15	0.10	11.0	3.65	112.54
Resume	0.64	0.81	0.89	0.46	1.07	2.92	0.76	0.53	1.63	0.42	0.91	0.45

Figure 7 presents the relationship between potassium ions and chloride ions shows that the points do not register on the dilution line of sylvite (KCl) with a slope equal to 1. This shows that the Cl⁻ and K⁺ ions do not come from the dilution of the sylvite. They then probably come from the atmosphere and/or from anthropogenic activities.

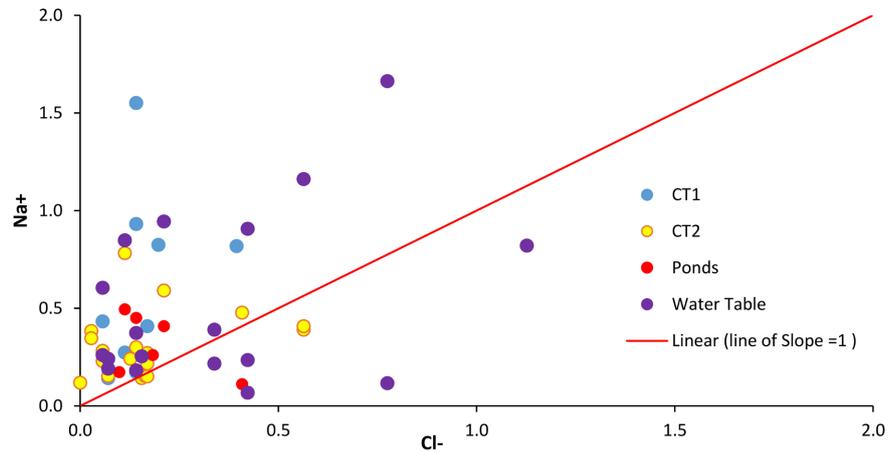


Figure 6. Diagram of $[\text{Na}^+]$ vs $[\text{Cl}^-]$ of the water of the upper Dallol Maouri basin.

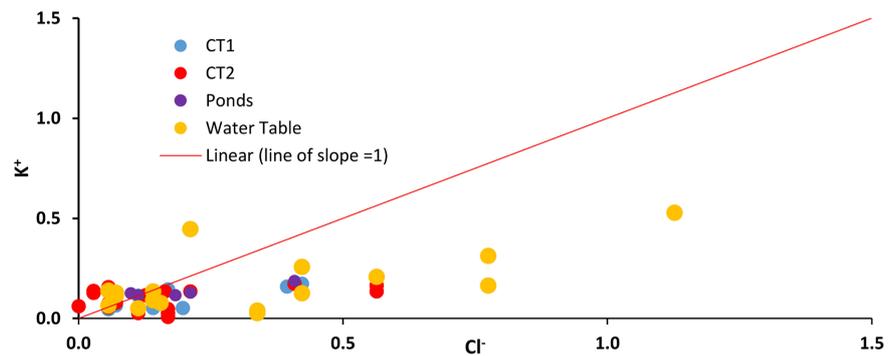


Figure 7. Diagram of $[\text{K}^+]$ vs $[\text{Cl}^-]$ of the water of the upper Dallol Maouri basin.

➤ **Diagram $[\text{Ca}^{2+} + \text{Mg}^+]$ vs $[\text{HCO}_3^- + \text{SO}_4^{2-}]$**

The diagram of $[\text{Ca}^{2+} + \text{Mg}^+]$ vs $[\text{HCO}_3^- + \text{SO}_4^{2-}]$ makes it possible to highlight the origin of the ions Ca^{2+} , Mg^+ and SO_4^{2-} . **Figure 8** shows that the points representing the CT2 aquifer samples lie on or close to the carbonate dissolution line. This allows us to say that the origin of the Ca^{2+} , Mg^+ and SO_4^{2-} ions of the CT2 water is largely the dissolution of calcite, dolomite and gypsum. As regards the water samples from CT1, they are all located below the line, therefore indicating an excess of $\text{HCO}_3^- + \text{SO}_4^{2-}$. This excess shows that the phenomenon of dissolution is not the factor controlling the mineralization of CT1 water and even if it exists, it is negligible. The water samples from the ponds in the North-East part, the groundwater recharge zone, are located on or close to the right. This shows a dominance of carbonate dissolution. The water samples from the ponds located on the plateaus are below the right, which shows the dissolution of the carbonates does not intervene in the process of their mineralization. Regarding groundwater samples, they are widely dispersed. This shows that the dominant process in the mineralization of groundwater would be other than the dissolution of carbonates.

➤ **Base exchange diagram: $[(\text{Ca}^{2+} + \text{Mg}^+) - (\text{HCO}_3^- + \text{SO}_4^{2-})]$ vs $[(\text{Na}^+ + \text{K}^+) - \text{Cl}^-]$**

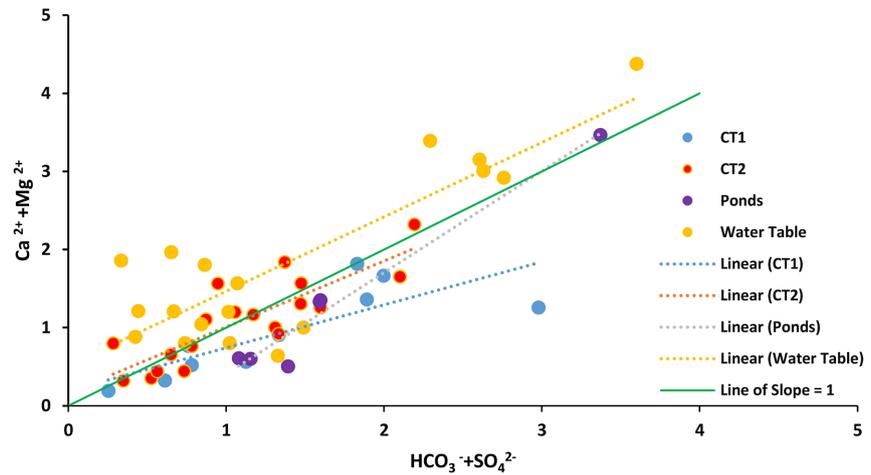


Figure 8. Diagram of $[Ca^{2+} + Mg^{2+}]$ vs $[HCO_3^- + SO_4^{2-}]$.

Some water mineralization processes have been identified in previous work [8] [19] [20] [24] [25] carried out in the Iullemeden basin (Niger). To explain this phenomenon of base exchange, the approach was based on the diagram of $[(Ca + Mg) - (HCO_3 + SO_4)]$ VS $[(Na + K - Cl)]$. This diagram has been used by several authors [25] [26] [27] [28] [29] to explain the base exchanges between the water and the clay minerals present in the reservoirs. Indeed, if $[(Ca + Mg) - (HCO_3 + SO_4)] > 0$ and $[(Na + K - Cl)] < 0$, the exchange phenomenon corresponds to a fixation of Na^+ and release of Ca^{2+} and when it is the opposite, the exchange phenomenon corresponds to a fixation of Ca^{2+} and the release of Na^+ [25]. This diagram emphasizes only the reactions which can exist between the clay minerals and the solution by getting rid of the ions possibly resulting from other reactions of dissolution of the carbonated and evaporitic minerals, but not of the possible contributions by hydrolysis of the silicates [26] [27] [28].

The projection of the various points on the diagram $[(Ca + Mg) - (HCO_3 + SO_4)]$ VS $[(Na + K - Cl)]$ shows that all the samples taken from the CT1 aquifer (blue dots) are located in the field Ca^{2+} uptake and Na^+ release (Figure 9). This highlights the origin of the sodium ions in the aquifer which is quite probably the exchange of bases (adsorption of Ca^{2+} and release of Na^+). This result is in agreement with that obtained from the ionic formula of CT1 which shows that sodium is the dominant cation in all samples of CT1. These results are also strengthened by the results obtained by [8] in 2003. The samples of water from the ponds of the North-East part, zone of recharge of the water table, are located at the level of the origin of the marker. This shows that these water are little or not affected by the exchange process.

3.3. Isotope Parameters of Water

3.3.1. Isotope Content of Rainfall in Niger

The characterization of the origin of the water of the unconfined aquifer therefore passes through the identification of the isotopic signal of the recharge poles towards the aquifer. This is why we first present the isotopic characteristics of

the poles of influence (precipitation in general). At the International Atomic Energy Agency (IAEA) station based in Niamey (IRD), the monthly isotopic contents of precipitation over 15 years, but not continuous from 1992 and 1999 except 1996, and from 2009 to 2016 vary between -8.4‰ and 3.41‰ vs VSMOW with a mean of -2.43‰ , a median of -2.42‰ and a standard deviation of 2.59‰ for $\delta^{18}\text{O}$. They vary between -59‰ and 28.75‰ vs SMOW with a mean of 12.65‰ , a median of 9.5‰ and a standard deviation of 18.81‰ for $\delta^2\text{H}$ (Figure 10). The weighted water height values are -4.3‰ for $\delta^{18}\text{O}$ and -26.4‰ for $\delta^2\text{H}$ [25].

The established local straight lines are all confused with small insignificant shifts. Thus, we see that these lines are located below the global meteoric line with slopes and deuterium excesses lower than those of the global meteoric water line. It can be concluded that these precipitation water undergo evaporation before falling and without significant local recycling of air masses of oceanic origin. This has been described at several meteorological stations in the sub-region such as the Bamako station in Mali; that of Dakar in Senegal; Kano in Nigeria and that of N'Djamena in Chad.

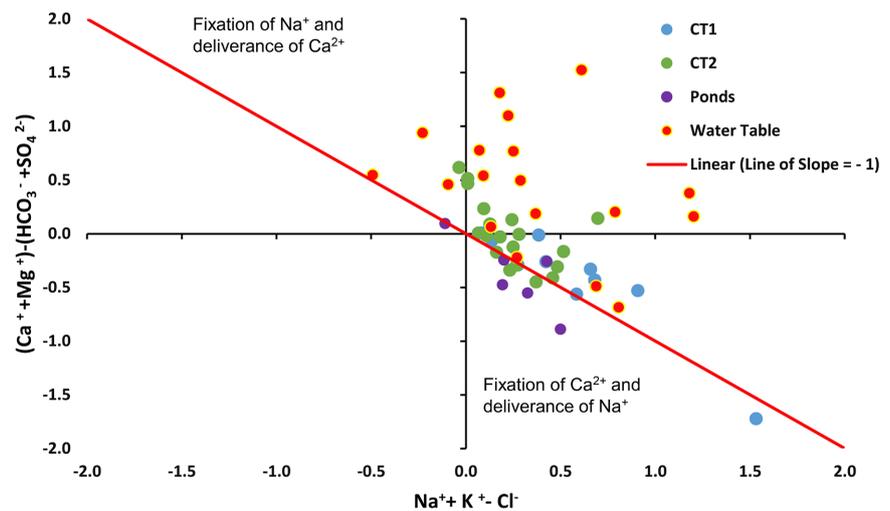


Figure 9. Diagram of $[(\text{Ca}^{2+} + \text{Mg}^{2+}) - (\text{HCO}_3^- + \text{SO}_4^{2-})]$ vs $[(\text{Na}^+ + \text{K}^+) - \text{Cl}^-]$.

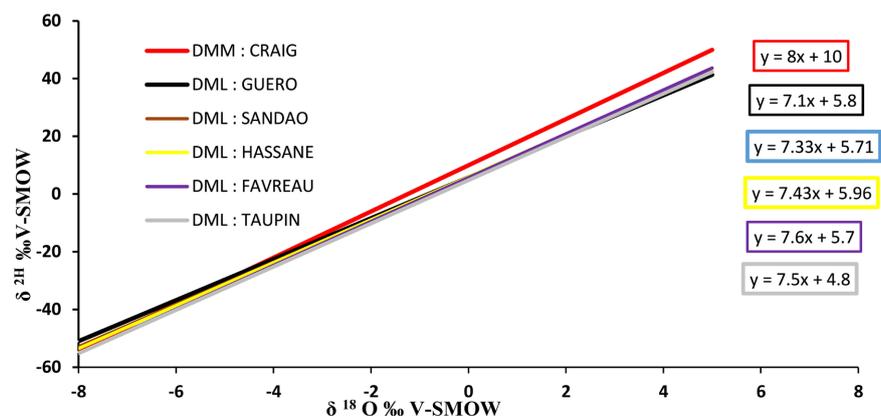


Figure 10. Local lines established in Niger and the line of global meteoric water.

3.3.2. Isotope Content of Upper Dallol Maouri Water

Generally, the isotopic composition of groundwater reflects the weighted isotopic composition of water affecting the recharge zone of the aquifer [30].

➤ Stable isotopes

The stable isotopes of the water molecule (oxygen 18 and deuterium) are intrinsic tracers of groundwater flow, very little subject to isotopic exchanges with the surrounding rock [30]. The analytical results of the oxygen-18 and deuterium contents of all the samples analyzed show a great variability of isotopic contents (Table 8). This is completely consistent and logical with the different water present in the area (surface water and groundwater).

In Figure 11 (The deuterium-oxygen-18 diagram), all the samples analyzed are shown. These samples can be individualized into three categories:

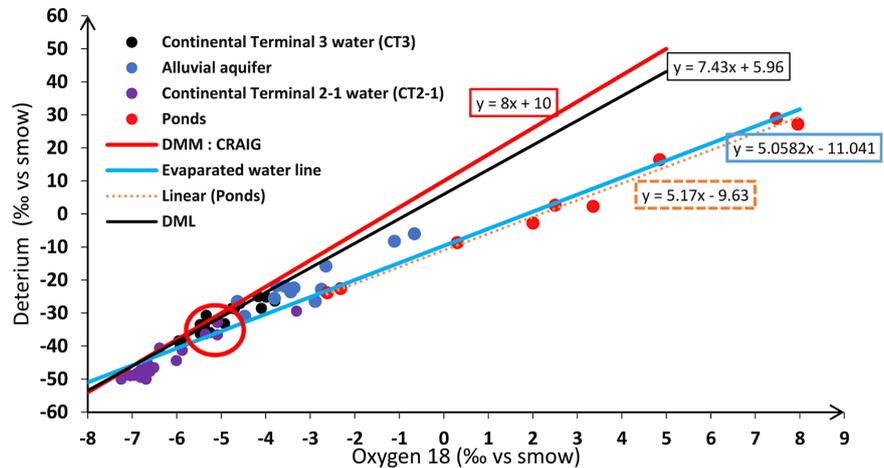
1). The first category is made up of water which lie on a straight line with the equation $\delta^2\text{H} = 4.78\delta^{18}\text{O} - 9.76$ ($r = 0.98$; $n = 9$). This straight line is almost similar to the straight line established from bodies of water subject to evaporation ($\delta^2\text{H} = 5.17\delta^{18}\text{O} - 9.63$). These are the water ponds. These analytical results obtained do not reflect the values of the weighted average of precipitation obtained during studies carried out near the study area by [8] and [19]. The straight line has a lower slope than those of the straight water Global meteors and the local line considered to be the entry signal. The results show that these pond water are much enriched in heavy isotopes compared to the precipitation water from which they result. The high values are found at the level of the plateau pools and the low values are found at the level of the pools located in the valleys. These very enriched isotopic contents of the ponds of the plateaus highlight the presence of a strong evaporation activity at the level of these bodies of water and corroborate the hypothesis of the absence of recharge at the level of the plateaus translated by an absence of seasonal variation piezometric levels of structures located on the plateaus, even if the structure is near a pond. These rules out any relationship between the water table (CT3) and the plateau ponds. Among the ponds located in the lowlands, those of Dinkim, Ambagoura where the values are very low having isotopic contents like the water of the alluvial aquifer. At Dinkim the isotopic contents are $\delta^{18}\text{O} = -2.62\text{‰}$ and $\delta^2\text{H} = -23.9\text{‰}$; $\delta^{18}\text{O} = -2.89\text{‰}$ and $\delta^2\text{H} = -26.5\text{‰}$ respectively for the pond and the alluvial water table, this shows a mixing between the water of the pond and the water of the water table (static level less than 2 m).

2). The second category corresponds to points located on or between the global meteoric water line and the local meteoric line, they have depleted isotopic contents compared to the first group (ponds). The average contents of this group are: -4.3‰ for oxygen-18 and -28.34‰ for deuterium. These average contents are like the average precipitation contents calculated from data from IAEA/ORSTOM/IRD Niamey. These are groundwater (CT3 and alluvial aquifers). Among this group, two subgroups are observed, and these create a zonation of the isotopic contents of the water table in the area. Figure 9 shows the spatial distribution of sampling and isotopic zoning.

Table 8. Statistical results of the oxygen-18 and Deuterium (2H) contents of the water.

	PONDS			ALLUVIAL			CT3			CT2			CT1		
	$\delta^{18}\text{O}$	$\delta^2\text{H}$	NBR	$\delta^{18}\text{O}$	$\delta^2\text{H}$	NBR	$\delta^{18}\text{O}$	$\delta^2\text{H}$	NB	$\delta^{18}\text{O}$	$\delta^2\text{H}$	NBR	$\delta^{18}\text{O}$	$\delta^2\text{H}$	NBR
AVERAGE	2.6	2.2	9	-3.4	-20.8	4	-4.4	-29.1	25	-6.2	-44.1	20	-7.0	-49.7	3
MEDI	2.5	2.3	9	-3.5	-21.9	4	-4.6	-28.6	25	-6.6	-46.9	20	-7.1	-50.0	3
GAP	19.3	3.8	9	9.5	1.5	4	9.0	1.5	25	0.9	6.0	20	0.3	0.6	3

NBR = Number of Samples Taken; AVG = Average; MEDI = Median; DEVIATION = Standard Deviation.

**Figure 11.** Correlation diagram between deuterium-oxygen-18 in water.

The first sub-group with enriched grades is recorded at the level of structures located in the northeast and southwest of the study area where the depths of the water table are shallow, particularly in the (Kolefo-Dangari and Tinidri-Ambagoura sector). These enriched values observed in the north-eastern and south-western part have two origins: the first (north-east) is linked to the outcrop of the Ct3 aquifer, which leads to an evaporation recovery of water from the aquifer and causes isotopic enrichment of the water. The second (south-west) is linked to the presence of an alluvial aquifer distinct and separated from ct3, leading to an evaporation of the water and causing the appearance of another zone where the contents are enriched.

The second subgroup corresponds to CT3 water, with average isotopic contents close to rainwater (-4.41 for oxygen-18 and -29.08 for deuterium). However, there is a particularity in the sectors of Toudoun Jaka-Tsadoura Fana and in the well of Kaiwa Fako where the wells have very depleted isotopic contents compared to the rest of the zone (Toudoun Jaka: $\delta^{18}\text{O} = -6.08\text{‰}$ Tsadoura Fana $\delta^{18}\text{O} = -6.82\text{‰}$ Kaiwa Fako $\delta^{18}\text{O} = -5.92\text{‰}$). These values are similar to the isotopic contents of CT2, which suggests zones of mixing of the water of the water table with those of the underlying CT2. Furthermore, no vertical variation in the isotopic contents was noticed, the example of the borehole capturing the water table of Makourdi at a depth of 100 m and the well located about 100 m from

the borehole capturing the first meters of the same water table. groundwater at a depth of 70 meters have the same isotopic contents except for analytical errors.

3). The third, these are water located below the line of global meteoric water and the local meteoric line, these water are offset from these lines towards negative values, they are more impoverished than the two groups mentioned above. These are the CT2/CT1 samples. The analytical results of these water (varying from -7.25‰ to -5.09‰ vs SMOW with an average of -6.55‰ vs SMOW for oxygen-18) are more homogeneous than the values found in the water table. These water have isotopic contents that are more than impoverished than the water of the water table and present an isotopic character of ancient water. This shows that, these water were recharged during wetter and colder climatic conditions than the climatic conditions that currently prevail. Finally, **Figure 9** shows two cases of water mixing, the first case represented in blue in the diagram, are the samples from the outcrop zone of the CT3 aquifer and those from the ponds. The second case represented in red in the diagram, are the water samples from the water table and those from CT2-CT1.

➤ **Relationship between groundwater and permanent ponds**

The contribution rates of pond water to groundwater recharge show that in Dinkim, the permanent pond contributes 84% to groundwater recharge and that of Taramna contributes 24% to alluvial groundwater recharge.

➤ **Relationship between groundwater and CT2 water**

The isotopic balance equation applied to samples with concentrations between the two poles shows that the contributions of fossil water vary from 43% to 94%.

➤ **Radioactive isotopes**

The analytical results of the tritium contents vary from 0.8 to 5.6 TU with an average content of 2.2 TU, a median of 1.7 and a standard deviation of 1.1 ($n = 9$). 50% of the samples have grades between 1 and 3 TU, 15% have grades between 3 and 5 TU and 10% have grades between 5 and 7. And 25% have grades below one TU.

3.3.3. Relationship between Oxygen-18 and Tritium Content of Groundwater

The relationship between tritium and oxygen-18 in the groundwater of the upper Dallol Maouri (**Figure 12**), shows two groups of water belonging to different locations and recharge periods:

1) Water whose tritium content is greater than 2 TU, these water are found in structures located in the beds of the Dallol Maouri or the chimneys of the hydrographic network, they are at a shallower depth. These water concern 50% of our samples analyzed (*i.e.* 6 out of the 12 samples). The contents vary from 2 to 5.6 TU. This confirms recent groundwater recharge.

2) Structures with tritium contents below 2 TU, all located on the Dallol Maouri plateaus, are characterized by depleted oxygen-18 contents. These structures are located on the plateaus and far from the recharge areas.

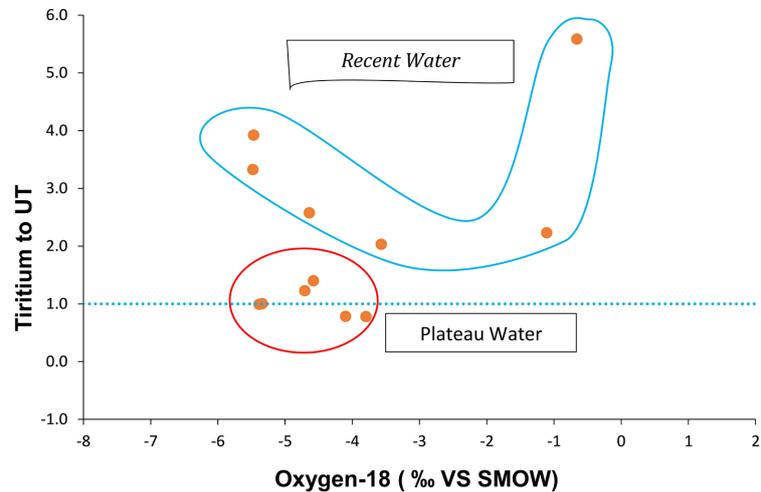


Figure 12. Relationship between tritium and oxygen-18 in groundwater.

3.3.4. Test to Estimate the Average Residence Time of Groundwater at the Top of Dallol Maouri

To estimate the residence times of water from the upper Dallol Maouri water table, tritium was used. Tritium (symbol ^3H) is an isotope of hydrogen (H) like deuterium (^2H). The natural values of tritium were around 5 TU before 1952. To this is added a production resulting from thermonuclear tests. During these nuclear tests (1953-1952), the contents resulting from these tests far exceed the natural contents (788.5 TU in Bamako and 1213 TU in N'Djamena).

Three groups of samples are distinguished according to the tritium content of these water:

- Samples with tritium contents around one TU \pm 0.3 TU. Are water that would have been recharged around the years 1997 to 2005 whose current system output contents (values calculated according to simple radioactive decay) are around 1 TU. These water, therefore, have “ages” ranging from 15 to 20 years. Six of our samples (50%) are concerned. They are all located on the plateaus. These results corroborate the recharge process revealed by the analysis of the contents of the stable isotopes of the water molecule and the study of the piezometry, which show an absence of recharge at the level of these structures.
- The samples with tritium contents between 1 to 3 TU \pm 0.3 TU are water which have higher contents than the outlet values of the recharged water before 1952 (0 TU), in the years 1997 to 2005 (<2 TU), but also contents lower than the contents of current precipitation water (5 TU). These are water that would have been recharged during the years 2008 to 2011, the ranges of outlet grades of which correspond to the grades of these water (ie “ages” of 10 to 12 years). Three of our samples are concerned (*i.e.* 25%). They are all located in the Dallol bed.
- The water whose contents are higher than 3 TU and do not reach 6 TU, these water have contents close to those of the current precipitations, these are water that would have been recharged during the last ten years. Three of our

samples are concerned (*i.e.* 25%).

4. Conclusions

The hydro-chemical and isotopic study of the water made it possible to characterize the surface water and aquifers of the prospected area. The contents of the chemical elements shown on the Piper diagram show that the water of the water table is at 75% of the calcium nitrate chloride facies, the water of the CT2/CT1 aquifers are calcium and magnesium bicarbonate, and the water of the ponds are characterized by calcium bicarbonate, calcium and magnesium bicarbonate, and calcium nitrate chloride facies. This strong variation in the facies of the ponds could be linked to the anthropogenic activities practiced around the ponds. The water is not very mineralized and slightly acidic. Groundwater is 75% calcium nitrate chloride facies, CT3/CT2 groundwater is calcium bicarbonate and magnesium, and pond water are characterized by calcium bicarbonate, calcium bicarbonate and magnesium, and calcium nitrate chloride.

The approach of the isotopes of the water molecule and chemistry made it possible to complete our results obtained from the piezometric study. The analysis of the contents of the sand isotopes of the water molecule ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) made it possible to characterize the different water present in the study area (surface and underground water). These results made it possible to highlight the presence of upward drainage zones between CT3 and CT2 with proportions of old water ranging from 43% to 94%, the absence of relations between the numerous plateau pools and the CT3, these ponds are characterized by a very high evaporation recovery but the ponds of the CT3 recharge zone contribute to the recharge of the aquifer (86%) in Dinkim. The water of the water table is recent but draws towards old water in the zones of ascending drainage. The analysis of the contents of the radioactive isotope of the water molecule (^3H) shows that the recharge zones of the CT3 aquifer are in the Ambagoura-Dinkim sector and the residence times of the water of the aquifer groundwater rise in the last decade in the recharge area and 15 to 20 years under the plateaus away from the recharge area.

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Conflicts of Interest

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

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