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Shallow Quaternary groundwater in the Lake Chad basin is resilient to climate change but requires sustainable management strategy: Results of isotopic investigation

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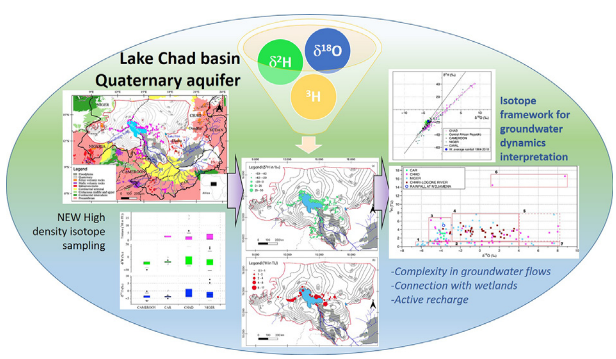
HIGHLIGHTS

- Despite arid conditions, shallow groundwaters in Sahel are recharging.
- A regional isotopic framework is useful to easily identify groundwater dynamics.
- Groundwater recharge and storage processes can be inhomogeneous as revealed by tritium.
- Interactions with surface waters and wetlands are a major phenomenon to consider.
- Groundwater management strategies need to take into account this complexity.

GRAPHICAL ABSTRACT



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ABSTRACT

Within the Lake Chad Basin, the unconfined Quaternary aquifer offers permanent and easy access to water resources. This transboundary regional aquifer is shared by Chad, Niger, Nigeria and Cameroon and extends over ~500,000 km^2. Climatic conditions and repeated droughts as well as the intensification of agriculture in the region have multiple negative impacts on the aquifer such as changes in groundwater level and its quality. Being a strategic water resource for the whole Chadian region, the groundwater potential of the Quaternary aquifer must be better characterized and understood to evaluate its resilience to climate change and anthropogenic impact. Stable isotopes and tritium of the water molecule were used to estimate water origin and residence time at the regional scale and to elucidate the interconnections between the different hydrological and hydrogeological components. Results show active recharge processes to the Quaternary aquifer as well as dynamic connections with surface waters (both river courses and wetlands) but also indicate less dynamic behavior of the Quaternary groundwater resource in some areas of the region. Based on the isotopic investigations, the Quaternary aquifer in the Chad basin was found to be resilient to climate change but its hydrogeological specificities (dependence to surface water from the upstream basins and transboundary nature of its structure) can make it prone to inadequate management strategies.

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1. Introduction

Groundwater is increasingly used on a global scale (Taylor et al., 2013; Alley et al., 2018; Podgorski and Berg, 2020) since it represents the second largest reservoir of fresh water, after glaciers, with considerable exploitation potential (De Marsily, 2009; Jones, 2011; Djebebe-Ndjiguim et al., 2013; Margat and Van der Gun, 2013). Currently, more than half of the world's population depends on groundwater supply, but strong regional disparities exist (Barlow and Clarke, 2017).

Groundwater resources in semi-arid regions face multiple stressors, such as rapid population growth with associated economic and agricultural developments, and climate change impacts (Huneau et al., 2011; Bouchez et al., 2019; MacDonald et al., 2021). Recent studies highlighted that climate change and contamination are growing concerns at the global scale (Jasechko et al., 2017) and especially critical in arid and hyper-arid African regions such as Eastern Sahara (Abdelmohsen et al., 2020; El-Saadawy et al., 2020), Central and Western Sahara (Gonçalvès et al., 2013) and Sinai Peninsula (Yousif et al., 2020). A lack of hydrological and hydrogeological data limits the detailed understanding of groundwater resilience to climate change (e.g., temperature growth, change of the precipitation regime, occurrence of hydrological extremes) in many African regions (Abotalib et al., 2021; Bam and Bansah, 2020; El-Saadawy et al., 2020; van Rooyen et al., 2021). However, sustainable water management should rely on a good understanding of fundamental hydrological characteristics such as active recharge areas, water transit times, groundwater recharge rate and connections between surface and groundwaters (Hiscock et al., 2002; Sophocleous, 2002; De Vries and Simmers, 2002; Huneau et al., 2011).

At present, hydrological processes that govern groundwater recharge and sustainability and their sensitivity to climate variability are poorly understood in sub-Saharan Africa (Taylor et al., 2013; Olsson et al., 2014; MacDonald et al., 2021). Sahel is considered to be one of the most fragile regions in the world, due to the population poverty, political instability and multiple crises, which make it particularly vulnerable to global changes (Fourissala and Gormo, 2012, Okpara et al., 2016). Hence, the extreme climatic conditions force the local population to use more groundwater to meet their daily needs as the economy is heavily dependent on agricultural activities. In the Lake Chad basin region, the unconfined Quaternary aquifer provides permanent and easy access to water resources. However, climatic conditions and repeated droughts have multiple negative impacts on this aquifer, both in terms of changes in the groundwater level and the quality of the water resource. As a strategic water resource of the population in the Lake Chad basin, the groundwater potential of the Quaternary aquifer needs to be better characterized to understand and manage its resilience to climate change.

Recently, Vaquero et al. (2021) and Candela et al. (2014) have shown by mathematical modeling approaches that the Quaternary aquifer in the Lake Chad basin might be resilient to climate change and that it recharges in the upstream part of the basin. Goni et al. (2021) also showed that in this region the heavy rains can recharge the shallow aquifers actively. Although some studies have been carried out in this area at the scale of Sub-Saharan Africa (Cuthbert et al., 2019) and at the scale of the Lake Chad basin (Bouchez et al., 2019; Goni et al., 2021; Mahamat Nour et al., 2021; Vaquero et al., 2021), the amount of available data is still insufficient to resolve many controversies concerning the hydrogeology of the basin, and little is known about the active recharge areas, groundwater flow directions and relationships to surface waters in the transboundary Quaternary aquifer that occupies the central part of the hydrological basin and is shared between different countries with different groundwater exploitation strategies.

In order to improve the regional knowledge on this aquifer, the International Atomic Energy Agency (IAEA), in cooperation with Chad, Cameroon, Niger and the Central African Republic, has developed the Regional African RAF7011 technical cooperation project (2013–2017) aimed at a better understanding and management of groundwater resources across the Sahel, including the lake Chad basin, through the use of isotope hydrology techniques. The isotope hydrology approach was selected because it is a convenient tool to gain new hydrogeological insight over large areas in a fast and cost-effective way. Stable isotopes and tritium ($\delta^{18}O$, δ^2H and ^3H) are also relevant hydrological tracers that can be applied in arid and semi-arid regions subject to strong temperature effect, well differentiated seasons and highly varying humidity conditions (Clark and Fritz, 1997; Jasechko, 2019).

Isotope hydrology investigations ($\delta^{18}O$, δ^2H and ^3H) on the Quaternary aquifer are here aimed at:

- providing evidence of active recharge processes in some parts of the basin,
- determining the existence of past recharge processes in some other parts,
- highlighting the major role of alluvial areas and wetlands in the recharge processes to the aquifer,

Obtained results are used to develop a new conceptual isotope framework for the interpretation of isotope data in the Lake Chad Basin region and the whole Sahel area, and encourage water resources managers to consider isotope data in water resource evaluation process.

2. Study area

2.1. Location

The Lake Chad Basin has an area of approximately 2,500,000 km^2 located in Central Africa, between 6° and 24° N and 8° and 24° E (Fig. 1). It extends mostly over the territories of Chad, Niger, Nigeria, Cameroon, and the Central African Republic. The Chad endorheic basin is an extended plain mostly covered by medium to fine-grained sands. The altitude varies from 3300 m asl in the north (Tibesti Mountains); 3000 m asl in the NW (Hoggar Mountains) and 3300 m asl in the SW (Adamawa Plateau) to 180 m asl in the Pays Bas (lowlands at the center of the basin). The central part of the basin is characterized by two different landscapes subdivided by the 14°N parallel; sand dunes and the absence of surface water sources are typical for the northern part (Kanem), while the south is composed of complex superposition of sand and clay richly watered by two main rivers that discharge into the lake: (i) the Chari-Logone River system (Chad) that supplies about 95 % of the annual volume of water that reaches the lake and (ii) the Komadougou-Yobé River system (Niger) that provides about 3 % of the annual inflow to the lake (Lemoalle et al., 2012; Mahamat Nour et al., 2021).

2.2. Geology

The Lake Chad basin is surrounded by mountainous areas corresponding to the outcrops of Precambrian rocks (Louis, 1970) and passing to Primary sandstone plateaus or Tertiary piedmont formations followed by deltaic deposits in the vast plains of the central region (Pias, 1970; Schuster et al., 2005). The geological structure of the Lake Chad basin is known from earlier research carried out by French Geological Survey (BRGM) and Office of Scientific and Technical Research Overseas (ORSTOM) as part of oil and hydrogeological research from 1943 to 1964. The Continental Terminal is composed of sandstone that crops out in the southern part of the basin. The Pliocene is composed of fluvio-lacustrine sands and clay and is followed by the Quaternary which occupies the central basin and consists mainly of sands with clayey intercalations (Roche, 1980). At the local scale, these formations are marked by strong lithological and granulometric heterogeneities, horizontal and lateral, but at the basin scale, they appear to be largely homogeneous and continuous enough to form a productive aquifer known as the Quaternary aquifer (Schneider and Thiéry, 2001; Massuel, 2001). This study will be focused on the latter, which occupies a transition zone between the North of the Sahara and the South of the Sahel with an area of 500,000 km^2 (Fig. 1).

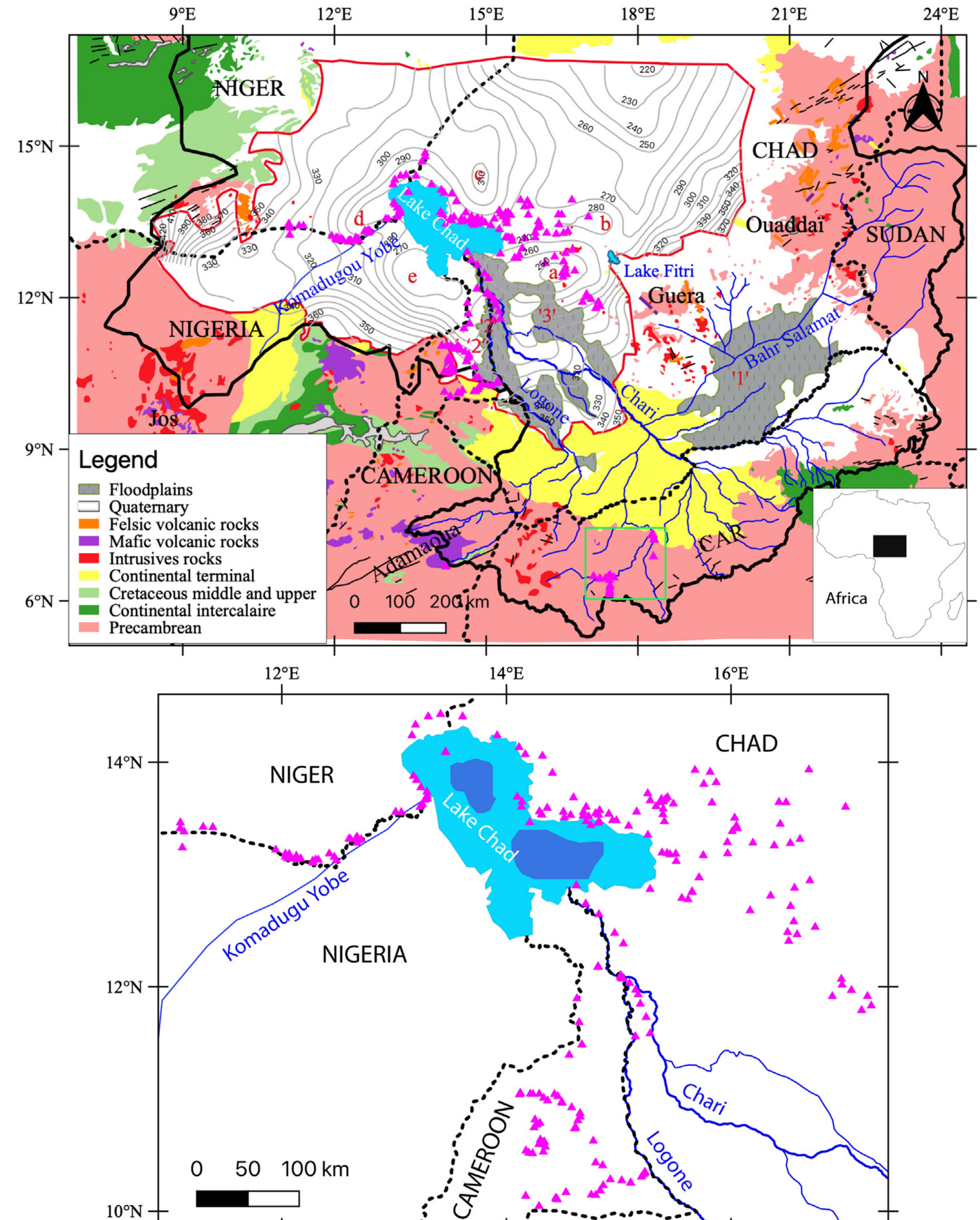

Fig. 1. Geological map of the Lake Chad basin (Louis, 1970). The solid red line the limit of the Quaternary aquifer, the solid black line the outline of the Lake Chad basin and the black dashed line the country limits. The piezometric levels (after BGR, 2011 modified). The pink triangle are the sampling points. '1': Plain of Salamat (Am timan); '2': Plain of the Yaéré; '3': plain of Massenya; a: Chari Baguirmi depression; b: Dome of Harr; c: Dome of Kanem; d: Kadzell depression and e: Borno depression.

2.3. Climate

This basin is characterized by a tropical climate. Depending on the height of annual precipitation, the Lake Chad basin is divided into four distinct climatic zones, from south to north: the Sudanese-Guinean climate with an average annual rainfall amount ranging from 600 mm to 1500 mm; the Sahelian-Sudanese climate with an average annual rainfall amount ranging from 400 mm and 600 mm; the Sahelian-Saharan climate with an average annual rainfall amount ranging from 100 mm and 400 mm; and the Saharan climate characterized by <100 mm of rainfall per year. The area is characterized by high temperatures throughout the year, very low humidity except during the rainy season from June to September. Intense solar radiation and strong winds lead to a high annual potential evapotranspiration of around 2200 mm for Central Chad.

N'Djamena (Fig. 2), which lies in the central basin and can be considered as the epicenter of the Quaternary aquifer, is characterized by Sahelian steppe climate (Mahamat Nour, 2019). The monthly average thermal regime shows two maxima: a first maximum in April, which is the warm season before the first rains, and a secondary maximum in October, at the end of the rainy season (Fig. 2a). The difference between the monthly average temperatures shows a minimum of +24 °C and a maximum of +34 °C. The interannual average temperatures are very variable (Mahamat Nour et al., 2021). Precipitation reveals an alternation of two periods: (Fig. 2b): a wet season (from May to October) and a dry season (from November to April). The rainiest months are July and August, which are at the heart of the rainy season. Interannual rainfall amounts vary significantly from one year to another. Measured with the Piche technique, evaporation correlates positively with air temperature and negatively with the rainfall amount (Fig. 2c) (Mahamat Nour, 2019). The seasonal cycle is well marked. The maximum monthly average

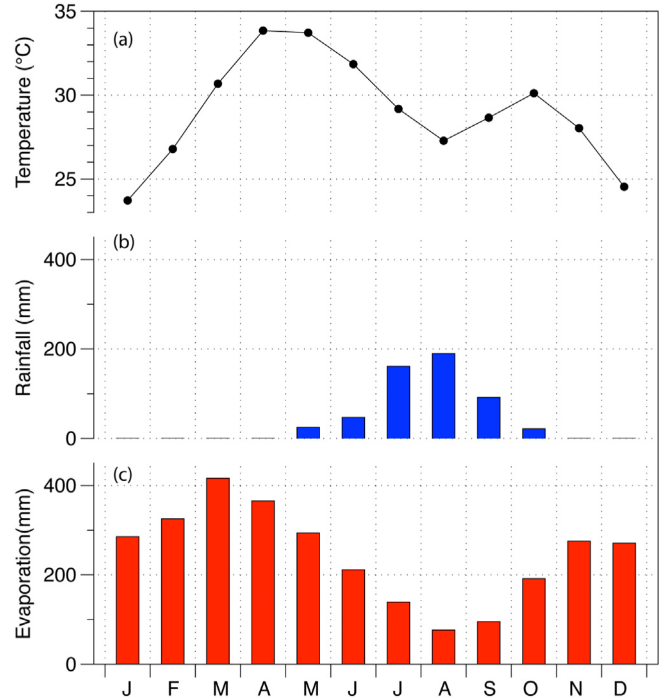

Fig. 2. Description of the meteorological parameters. N'Djamena station from 1984 to 2014 obtained from the General Directorate of National Meteorology of Chad (DGMN).

evaporation is observed in March and reaches 416 mm. The minimum is obtained in August with 77 mm. The year-to-year average is 2979 mm.

2.4. Hydrology

The hydrology of the basin is dominated by the Lake Chad features. This basin drains an area of 610,000 km^2 (Mahamat Nour et al., 2021), but most of the waters derive from the southern part of the basin (Chari-Logone river system). The Logone River has its source on the Adamawa plateau in Cameroon, at an altitude ranging from 305 to 835 m (Cabot, 1965; Gac, 1980). The Chari River starts in the Central African Republic at an altitude of between 500 and 600 m. During the flood, the Logone and the Chari inundate the surrounding plains with their discharges (Olivry et al., 1996; Nkiaka et al., 2018). The flood plains of the Chari-Logone basin are of particular importance in contributing to the renewal of groundwater in the basin (Seeber et al., 2014). Recent studies by the Lake Chad Basin Commission (LCBC) showed that aquifer recharge comes partly from stagnant water in floodplains (Vassolo et al., 2016). They also play an important role in the hydrological balance of the Chari-Logone basin, in particular by constituting large areas of evaporation and having a potential impact on water chemistry (Lienou, 2007; Delclaux et al., 2011; Seeber et al., 2014; Lemoalle et al., 2014). The precipitation over these flooded plains does not compensate for the net loss by evaporation. The area of the flood plains is variable and depends on rainfall amount that has fallen over the basin (Jung et al., 2011; Vassolo et al., 2016). The main flood plains of the Chari-Logone basin are namely (Fig. 1):

– The Yaéré plain: The Yaéré is a floodplain in Northern Cameroon. This plain is regularly flooded by rains and overflows by the Logone waters. The accumulated water is taken up by the evapotranspiration effect. The average extent of flooded surface between 2000 and 2014 was 2767 km^2 (Vassolo et al., 2016).
– The Massenya plain: along the Bahr Erguig River, partially silted up, which is a diffluent that occasionally feeds the floodplain of Massenya.
– The Salamat plain (around the city of Am Timan): along the Bahr Salamat River sub-basin which forms temporary marshes and floods a depression of around 20 km long. In wet periods, the floodplain of Salamat is very largely flooded, except the sandy ridges.

2.5. Hydrogeology

The hydrogeology of the region is structured by three main aquifers (Fig. 3):

– The Continental terminal aquifer is confined in the center of the basin and around the Lake Chad and unconfined in the "Pays-Bas" region (low-lands of the North of Kanem) and south of Chad. It is clearly artesian around the Lake Chad over an area of approximately 60,000 km^2 and is exploited in Niger and Nigeria by several artesian boreholes.
– The Lower Pliocene aquifer lies between 250 and 300 m below the ground surface. There is no clear boundary between this aquifer and the Continental Terminal aquifer. Previous isotopic studies have highlighted palaeo-recharged waters dated from 20,000 to 1,000,000 years old, both in the Pliocene and in the Continental Terminal (Leduc et al., 1998; Schneider and Wolf, 1992; Bouchez et al., 2016).
– The Quaternary aquifer is located between the depth of 50 and 180 m. The Quaternary aquifer is considered unconfined or semi-captive and continuous throughout its area of occurrence. Studies carried out in the Chari Baguirmi aquifer by Djoret (2000), Abderamane (2012) and Bouchez (2015) have shown that the static levels vary from 5 m at the edge of the Chari to 80 m at the center of the piezometric depression of the Chari-Baguirmi, which is the main piezometric depression in the area.

The water table morphology of the Quaternary aquifer is very complex and forms numerous circular structures, domes as well as depressions (Vassolo et al., 2016) that can be indicative for the hydrological connections between shallow and deep aquifers (Abotalib et al., 2021). The first piezometric map of the Quaternary aquifer was published in the 1970s by the LCBC and was further updated by the BGR (2011) (Fig. 1). The aquifer is

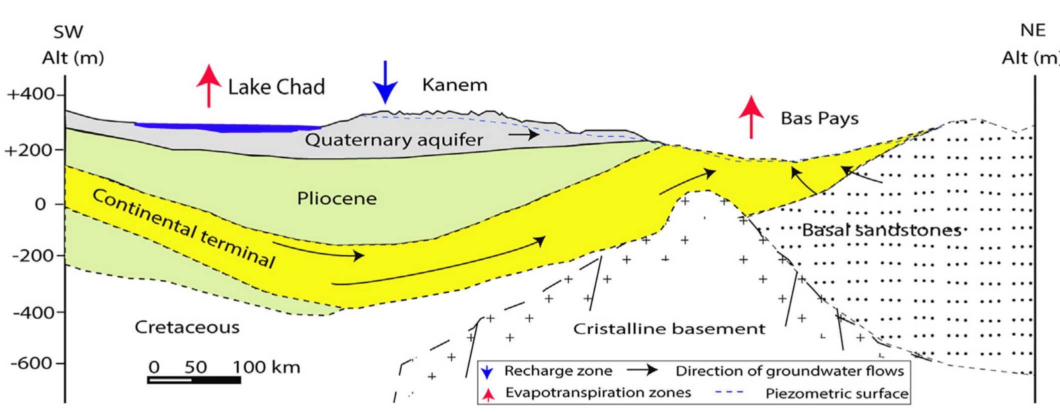

Fig. 3. SW-NE hydrogeological section through the Lake Chad basin (after Schneider and Wolf, 1992, modified).

characterized by the existence of domes within the Kanem and Harr dune systems throughout Chad and three piezometric depressions around the Lake Chad (Leblanc, 2002). The piezometric depressions have an average amplitude of 40 m, the most important of which are in Bornou (Nigeria), in Yaéré in Cameroon and in the Chari-Baguirmi plain (Chad). These hydrodynamic anomalies have been recognized throughout the Sahel and have been the subject of several theories on their origin and formations (Durand, 1993, Njitchoua and Ngatcha, 1997). In the north of the basin, the Quaternary underground flows are oriented from the northwestern limits and the dome of Kanem towards the piezometric depression of Niger. The lowest points of the water table are in the "Pays-Bas" region of Chad (Djourab). The hydraulic gradients are low (0.5 to 1 ‰) with a maximum amplitude of variation in the piezometric level of about 100 m across the entire aquifer (Bouchez, 2015). The capacity of the aquifer has been estimated between 1 and 500 million m^3.

An average value of 6.10^{-3} m^2/s for the transmissivity of the Quaternary aquifer is proposed on the basis of boreholes investigated in the Chari-Baguirmi region (Schneider and Wolf, 1992). Average permeability is estimated around 3.10^{-5} m/s in the Komadougou Yobé River region and to $1{,}2.10^{-4}$ m/s in the Chari-Baguirmi Region (Zaïri, 2008; Abderamane et al., 2013). The porosity also varies a lot with a median value around 10 % (Schneider and Wolf, 1992). Values between near 0 and 10 % are commonly used in these sandy-silty environments. A modeling study of the upper Chari basin showed that the main contribution to Chari flows might be limited to a 140,000 km^2 sub-basin located in the southern tropical zone, where the recharge rate is 72 ± 6 mm / year (Gonçalvès et al., 2020).

3. Methodology

3.1. Sampling strategy

The sampling campaign were designed to get representative samples from the head water catchment (in the North of the Central African Republic) to the final water collector (Lake Chad), through the intermediate wetland regions which accompany the Chari-Logone and the Komadougou-Yobé River systems. The sampled groundwaters are mainly located in the center of the basin (Chad), in Cameroon (Fig. 1) and along main roads (Niger) due to numerous sampling campaign restrictions because of security issues and logistical difficulties to access the most remote regions (Central African Republic). No sampling was organized in Nigeria for security reasons.

3.2. Regional input function for rainfall and rivers

The existing data on the $\delta^{18}O$, δ^2H as well as some ^3H data in rainfall was extracted from the IAEA GNIP network database (Global Network for Isotopes in Precipitations) (https://www.iaea.org/services/networks/gnip). The N'Djamena GNIP station is the most representative of the regional conditions, with a considerable length of rainfall isotopic composition record between 1960 and 2019, but the record is discontinuous through time. It was interrupted in 1978 and then resumed in 2015 in the framework of the IAEA RAF7011 project. For the Lake Chad basin region, the rainfall isotope content of the N'Djamena station is the most appropriate to provide information on local precipitation. It is nevertheless located in the downstream part of the watershed and therefore very far from the source of the rivers supply (Chari-Logone system). This isotopic dataset is used to define a Local Meteoric Water Line (LMWL) in relation to the Global Meteoric Water Line (GMWL) (Craig, 1961) and to calculate a long-term weighted average (Fig. 4). Deuterium excess (d-excess, ‰), as a measure for non-equilibrium conditions during water evaporation, was defined by Dansgaard (1964) as the intercept of the GMWL: d-excess $= \delta^2H - 8\delta^{18}O$.

Isotopes data in rivers were extracted from the IAEA GNIR (Global Network for Isotopes in Rivers) (https://www.iaea.org/services/networks/gnir) for the Chari-Logone River system for the 2015–2019 period at the N'Djamena-Chari station.

A radioactive water isotope, tritium, was used to study the circulation of water in the hydrological cycle (Mahlangu et al., 2020) and determine recharge dynamics in aquifers (Allison and Hughes, 1978). To determine the recharge period of recent rains, the tritium content of groundwater in an area should be compared with that of recent rainfall in the same area (Morgenstern et al., 2010). A tritium content greater than zero in groundwater will indicate recent recharge, while zero tritium content in groundwater will indicate slow or no recharge (Abiye, 2013).

3.3. Groundwater database

This study is mainly based on data produced from a large hydrological and isotopic survey carried out in the framework of the IAEA Technical Cooperation project RAF7011 (2013–2017). This project was aimed at

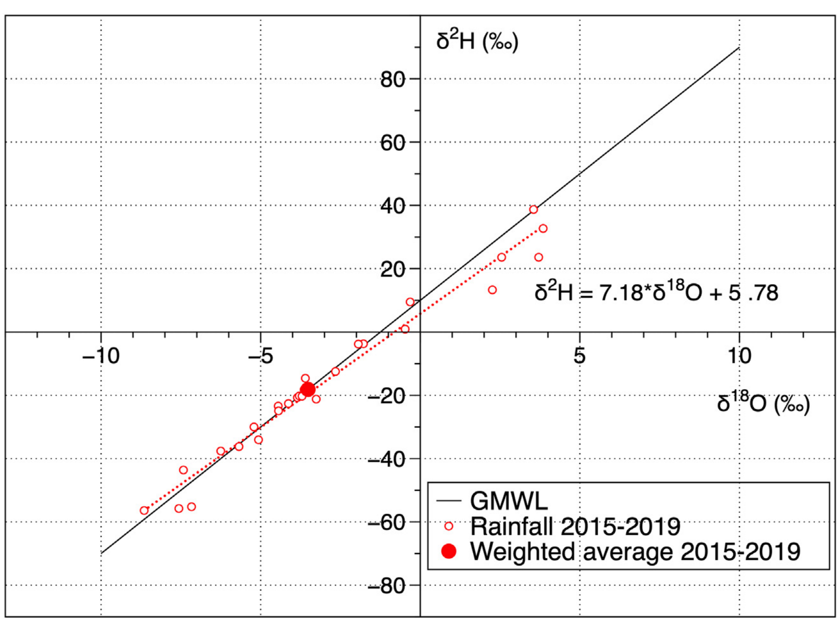

Fig. 4. Isotopic composition of precipitation at N'Djamena station (GNIP data). Linear regression for N'Djamena station rainfall for the period 2015–2019: $\delta^2H = 7.18 \cdot \delta^{18}O + 5.77$ ($R^2 = 0.97$).

Table 1
Data characteristics, sampling period, type and place of analysis.

Country	Sampling date	Analysis type	Number of samples	Aquifer
Central African Republic	August–November 2014; April 2015	$\delta^{18}O$ and δ^2H	61	Quaternary and substratum
		^3H	9	
Cameroon	April 2013	$\delta^{18}O$ and δ^2H	54	Quaternary
Chad	July 2013	$\delta^{18}O$ and δ^2H	115	Quaternary
	January–April 2014	^3H	86	
Niger	February 2013	$\delta^{18}O$ and δ^2H	50	Quaternary
		^3H	50	

securing a better understanding and management of groundwater resources across the Sahel, including the Lake Chad Basin. In this context, data (Table 1) on the isotopic composition of groundwater including $\delta^{18}O$, δ^2H and ^3H, from four major countries of the Lake Chad region was obtained, the Central African Republic (Ouham Prefecture around the Batangafo city and Ouham-Pendé Prefecture around Bossangoa city), Cameroon (Grand Yaéré plain), Chad (central Chad and Lake Chad region) and Niger (Komadougou-Yobé River valley around Diffa city).

For the analysis of stable isotopes ratios of the water molecule ($^2H/^1H$ and $^{18}O/^{16}O$), samples were collected without headspace in pre-cleaned 20 mL amber glass bottles. Analyses were performed by laser absorption spectroscopy at the Laboratoire de Radio-Analyses et Environnement (Sfax University, Tunisia). Ratios of $^{18}O/^{16}O$ and $^2H/^1H$ are expressed in delta values, $\delta^{18}O$ and δ^2H (‰), relative to the Vienna Standard Mean Ocean Water(VS MOW). The analytical precision was better than 0.5 ‰ for δ^2H and 0.2 ‰ for $\delta^{18}O$. Samples for ^3H determination were collected in the field in 0.5 L plastic bottles. Analyzes were performed by electron enrichment and liquid scintillation counting method in 2014 (Thatcher et al., 1977; Clark and Fritz, 1997) at HYDROSYS LABOR Analytical Laboratory Ltd. (Budapest, Hungary). Tritium contents have been reported in the Tritium Unit (TU), where one TU equals one atom of tritium per 10^{18} hydrogen atoms. The detection limit is 0.5 TU and analytical uncertainty ranges from 0.2 to 0.4 TU per sample.

4. Results

4.1. Isotopic composition in $\delta^{18}O$, δ^2H and ^3H in rainfall

At the N'Djamena station, there is a slight difference between the weighted average value obtained for 1960–1995 (−3.92 ‰ in $\delta^{18}O$ and − 19.02 ‰ in δ^2H) and for 2015–2019 (−3.51 ‰ in $\delta^{18}O$ and − 18.12 ‰ in δ^2H). The d-excess values were 12.34 ‰ (1960–1995) and 9.96 ‰ (2015–2019). The LMWL is $\delta^2H = 7.18\delta^{18}O + 5.77$ ($R^2 = 0.97$) for 2015–2019 (Fig. 4). The overall weighted average over the entire period is −3.72 ‰ in $\delta^{18}O$ and − 18.57 ‰ in δ^2H for 1960–2019.

The annual mean weighted tritium content in rainfall obtained at the N'Djamena station for four years of monitoring (2015–2016) shows values that vary between 4.4 and 5.4 TU (Table 2). The monthly values for the year 2015 are variable; the beginning of the rainy season (June) has low levels compared to the middle of the season (August) for the same year. In contrast, the other years (2016, 2017 and 2018) do not show seasonal variability except for a slightly different value (3.8 TU) in June 2016.

Table 2
Tritium in rainfall at N'Djamena GNIP station from 2015 to 2018.

Month	2015		2016		2017		2018	
	^3H (TU)	Rainfall (mm)	^3H (TU)	Rainfall (mm)	^3H (TU)	Rainfall (mm)	^3H (TU)	Rainfall (mm)
May			5.7	25.8				
June	2.7	81.2	3.8	47.9	5.1	49.1	5.3	123,0
July	4.5	235.7	6.6	211.2	5.4	153.9	5.4	191,0
August	5.1	162.0	5.0	210.4	5.7	134.4	4.8	257,0
September	4.7	81.9	4.8	137.7			7.2	183,0
October	4.0	1.1	5.3	25.2			4.1	54,0
November							4.3	0,3
Weighted average (TU)	4.4		5.4		5.4		5.5	

4.2. Isotopic composition of surface waters

There is a two-month lag between the isotopic minimum and the maximum flow of the Chari-Logone River. The most depleted isotopic composition is observed in August and September (e.g., for year 2018: −3.79 ‰ in $\delta^{18}O$ and − 21.40 ‰ in δ^2H). These minima occur in the middle of the rainy season. The most enriched isotopic composition is encountered in April and May (e.g., for the year 2017, 3.52 ‰ in $\delta^{18}O$ and 16.67 ‰ in δ^2H), when the flow is at the minimum (Fig. 5). Two periods are discerned (Fig. 5): (i) The period from September to May corresponds to increasing isotopic enrichment (increases in $\delta^{18}O$ and δ^2H) and (ii) the period from June to August corresponds to isotopic depletion (decreases in $\delta^{18}O$ and δ^2H).

The $\delta^{18}O$ vs δ^2H isotopic composition of the waters of the Chari-Logone in N'Djamena (Fig. 5) varies respectively between −3.79 to +3.52 ‰ in $\delta^{18}O$ and − 21.40 to +16.71 ‰ in δ^2H. The isotopic signal of the river water is mostly marked by evaporation apart for the months of July, August and September. The curve on Fig. 5d shows the ^3H in the Chari-Logone waters over time from 2015 to 2018. A seasonal variability of tritium contents is observed. It fluctuates between 1.9 TU (April) to 5.6 TU (August). These high levels of ^3H in the river are very similar to the levels of ^3H in rainwater in N'Djamena (Table 2). They are observed in the middle of the rainy season.

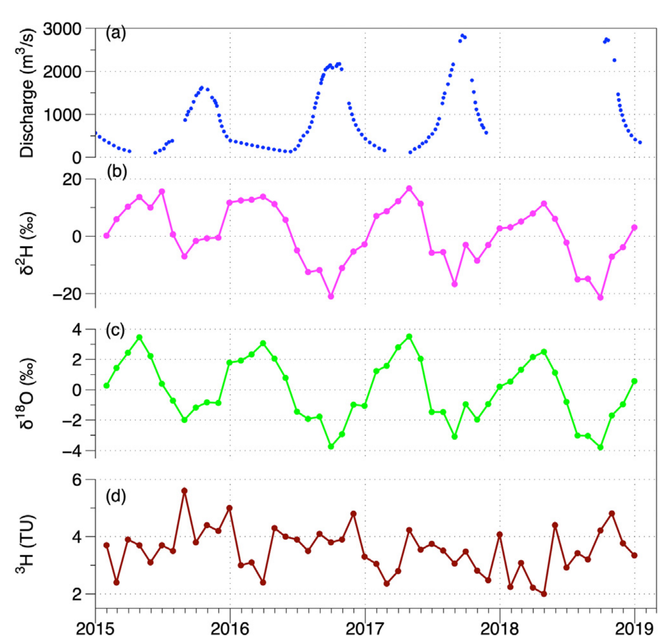

Fig. 5. Variation of isotope content and discharge over time of the Chari-Logone in N'Djaména (GNIR data).

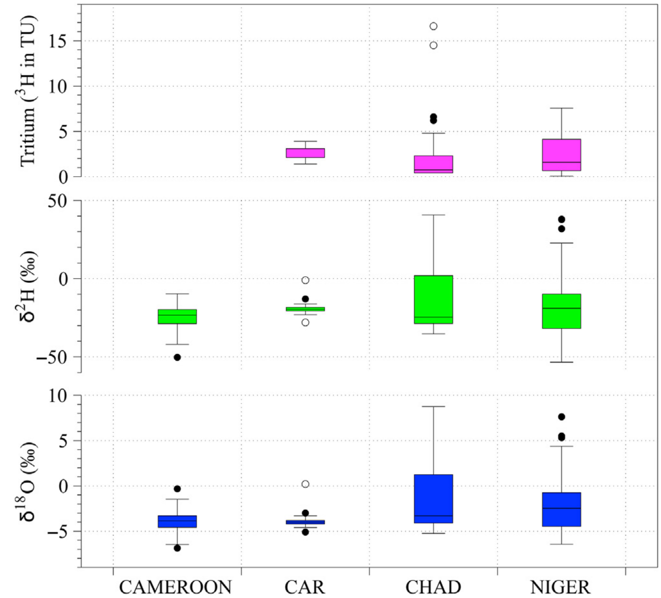

Fig. 6. Boxplot showing isotopic values for groundwater of the Quaternary aquifer in Cameroon, CAR, Chad and Niger.

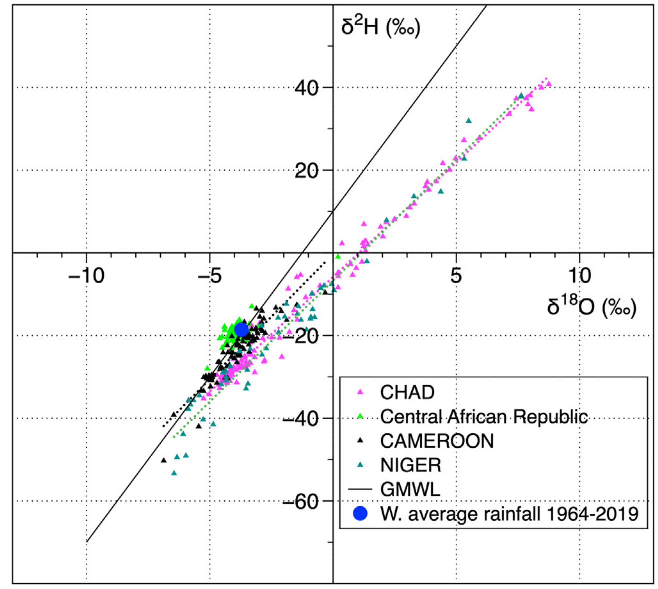

Fig. 7. δ^{18}O versus δ^2H isotopic composition of groundwater in the study area. Chad: $\delta^2H = 5.55 \cdot \delta^{18}O - 5.83$ ($R^2 = 0.90$); Central African Republic: $\delta^2H = 4.13 \cdot \delta^{18}O - 3.01$ ($R^2 = 0.70$); Niger: $\delta^2H = 5.86 \cdot \delta^{18}O - 6.73$ ($R^2 = 0.97$) and Cameroon: $\delta^2H = 6.05 \cdot \delta^{18}O - 0.32$ ($R^2 = 0.85$). The values of the weighted averages are those to N'Djamena.

4.3. Isotopic composition of groundwater

The Fig. 6 displays a boxplot showing the ranges of values encountered for δ^{18}O, δ^2H and ^{3}H in groundwater for the different countries of the Lake Chad basin. In Central African Republic, the ranges of values encountered are: −5.1 to 0.2 ‰ in δ^{18}O, −28 to −1 ‰ in δ^2H and 1.4 to 3.9 TU in ^{3}H. In Cameroon, the ranges of values encountered are: −6.9 to 0.3 ‰ in δ^{18}O and − 50.3 to −9.7 ‰ in δ^2H. In Chad, the ranges of values encountered are: −5.3 to 8.8 ‰ in δ^{18}O; −35.3 to 40.8 ‰ in δ^2H and < 0.4 to 16.6 TU in ^{3}H. In Niger, the ranges of values encountered are: −6.5 to 7.6 ‰ in δ^{18}O; −53.4 to 38 ‰ in δ^2H and 0 to 2.4 TU in ^{3}H.

The groundwater samples from the Central African Republic and Cameroon are close to the weighted mean isotopic composition of rainfall in N'Djamena (Fig. 7). They are, on average, −4.5 and − 25 ‰ in δ^{18}O and δ^2H, respectively. Results for samples from Chad and Niger are plotted along evaporation lines with similar slopes, 5.55 and 5.85 respectively (Fig. 7).

Fig. 8 shows the spatial evolution of isotopic values (δ^2H and ^{3}H) of groundwater in the Quaternary aquifer throughout the Lake Chad basin. The spatial distribution of δ^2H in Fig. 8a shows evaporated groundwater signatures around Lake Chad and its tributaries (Chari-Logone, Komadougou Yobé).

5. Discussion

5.1. Input isotopic signal and recharge of the aquifer

The conservative δ^{18}O and δ^2H isotopes in precipitation showed prevailing hydroclimate processes that occur before recharging (Stadnyk et al., 2005). A slight enrichment of the isotopic values in time (0.4 ‰ for δ^{18}O and 0.9 ‰ for δ^2H) and a decrease in the d-excess at the N'Djamena station is comparable to these observed in Cape Town, South Africa (Vystavna et al., 2020, 2021). This change is related to the air temperature growth intensification of sub-cloud evaporation and the contribution of ^{18}O-enriched vapor due to the evaporation of surface water under the warming conditions (Vystavna et al., 2020, 2021). The slope of the LMWL is lower than 8 additionally indicating the prevalence of the non-equilibrium processes such as evaporation (Dansgaard, 1964) under which the surface water and groundwater recharge occurs. Observed evaporation growth trend shows that climate change and air temperature growth can even more impact the evaporation conditions and recharge patterns (Niang et al., 2014).

Fig. 6 for groundwater of Chad and Niger shows a great variability in isotopic values due to the different recharge types (from river, Lake Chad, direct rainfall, etc.) and the evaporation process. Here, waters depleted in ^{18}O and ^{2}H and without tritium content indicate the occurrence of older evaporated waters recharged many decades ago. The Central African Republic shows much more homogeneous values mainly because of direct, fast and continuous recharge by rain. These waters are not affected by evaporation. Cameroon waters show less variability than Chad and Niger and tend to indicate more homogeneous and less complex recharge processes to the aquifers. The ^{18}O vs ^{2}H diagram of Fig. 7 clearly demonstrates variability in stable isotope isotopic signatures encountered in the region. This is in line with the vast study area that covers several hydroclimatic zones, and where some are subject to intense evaporation processes (Huneau et al., 2011; Bello et al., 2019). The close position to weighted mean of precipitation (Fig. 7) indicates that these groundwaters are currently recharged by local precipitation. Some of the Cameroonian samples display very depleted isotope signatures that can be related to palaeorecharge processes but we also observe very enriched values, which is evidence of strong evaporation effects (Goni et al., 2021). There are very negative values (−6.5 and − 55 ‰ respectively in δ^{18}O and δ^2H) for some samples from Niger. These more depleted values are associated with very low tritium contents <1 TU. These samples have certainly been recharged during a wetter period than present (Bouchez et al., 2019), as some groundwater samples from Cameroon with the same signature. The isotopic composition of precipitation in July and August shows that the values agree with groundwater isotopic signature in the upstream part of the basin towards the southeast and recharged by the two months of heavy rains (Mahamat Nour et al., 2021). The head of the basin (located over the territory of Central African Republic and Cameroon) is the recharge zone of the Chari-Logone basin (Gonçalvès et al., 2020; Vaquero et al., 2021). This part of the Lake Chad basin can be considered as the main water feeder of regional aquifers and will also feed the Quaternary aquifer downstream. Recent studies by Bouchez et al. (2016), mainly based on rainfall-runoff models, showed that the groundwater in the upstream zone would contribute up to 60 % of the base flow of the Chari-

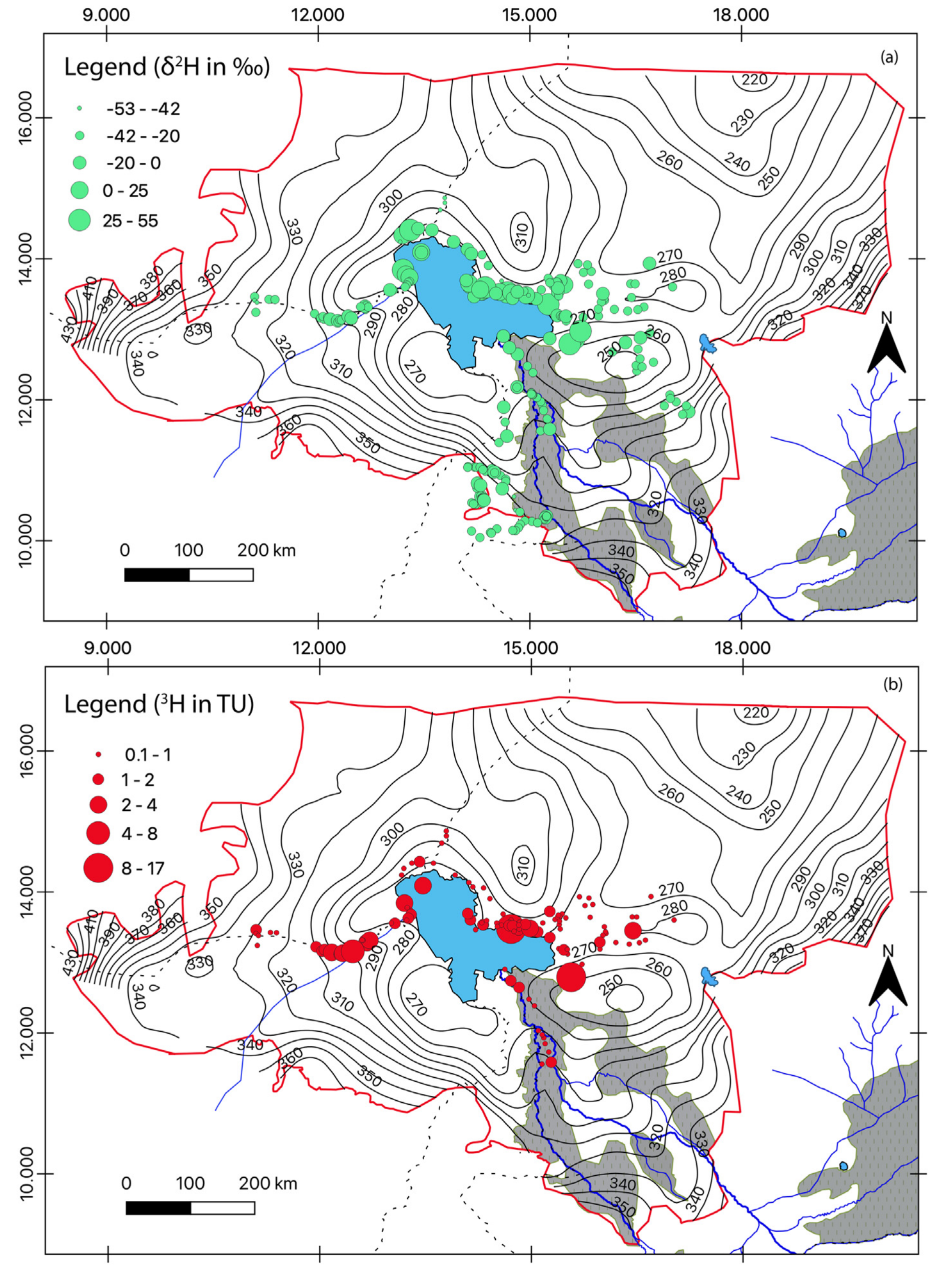

Fig. 8. Spatial distribution of isotopic contents of δ^2H (a) and ^{3}H (b) in the groundwater of the Quaternary aquifer of the Lake Chad basin. Grey areas are flood plains.

Logone. Studies by Goni et al. (2021) have also shown that, alongside Nigeria, recharging takes place along the Komadougou Yobé watercourse with very similar modalities. The depleted δ^2H values (Fig. 8a) and very low or zero ^{3}H values (Fig. 8b) observed are indicative of inertial zones with long residence time present in the Quaternary aquifer in central Chad, Niger and Cameroon.

As a shallow unconfined aquifer, the Quaternary deposits undergo different modes of recharge throughout the aquifer, which covers most of the Lake Chad basin. Fig. 8 clearly shows a wide dispersion of isotopic data across the Lake Chad basin. Groundwater samples from the Central African Republic can be considered to reflect the modern isotopic signature of groundwater in the southern head of the watershed. Heavily evaporated water with little or no tritium is also common in central Chad and eastern Niger, indicating that the Quaternary aquifer may contain “old” groundwater, >60 years old, that was previously evaporated or mixed with evaporated water. This mixing hypothesis has been demonstrated in the Lake Chad Basin and Niger Basin by Leduc et al. (1998) and Bouchez et al. (2019).

The work of Abderamane et al. (2013) showed that groundwaters in the center of piezometric depressions are interpreted as remnants of a massive recharge phase, consistent with the African Holocene wet period and the existence of a mega-Lake Chad during this period (Schuster et al., 2005). Zaïri (2008) interpreted that the water between the river boundary zone and the center of the piezometric depressions results from a mixture of recently recharged water and ancient water. Most aquifer recharge occurs by concentrating runoff in endoreal pools (Vassolo et al., 2016) or rare temporary streams, and is followed by very rapid infiltration through banks (Leduc et al., 1998). Our findings are supported by the geological conditions in the study area, such as the presence of piezometric domes, that are generally favorable for the development of the hydrological connections between shallow and deep aquifers (Abotalib et al., 2021).

5.2. Interaction between surface water and groundwater

The isotopic signature of Chari-Logone River waters changes strongly with the discharge (Fig. 5) and the high-water period appears most favorable in contributing to recharge in the shallow aquifer from September to November, when the isotope signature of the rivers averages −2 ‰ for $\delta^{18}O$ and − 10 ‰ for $\delta^{2}H$ (Mahamat Nour, 2019). Recharge of the aquifer is also provided by the intense rainy season episodes in the region. The months of July and August seem to have the most weight in the recharge process, as revealed by their signature in the groundwater of the region (Ngatcha et al., 2007; Goni et al., 2021). These two modes of recharge have already been observed by Kadjangaba (2007) for the N'Djamena region, Abderamane et al. (2013) for the Chari Baguirmi aquifer and Goni et al. (2021) in Nigeria. Another means of recharge to the Quaternary aquifer by surface water, including through wetlands such as swamps and alluvial plains, have also been highlighted by various authors, such as Ngatcha et al. (2007) and Bello et al. (2019) for northern Cameroon. A recent modeling study by Vaquero et al. (2021) indicated that groundwater flows across international boundaries exist between countries sharing the basin, except between the Central African Republic and Cameroon. However, other studies (Djoret, 2000; Fontes et al., 1970) indicate little contribution of Lake Chad waters to recharge of the Quaternary aquifer. The limited influence of Lake Chad waters on groundwater stems from the high evaporative recovery in the Sahelian zone (Taupin et al., 2000) and low permeabilities that reduce lateral inflow (Bouchez et al., 2016).

The reverse process can also be observed. During the low-flow period, the Chari and Logone rivers are supported by the groundwater flow. This is demonstrated by the GNIR data (Fig. 5), where the lowest tritium content of the Chari-Logone River is observed during low water, which is characteristic of the Quaternary groundwater signature, generally significantly lower than the rainfall input. Therefore, we conclude that during the high-water period rivers recharge the Quaternary alluvial aquifers, while during the low water period the aquifers contribute to the rivers' flow.

If compared with the stable isotopic signature of water, age indicators like tritium can be of great use to highlight major hydrogeological processes able to improve the understanding of the groundwater resources behavior. Indeed, tritium in groundwater is unequivocal evidence of recharge after the onset of thermonuclear-bomb testing in the 1950s (Jasechko et al., 2017).

Based on our investigations, the diagram in Fig. 9, valid for the whole Central African region, combines both types of information and is proposed to the identify groundwater origin:

- Type 1. Groundwaters with very low $\delta^{18}O$ and negligible tritium content. These are mostly observed in Niger and can be identified as palaeowater (Joseph, 1989), i.e. recharged during a more humid and colder period than today. The previous work of Djoret (2000) on stable isotopes and ^{14}C in the Chari-Baguirmi also indicates the presence of very old groundwaters (up to 14,000 BP) in the Quaternary aquifer of Chad and confirms this observation.
- Type 2. Groundwaters with negligible to low tritium content (TU ≤ 1) and varying $\delta^{18}O$ signature. These are observed in central Chad and Niger. They correspond to "old" waters infiltrated before the 1960's. Some samples can display $\delta^{18}O$ contents that signal a strong influence of evaporative effects during the recharge or during the storage in the aquifer (Fontes et al., 1970; Maduabuchi et al., 2006).
- Type 3. Groundwaters with tritium contents between 1 and 7 TU and $\delta^{18}O$ signature close to that of central Chad rainfall and Northern Central African Republic shallow groundwaters. These groundwaters are of very recent origin and can be considered as "recent" waters. Some samples (from Central African Republic and part of the samples from Chad and Niger) have $\delta^{18}O$ content (between −5 and − 3 ‰), corresponding to the current isotopic composition of regional rainwater and highlighting their origin as mostly coming from the rainy season rainfalls.
- Type 4. Groundwaters with tritium content between 1 and 8 TU and very varying $\delta^{18}O$ content (between −3 and 4 ‰) close to the isotopic composition of the Chari-Logone and Koumadougou Yobé rivers water. These groundwaters are of "modern" origin and influenced by mixing processes with surface waters due to more or less direct recharge by the Chari-Logone and Komadougou Yobé rivers (Bello et al., 2019; Goni et al., 2021).
- Type 5. Groundwaters with tritium contents from 0 up to 8 TU and strongly enriched $\delta^{18}O$ contents (between 4 and 9.5 ‰), which are detected in Chad and Niger and correspond to extremely evaporated samples of groundwater. Theses samples testify to the extreme conditions of the region and the strong impact of evaporation on the groundwater resources.
- Type 6. Groundwaters with very high ^{3}H content, clearly above the regional modern rainfall content. These values, up to 17 TU, correspond to residual groundwaters infiltrated at the time of the 1963 bomb peak of tritium in the atmosphere. This type of groundwater is clearly subject to very slow dynamics in the aquifer (Nimz, 1995). This type of groundwaters with relatively high tritium content is rather rare and specific groundwater flow processes have to be considered here to explain this by combining at the same time a semi-confined evolution of

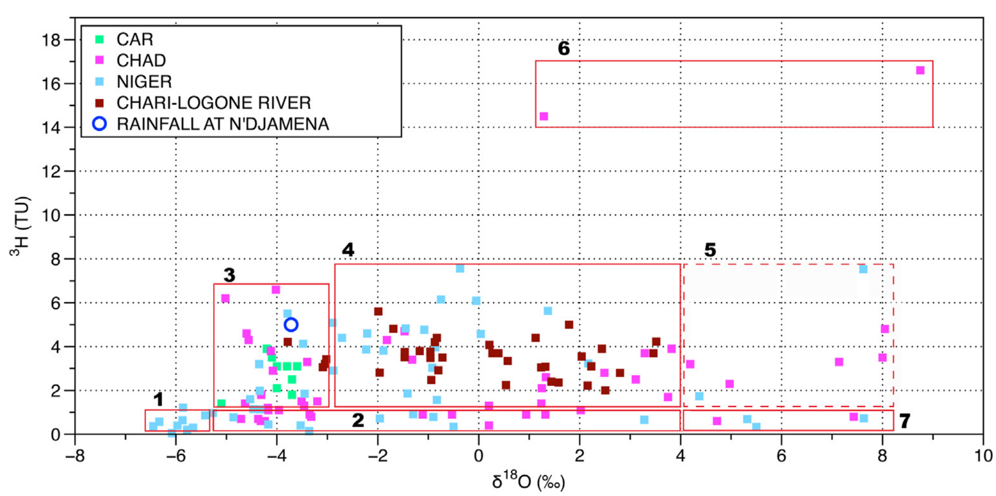

Fig. 9. Diagram showing the distribution of ^{3}H vs $\delta^{18}O$ content of groundwater of the Quaternary aquifer in the Lake Chad Basin area allowing identification of different groundwater types. Type 1: Palaeowaters (recharged during a more humid period than today), Type 2: "old" waters infiltrated before the 1960's, Type 3: "Recent" waters exhibiting isotopic composition of regional rainwater indicating rainy season rainfalls as main origin, Type 4: Modern waters influenced by mixing processes with surface waters, i.e direct recharge by the Chari-Logone and Komadougou Yobé rivers, Type 5: groundwater impacted by evaporation, Type 6: residual groundwaters infiltrated exactly at the time of the 1963 bomb peak of tritium in the atmosphere, and Type 7: strongly evaporated groundwater with no tritium content resulting from paleo-lake Chad waters infiltration during higher lake levels of the Holocene.

groundwater associated with mixing processes including dispersion. The hydrogeological data are too spares in this area of the basin to quantitatively calculate the groundwater evolution which should be in-between piston and exponential flows. What we know is that from the GNIP database tritium in N'djamena monthly-rainfall reached about 1371 TU in 1963, which is relatively high for such low latitude region, but is confirmed by Terzer-Wassmuth et al. (2022) by the mean of isoscape reconstruction. So, it is then not unrealistic to observe theses values, that have been carefully checked at the laboratory.

– Type 7. Strongly evaporated groundwater with no tritium content resulting from paleo-lake Chad waters infiltration during higher lake levels of the Holocene like in the Bahr el Ghazal region (Vassolo et al., 2015).

5.3. Synthesis and recommendations to managers

Our results showed that applying isotopes we were able to determine the various mechanisms of the aquifer recharge. Stable water isotope results indicated the contributions from near-surface water sources to the Quaternary aquifer recharge occurring during the rainy season. Tritium analyses revealed a direct recharge of groundwater by heavy precipitation in the Central African Republic part of the basin as well as in other parts of the Chad and Niger. The analysis of isotopes in Chari-Logone and the Koumadougu Yobé rivers showed that surface water, rivers and potentially seasonal wetlands, play an important role in the lateral recharge of the Quaternary aquifer along their respective courses. The proposed framework by coupling stable and radioactive isotope data was useful to interpret hydrological and hydrogeological data at the Central African region level, that can sometimes appear complex for non-specialists. Unlike other methods (piezometers for monitoring and management of groundwater, geophysical surveys, etc.), which are expensive and very difficult to deploy, the isotopic methods remain the best tool for the study and understanding of groundwater, especially in large regions with relatively little hydrogeological background information.

Considering the transboundary nature of the water resource in the Lake Chad basin and the highlighted strong hydrological links within the whole basin (from head waters to the Lake Chad waters), it is important to promote further in-depth transnational hydrogeological investigations of this shared strategic aquifer, which is used for irrigation as well as for drinking water supply. It can be recommended to decision-makers (including governments and financers-donors) to put in place clear regulations for the management of shallow groundwater resources, which are the most intensively exploited and can be the object of potential users' conflicts in the near future.

The groundwater resources of the Quaternary aquifer of the Lake Chad basin appear to be resilient in some large places, mainly due to the various sources of their recharge. But developing rational and careful management must be a priority for transnational institutions like the Lake Chad Basin Commission to avoid a regional hydrological crisis. Indeed, in an endorheic basin like the Lake Chad basin, where surface waters and groundwaters are inter-dependent and with no outflow towards the sea, both qualitative and quantitative dimensions of water management must be considered together. It is important to plan regional development of agriculture and populations in agreement with the protection of the hydro-ecosystems having a role in the groundwater recharge, groundwater buffering and groundwater storage, like river alluvial annexes and major wetlands areas, and to maintain minimal and operational threshold levels for the river discharge. Without consideration for theses eco-hydrological processes, groundwater shortage could become a new limiting factor for the development of the region.

The south of the Lake Chad basin (Central African Republic, Cameroon and Southern Chad) is the main contributing source to the water resources of the whole basin. Considering its strong impact on the aquifer recharge, this part of the basin must be protected from any activity which might influence surface water flows (dams, irrigation, etc.) and which might cause pollution (intensive agriculture, industries, etc.).

6. Conclusion

The Quaternary aquifer of the lake Chad basin can be considered as resilient in many zones of its extension, as interpretation of isotopic data indicates active recharge processes in several areas of the basin. Nevertheless, if the hydrogeological behavior of the Quaternary aquifer shows good connectivity, and sometimes a kind of dependence on river surface waters or to water stored in swamp areas, other sectors are less favorable to active recharge processes and show a clear tendency to inertial flow conditions and to long term storage of groundwater. Improving the available isotope hydrological information of the region can help secure knowledge of the actual situation and dynamics of hydrogeological processes. It can also provide important information and characteristics about the renewability of hydrogeological processes in an efficient, fast and economical way necessary for groundwater resources managers to ensure the long-term sustainability of this very important socio-economic resource for the whole Central African region.

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CRediT authorship contribution statement

A. Mahamat Nour: Investigation, Writing – original draft, Writing – review & editing. **F. Huneau:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision. **A. Mahamat Ali:** Conceptualization, Methodology, Writing – review & editing. **H. Mahamat Saleh:** Investigation, Writing – review & editing. **S. Ngo Boum-Nkot:** Conceptualization, Methodology, Writing – review & editing. **B. Nlend:** Investigation, Writing – review & editing. **C.L. Djebebe-Ndjiguim:** Investigation, Writing – review & editing. **E. Foto:** Conceptualization, Methodology, Writing – review & editing. **R. Sanoussi:** Conceptualization, Methodology, Writing – review & editing. **L. Araguas-Araguas:** Conceptualization, Methodology, Writing – review & editing. **Y. Vystavna:** Writing – original draft, Writing – review & editing.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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