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PAPER

Groundwater recharge processes in the Lake Chad Basin based on isotopic and chemical data

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Abstract

The Lake Chad Basin is Africa's largest endorheic basin. Because water supply for the rural population and most of the urban population depends on groundwater, assessment of groundwater recharge is crucial. Recharge sources for the upper Quaternary aquifer are precipitation, rivers, and swamps. Using water chemistry, and environmental (^{18}O, ^{2}H, ^{3}H) and carbon (^{14}C) isotopes, recharge processes can be assessed and groundwater ages roughly estimated. For this purpose, more than 1,000 samples from groundwater, surface water and precipitation were analysed for hydrochemistry and environmental stable isotopes. Furthermore, ^{3}H measurements and ^{14}C values of dissolved inorganic carbon for groundwater from the northeastern part of the Basin are included in the evaluation. The environmental isotope distribution shows recent recharge from precipitation north of Lake Chad (Kanem Region), where very low ^{3}H values indicate occurrence before the 1960s bomb peak. Focused recharge from fresh river water is typical for Salamat Region in south Chad and the Komadugu Yobe wetlands between Nigeria and Niger. Slightly high δ-values in water occur in the Waza Logone area between Chad and Cameroon. Groundwater along the Lake Chad shore and the Bahr el Ghazal corridor show high δ-values ($\delta^{18}O$ –0.78 to 7.45‰, $\delta^{2}H$ –13.6 to 30.8‰). Recharge is caused by surface water that undergoes evaporative processes before percolation. Groundwater ages of 600–4,150 years, estimated from ^{14}C analyses combined with high SO_4 concentrations, along the Bahr el Ghazal indicate that recharge was caused by residuals of the Mega Lake before it dried out completely.

Keywords Isotope hydrology · Groundwater renewal · Africa · Transboundary aquifer · Arid regions

Introduction

Water availability worldwide is under threat because of rapid population growth and the consequent increase in withdrawal for domestic, industrial, and irrigation uses (Mohan et al. 2018). As a result, both surface water and groundwater resources are experiencing overexploitation. Regarding groundwater, 37 of the world's largest aquifer systems were studied by Richey et al. (2015a, b), of which 21 were reported to be depleted. When adding the climate change factor, it becomes clear that there is an urgent need for adequate management of these resources to ensure social and economic development.

Groundwater recharge is often the limiting factor for groundwater withdrawal under sustainable conditions (Döll and Flörke 2005); thus, the estimation of present recharge is critical, especially in arid and semiarid areas. This is particularly true for the 400-km-wide band across Africa known as the Sahel region, where large aquifers are present, but data collection concerning climate, precipitation, and groundwater head is very scarce due to lack of monitoring stations.

The Lake Chad Basin (LCB) is an endorheic basin located in the central part of northern Africa. It has an area of 2.4 million km^2 and is inhabited by approximately 45 million people (LCBC 2016). Because of its location and extension, the LCB

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mirrors the climatological, hydrological, and societal situation of the semiarid Sahel region. It lies in an area of transition from perennial to ephemeral river systems and where reliable water supply using surface water suffers uncertainty. Therefore, it is often subject to conflicts among water uses (Ashton 2002), especially in the surroundings of the Lake Chad (Rizzo 2015). It is here where effective water management is needed the most.

Studies on groundwater recharge in arid to semiarid areas involve mainly local or semiregional evaluation. They often use the chloride mass balance technique (Gaye and Edmunds 1996; Edmunds et al. 2002; Edmunds and Tyler 2002) combined with stable water isotopes (Allison and Hughes 1983; Barnes and Allison 1988; Barnes et al. 1989; Leduc et al. 2000; Beyer et al., 2015; Adomako et al. 2010; Gaj et al. 2016; Tewolde et al. 2019; Goni et al. 2019; Mahamat Nour et al. 2022) and hydrochemistry (Njitchoua et al. 1995; Edmunds et al. 1999; Zagana et al. 2007a). Recharge has also been assessed by means of the mass balance equation (Zagana et al. 2007b; Ndubuisi 2007) and combination of empirical models (Adelana et al. 2006). Additionally, modelling of ^{3}H and ^{14}C (Favreau et al. 2002) and modelling of environmental isotopes by including evaporative fractionation in soil profiles (Zhou et al. 2021) or the analysis of aquifer hydrodynamic characteristics (Ngounou Ngatcha et al. 2007) have been used to determine recharge. Recharge distribution has also been mapped using satellite-based thermal data (Leblanc et al. 2003). Many of these studies were included in a global assessment of groundwater recharge in semiarid areas by Scanlon et al. (2006).

Using numerical flow modelling, diffuse recharge has been calibrated for the whole LCB (Boronina et al. 2005; Vaquero et al. 2021) and limited regions like the Waza Logone area (Candela et al. 2014; Nkiaka et al. 2018), the Chari Baguirmi region (Massuel 2001), and the Komadugu Yobe River region (Leblanc 1997; Zairi 2008; Genthon et al. 2015). Diffuse recharge distribution has been also determined based on chloride-36 analyses throughout the area (Bouchez et al. 2019).

This work will concentrate on the distribution of environmental isotopes combined with ^{3}H values and chemical composition of groundwater as well as assessment of groundwater age through ^{14}C, to attempt to define areas of present and past recharge throughout the whole LCB. A very valuable and extensive amount of data is available at the Lake Chad Basin Commission (LCBC) from a series of cooperation projects with the German government.

Study area

Location, climate, and hydrology

The LCB is located in the central part of northern Africa and extends from 5 to 25°N and from 7 to 25°E (Fig. 1).

Due to its size, the LCB expands over various climates and ecosystems. Following the updated Köppen-Geiger climate classification (Peel et al. 2007), the northern part of the basin corresponds to Saharan climate (hot arid desert) with very low precipitation, mean annual temperature above 18 °C, daily temperature amplitude greater than 35 °C, and annual temperature amplitude greater than 60 °C (White 1983). Southward lies the 400-km-wide Sahelian band (hot arid steppe). It is characterised by mean annual temperatures between 26 and 30 °C and precipitation between 150 and 500 mm (White 1983). Precipitation occurs over 3–4 months and is closely linked to the West African Monsoon, which is known for its extremely variable manifestation (Hall and Peyrillé 2006). To the south, the tropical region (tropical savannah) is encountered. Here mean annual temperature varies in a range of 24–28 °C and mean annual precipitation is from 500 to 1,400 mm (White 1983) or 1,700 mm according to ERA5 data for the period 1979–2005.

From a hydrological point of view, the most prominent feature in the region is Lake Chad, which receives most of its water from the tropical savannah through the Chari-Logone River system (Fig. 1). The Komadugu Yobe River usually provides small flow to the lake (Olivry et al. 1996), but it has become insignificant in recent decades because of flow retentions and diversions (Geerken et al. 2011). Several wetlands and periodically inundated areas spread over the LCB, like the lakes Chad and Fitri, the Waza Logone wetlands on the border between Chad and Cameroon, the Komadugu Yobe wetlands in Nigeria, the Salamat wetland between Chad and Central African Republic, and the Massénya wetland in Chad (Fig. 1).

Hydrogeology

The upper unconfined to semiconfined aquifer is composed of Quaternary aeolian sands (Fig. 1) interbedded by fluvio-lacustrine silt and clay in areas prone to periodical flooding along the Lake Chad shore and the wetlands (Durant and Mathieu 1980; Schneider and Wolff 1992; Moussa et al. 2013). This large transboundary aquifer extends over most of the LCB and has an area of ~500,000 km^{2} (Leblanc et al. 2007) with an average thickness of 100 m that varies from 190 m in the Kanem dunes to the north in Chad to a few meters towards the boundaries in the south (UNESCO 1969; Bouchez et al. 2019). It is known as the Upper Aquifer of the Chad Formation in Nigeria (Barber 1965; Eberschweiler 1993a, b) and is an important groundwater resource for Cameroon, Chad, and Niger, whereas in Nigeria it is used mainly for local rural water supply (Miller et al. 1968), due to low thickness and discontinuity (Barber 1965).

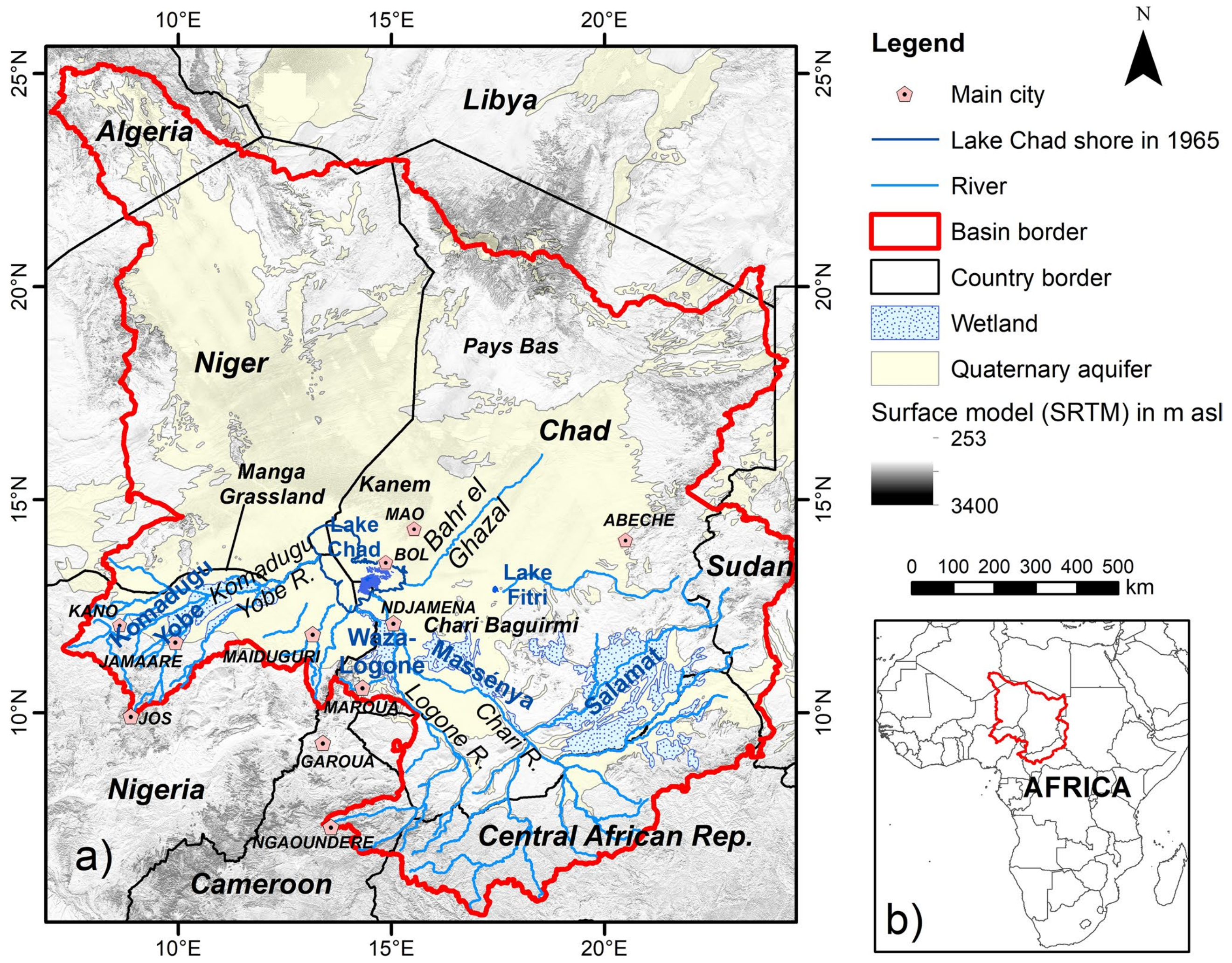

Fig. 1 Location of the study area. **a** Map of the Lake Chad Basin (LCB) with the extension of the Quaternary aquifer (yellow-shaded area); **b** the LCB in the sub-Saharan northern part of Africa

The Quaternary aquifer is underlain by the upper Pliocene (Fig. 2), an aquitard composed of up to 300 m of greenish clay, and the lower Pliocene, represented by fine to coarse sand deposits, which often cannot be differentiated from the underlying Continental Terminal (CT) (Schneider and Wolff 1992). The lower Pliocene (Fig. 2), known as the Middle Aquifer of the Chad Formation in Nigeria (Barber 1965), is encountered at depths between 250 and 300 m and is artesian in the surroundings of the Lake Chad. It provides groundwater to Nigerian cities in the basin, like Maiduguri.

The Oligo-Miocene CT (Fig. 2), composed of fluvio-lacustrine deposits, is characterised by an alternation of sandstone and clay banks (Lang et al. 1990; Eberschweiler 1993a) of variable thicknesses that can reach up to 600 m, but on average is 100 m (Eberschweiler 1993b). This is the lowest aquifer that lies directly over the granitic basement complex (Arad and Kafri 1975) or in discordance on Cretaceous formations (Massuel 2001). It is known as the Lower Aquifer of the Chad Formation in Nigeria (Barber 1965) and its groundwater quality is very poor due to mineralisation (Eberschweiler 1993b). Where the Cretaceous formations are present (Cameroon and Niger), they lay on the crystalline basin; however, it is not certain that they extend throughout the whole basin (Massuel 2001).

Recharge

Presently, the Quaternary aquifer in the LCB receives recharge through seepage from wetlands (Tewolde et al. 2019) and perennial rivers (Bouchez et al. 2019), as well as along the Lake Chad shore (Isiorho et al. 1996); however, because of river scarcity in the LCB, the largest volume of recharge results from diffuse rainfall. Estimations vary considerably depending on the study area and the method used (Table 1). Values between 2 mm/annum have been

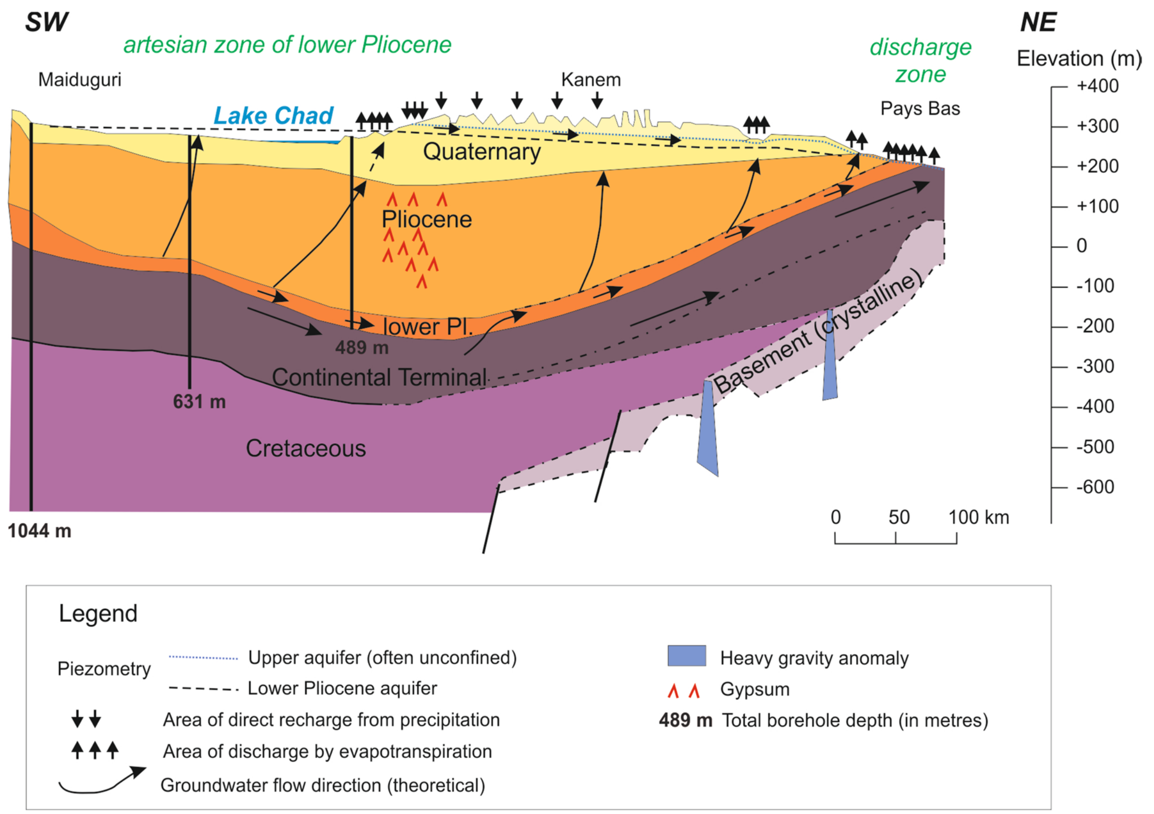

Fig. 2 Schematic SW–NE cross-section through the Lake Chad basin (after Schneider and Wolff 1992)

assessed in southern Niger (Leduc et al. 2000) and 16–30 mm/annum in northern Nigeria (Edmunds et al. 2002). For Chad, values fluctuating from less than 1 mm/annum in the north, 3–19 mm/annum in the Salamat region, and in the range of 117–163 mm/annum in the Waza Logone region have been reported (Tewolde et al. 2019). Bouchez et al. (2019) estimate a diffuse precipitation recharge of 16±27 mm/annum throughout the basin and conclude that this recharge volume is much higher than the actual withdrawals in the LCB, confirming findings from Bonsor et al. (2018). Using GRACE products and land surface models, they found that, although seasonal variations can be identified, no long-term trend in groundwater levels is visible.

Groundwater quality

Groundwater quality of the Quaternary aquifer is variable and depends on residence time in the hosting rocks (Bouchez et al. 2019). According to Arad and Kafri (1975), calcium-bicarbonate isotopically light groundwater is encountered in the south and southwest of the LCB and is an indication of present recharge by precipitation. General groundwater flow is towards the northeast and composition changes to distinctive chemical groups along flow paths (Arad and Kafri 1975). Brines and evaporates can be found in many depressions between the Kanem sand dunes north of the lake (Eugster and Maglione 1979), along the Bahr el Ghazal to the northeast of the lake (Schneider and Wolff 1992) as well as in its northern pool of the lake, which has been more or less dry since 1983 (Neukum et al. 2017).

Groundwater quality of the Quaternary Upper Aquifer in Nigeria is in general excellent for drinking water purposes, apt for industrial use, and suitable for irrigation except on clay soils (Barber 1965). Good drinking water quality has also been reported for the Cameroon part of the basin (Bello et al. 2019).

It is known that excess sodium is common in the Chari Baguirmi region (Abderamane et al. 2012) and the northern pool of the Lake Chad (Neukum et al. 2017). Because the Quaternary aquifer is composed of weathered igneous rocks from the granitic basement, Arad and Kafri (1975) conclude that these igneous rocks are the source of sodium in groundwater through alteration of plagioclase, particularly albite in kaolinite (Abderamane et al. 2012). Potassium is also present in these rocks at similar concentrations, but it tends

Table 1 Summary of publications with estimated recharge in parts of the LCB

Region	Recharge (mm/annum)	Method	Publication
Focused recharge			
SW lakeshore (Nigeria)	745	Seepage meter	Isiorho et al. 1996
Sahelian LCB close to rivers	78±7	^{36}Cl, Cl	Bouchez et al. 2019
Salamat wetland	111	Chloride mass balance	Tewolde et al. 2019
Waza Logone wetland	117–163	Chloride mass balance	Tewolde et al. 2019
Diffuse recharge			
SE Niger	2	Isotopes (δ^{18}O, δ^{2}H, ^{3}H, and ^{14}C)	Leduc et al. 2000
Manga Grassland, NE Nigeria	49	Model	Carter et al. 1994
	44	Chloride mass balance	Edmunds et al. 1999
	132	Piezometric data	Goes and Zabudum 1999
NE Nigeria	60	Chloride mass balance	Edmunds et al. 1999
	16–30	Chloride mass balance	Edmunds et al. 2002
	43	Chloride mass balance and Cl in dug-wells	Edmunds et al. 2002
	19	Model of chloride profiles	Goni et al. 2005
N Nigeria	169 for Maiduguri to 837 for Kano	Soil moisture deficit	Ndubuisi 2007
N Cameroon	25–125	Aquifer hydrodynamic characteristics	Ngounou Ngatcha et al. 2007
Salamat region, S Chad	3–19	Chloride mass balance	Tewolde et al. 2019
Southern LCB	240±170	^{36}Cl, Cl	Bouchez et al. 2019
Sahelian part of the LCB unconnected to rivers	16±27	^{36}Cl	Bouchez et al. 2019

to precipitate and thus is not representative in groundwater chemistry.

Fluoride is present in the area (Fantong et al. 2010; Bura et al. 2018), which is of geogenic origin and not widespread. Nitrate pollution as a result of leaking pit-latrines and a general lack of hygiene has been reported from numerous cities within the basin (Ngounou Ngatcha and Daïra 2010; Goni et al. 2019; Bon et al. 2020). It is also a problem in agricultural regions, due to overuse of fertilizers and in pastoral areas because of mismanagement of water points (Vassolo and Daïra 2012; Huneau 2017).

Materials and methods

Groundwater chemistry combined with environmental isotopes (δ^{18}O and δ^{2}H), ^{3}H, and ^{14}C are used to determine the groundwater recharge of the Quaternary aquifer in the LCB. Furthermore, mapping the distribution of groundwater quality and isotopes allows for depicting areas that presently receive recharge as well as areas that do not participate in the actual water cycle.

Laboratory results from regular groundwater sampling throughout the basin over the last 12 years are available. In total, 1,267 full chemical analyses, 1,203 environmental isotopes analyses, 142 tritium analyses, and seven carbon-14 analyses exist at the LCBC from a series of cooperation projects with the German Federal Institute for Geosciences and Natural Resources (BGR). Additionally, environmental isotopes in 386 event-based precipitation samples, collected at six stations scattered in the basin, as well as 110 samples for the Chari River in N'Djamena over the period July 2016–September 2021, are available. Because all analyses were performed in the same laboratories, relative comparability of the results is very high. Ion balance was less than 10% for 1,128 (97.4%) samples and less than 5% for 1,128 (89%) samples.

Coordinates of the sample points were recorded during sampling campaigns by means of a Garmin™ GPS device. Temperature, electrical conductivity (EC), and pH were measured on-site using a digital multi-parameter instrument (WTW™-Multi 3430 and HACH HQ40d with IntelliCAL™ electrodes). Groundwater was extracted either by pumping with the installed pump, a submersible pump (Grundfoss™MP1), or a bailer. Sampling from chemical analyses consisted in filling a 100-ml PVC bottle with filtered and HNO_3-acidified water for cation analysis. Addition of HNO_3 lowers the pH value to ~2, avoiding precipitation, bacterial growth, adsorption on the bottle's wall, etc. Furthermore, a 500-ml PVC bottle was filled with unfiltered and nonacidified water for anion analysis. Samples were collected after rinsing the bottles three times with water from the sampling site and kept in a cool box during the field campaign. For isotope analyses, 30-ml amber glass bottles

Table 2 Summary of rainfall collectors installed in the LCB

Location	Longitude (°)	Latitude (°)	Elevation (m asl)	Study period	No. of years (analyses)	Range of values		LMWL monthly weighted		Weighted average all data		
						$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	Slope (‰)	Intercept (‰)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	d-excess (‰)
N'Djamena	15.0013	12.12819	295	2016–2021	6 (184)	–9.9 to 3.8	–74.5 to 39.0	7.1	7.3	–5.0	–27.0	10
Mao	15.31217	14.13196	343	2018–2021	4 (80)	–10.4 to 7.3	–74.1 to 23.8	6.2	4.2	–4.8	–28.6	10
Bol	14.73753	13.44474	294	2018–2021	4 (68[a])	–11.0 to –0.6	–73.4 to 6.7	6.4	3.1	–5.9	–36.6	11
Abéché	20.83969	13.84453	536	2018–2021	4 (72[a])	–7.7 to 1.9	–46.6 to 18.4	6.3	2.7	–3.9	–21.5	10
Maiduguri	13.21856	11.86296	318	2018–2021	4 (40[b])	–10.4 to 3.3	–74.7 to 27.4	7.2	8.5	–5.1	–28.4	13
Kano	8.58167	11.96583	490	2018–2019	2 (9[b])	–6.9 to 2.7	–42.1 to 5.4	8.0	+13.1	–4.8	–25.4	13

Elevation was estimated from Shuttle Radar Topography Mission (SRTM) in m asl (meters above sea level), *LMWT* local meteoric water line, Coordinates in WGS 84 system

[a] 2021 samples not yet analysed

[b] 2019 to 2021 samples not yet analysed

with PE-seal caps filled with untreated and unfiltered water were used. In the case of tritium and ^{14}C, 1,000-ml PE bottles were filled with unfiltered and untreated water. Samples were stored at 6 °C until the time of packaging, and were then airfreighted to the laboratory in Hanover (Germany) in cool boxes packed with cooling elements.

Concentrations of major and minor ions were measured using a DIONEX ICS-3000 ion chromatograph (Cl, Br, F, NO_3, NO_2, SO_4), a SPECTRO ARCOS ICP-OES instrument (Na, K, Ca, Mg, P, Fe, Mn, Al, Si), and a UNICAM UV 300 photometer (NH_4, NO_2, PO_4). Commercial standard solutions are used for daily calibration and limits of quantitation are determined by 10-point calibration according to the DIN 32645 standard. HCO_3 and CO_3 concentrations were determined with a SCHOTT Titroline Alpha Plus automatic titration system according to a modified DIN 38409-H7-2 standard by evaluation of titration curve shapes for the identification and quantitation of these species. The contribution of PO_4 to alkalinity was estimated from ICP-OES concentration data.

All stable isotopes (^{18}O and ^{2}H) values were determined using a PICARRO L2130-i and L2140-i cavity ring-down laser spectrometers. Samples were measured at least four times and the reported value is the mean one. All values are given in delta notation in per mill (‰) vs. Vienna Standard Mean Ocean Water (VSMOW). Raw data were checked for organic contamination using the software ChemCorrect (unaltered software settings), then corrected for memory effects and drift. Furthermore, they were normalized to the VSMOW/SLAP scale. External reproducibility, defined as standard deviation of a quality check standard during all runs, was better than 0.20 and 0.8‰ for $\delta^{18}O$ and $\delta^{2}H$, respectively.

Tritium was measured at the Bremen University, Germany, by mass spectrometry of its decay product Helium-3. After degassing, each sample was stored for ~6 months in glass bulbs. Next, the glass bulbs were connected to the sample inlet system and unsealed under high-vacuum conditions. Accumulated Helium-3 was separated from water and analysed for Helium-3 and Helium-4 with a sector field mass-spectrometer (MAP 215-50). Helium-4 serves to quantify sample contamination by air. The system is calibrated by defined amounts of atmospheric air and is able to detect 0.01 TU or 0.6 mBq/L in water.

Carbon-14 was measured by Beta Analytics Inc. (USA) by counting the number of ^{14}C atoms present in the sample through accelerator mass spectrometry (AMS).

Deuterium-excess—d-excess (‰) = $\delta^{2}H$ (‰) – 8 × $\delta^{18}O$ (‰)—is used to determine evaporation effects in the recharge processes. It depends on evaporation conditions at the ocean and varies with cloud transport to the precipitation site (Bershaw 2018). According to the Global Network of Isotopes in Precipitation (GNIP), its global average value

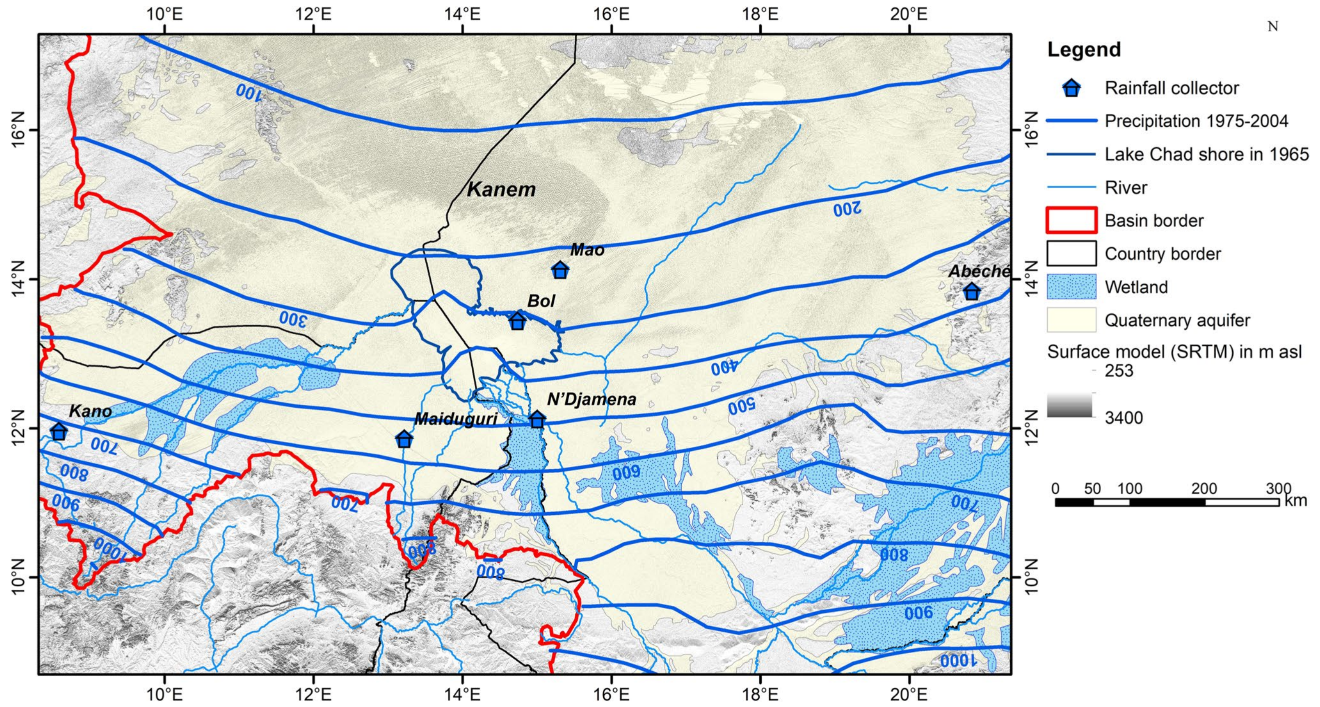

Fig. 3 Location of the rainfall collectors in the LCB and distribution of the long-term mean annual precipitation for the period 1975–2004 using data from the Climate Research Unit (CRU)

under oceanic evaporation conditions is 10‰ (Florea et al. 2017), when air humidity is above 85% (Fritz and Fontes 1980; Clark and Fritz 1997). Under evaporative conditions, the residual water is enriched in both δ^{18}O and δ^{2}H, but, because the relative enrichment of δ^{18}O is larger than for δ^{2}H, d-excess results are lower than 10‰.

Results and discussion

Groundwater recharge areas can be delineated using environmental isotopes and groundwater quality data. Furthermore, it is possible to describe recharge processes using the isotopic characteristics of groundwater.

Isotopic composition

There are two groundwater recharge sources in the LCB: precipitation and surface water (rivers, lakes, and wetlands). These sources have dissimilar isotopic compositions and, thus, mark groundwater differently.

Concerning precipitation, the project has installed six rain collectors in the basin at N'Djamena, Mao, Bol, and Abéché in Chad as well as at Maiduguri and Kano in Nigeria (Table 2; Fig. 3). Isotope values for the Kano station are only available for the rainy season in 2018. In the case of Maiduguri, the study attained samples for four rainy seasons (2018–2021), but analyses are available only for 2018. These two stations were not considered for further analyses. Analyses for Bol and Abéché do not include samples from 2021.

According to Table 2, groundwater presently recharged by precipitation should be close to the weighted average isotope values of precipitation with δ^{18}O values between –3.9‰ and –5.9‰ and δ^{2}H values in the range of –21.5 to –36.6‰. Precipitation at Bol presents the most depleted concentrations for both isotopes, probably due to its proximity to the Lake Chad. The open surface water is able to supply depleted isotope values and, thus, change the composition of precipitation locally.

Since 2016, the most depleted values of δ^{18}O and δ^{2}H in the Chari River at N'Djamena are –4.6 and –27.5‰, respectively, which correspond to the mean weighted average of precipitation in N'Djamena (–5‰, –27‰). This means that during high water, the flow originates from rainfall. The most δ^{2}H-enriched values are 3.9‰ for δ^{18}O and 19.8‰ for δ^{2}H. The water line for the Chari River (Fig. 4a) results in $\delta^{2}H = 5.0 \times \delta^{18}O–1.1$. Mean values for δ^{18}O and δ^{2}H are –0.62 and –4.2‰, respectively. In N'Djamena, the Chari water line intercepts the local meteoric water line at $\delta^{18}O =$ –4.0‰ and $\delta^{2}H =$ –21.1‰.

A regression line for groundwater is defined by $\delta^{2}H = 5.5\ \delta^{18}O – 4.9$ (Fig. 4a). Mean values for δ^{18}O and δ^{2}H are –2.2 and –17.2‰, respectively. δ^{2}H varies between –7.0 and

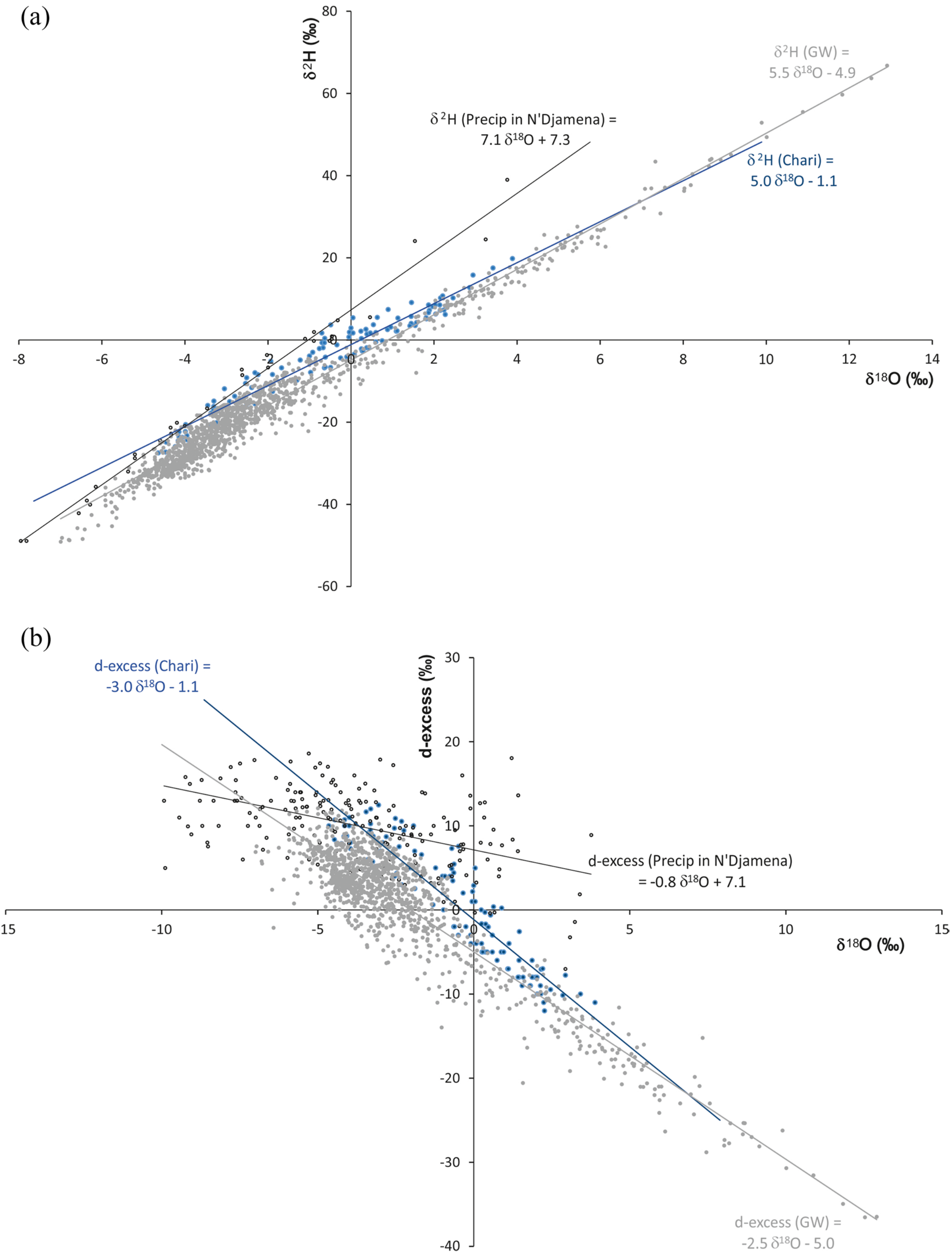

Fig. 4 Meteoric water lines for precipitation in N'Djamena (black) and the Chari River in N'Djamena (blue), as well as groundwater (GW) in the LCB (grey): **a** $\delta^{18}O$ vs. $\delta^{2}H$ space and **b** d-excess vs. $\delta^{18}O$

12.9‰, and $\delta^{2}H$ between –49.1 and 66.8‰. In the graph of Deuterium excess (d-excess) vs. $\delta^{18}O$ (Fig. 4b), the regression lines for river water and groundwater are steeper compared to the local precipitation line. This is an indication of evaporation effects experienced by both river water and groundwater.

Mahamat Nour (2019) reported that the Quaternary aquifer discharges into the Chari and Logone rivers during the

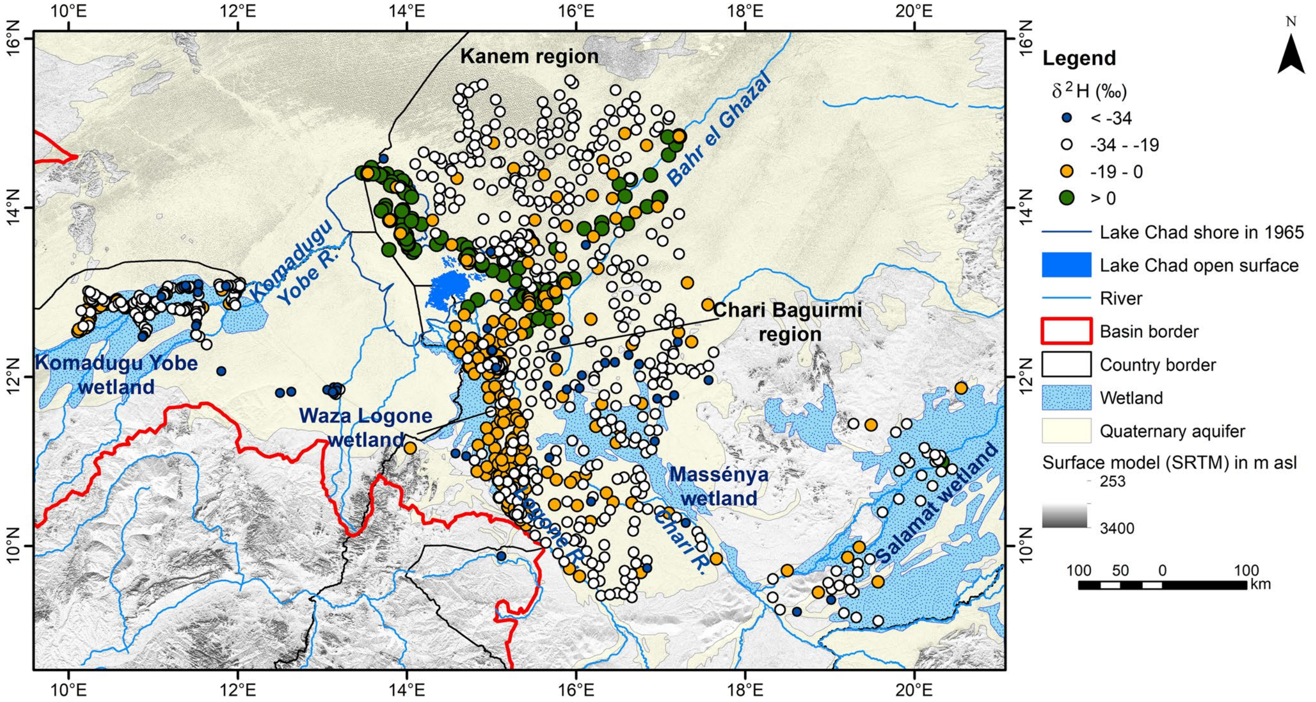

Fig. 5 Distribution of δ²H (‰) in the LCB

dry season and exfiltrating groundwater had a mean isotopic composition of –1.5 and –7.2‰ for δ^{18}O and δ^2H, respectively for the years 2013, 2015, and 2016. Here, the δ-values are more positive compared to the mean weighted precipitation values (Table 2), indicating evaporation effects during recharge.

Mapping the distribution of δ^2H (‰) in the LCB allows for depicting the areas in which recharge takes place. Diffuse recharge from recent precipitation (white dots) occurs in the Kanem region (Fig. 5). The orange dots in this region indicate more positive δ-values and thus, evaporation in the recharge process. Although precipitation in the area is very low, it appears that recharge can ensue because of the concentration of rainwater along the interdunal valleys. Present recharge also occurs in the Chari Baguirmi region in central Chad, where precipitation amounts are large enough to allow infiltration and percolation. Groundwater in the surroundings of the wetlands Salamat in south Chad and Komadugu Yobe at the border between Nigeria and Niger also show present recharge. In this case, it is either focused recharge during high water levels, when rivers are mainly fed by rainfall, or diffuse recharge through ponding water in the wetlands. The map (Fig. 5) indicates present groundwater recharge in the Waza Logone area with more positive δ-values (orange dots), which is the result of recharge with surface water that has experienced some evaporation. Very positive δ-values are encountered in the northern part and along the eastern shore of Lake Chad as well as along the lake's shore and the Bahr el Ghazal (dark green dots). In these areas, recharge is caused by surface water that heavily evaporates before percolating.

Table 3 Statistics for d-excess measured in precipitation, Chari River and groundwater in the LCB

Statistic	Precipitation in N'Djamena	Chari River in N'Djamena	Groundwater in LCB
Min (‰)	–7	–12	–37
Max (‰)	19	12	12
Median (‰)	10	2	1
Mean (‰)	10	2	3

Deuterium-excess values for precipitation in N'Djamena vary from –7‰ (2017) to 19‰ (2018) with a value of 10‰ for both median and average (Table 3), which indicates an oceanic origin of precipitation that does not experience evaporation when transported across the continent. This confirms findings by Goni et al. (2021). They report that recharge in the LCB takes place in the middle of the rainy season, when precipitation events are strong and air humidity above 85% and thus, with d-excess values of approx. 10‰. Deuterium-excess values for the Chari River, the other possible source of recharge, are in the range of –12 to 12‰ with a median of 2‰ and an average of 1‰, which clearly indicates evaporation effects (Table 3). In

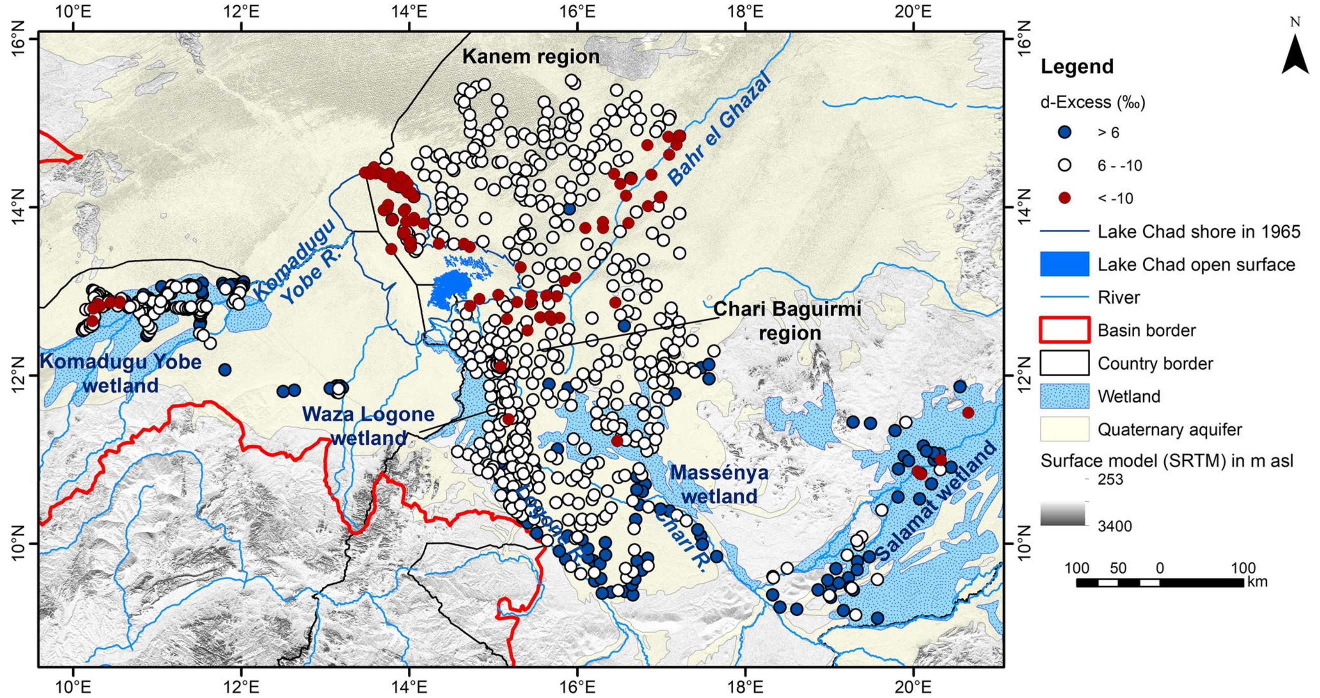

Fig. 6 Distribution of d-excess (‰) in the LCB

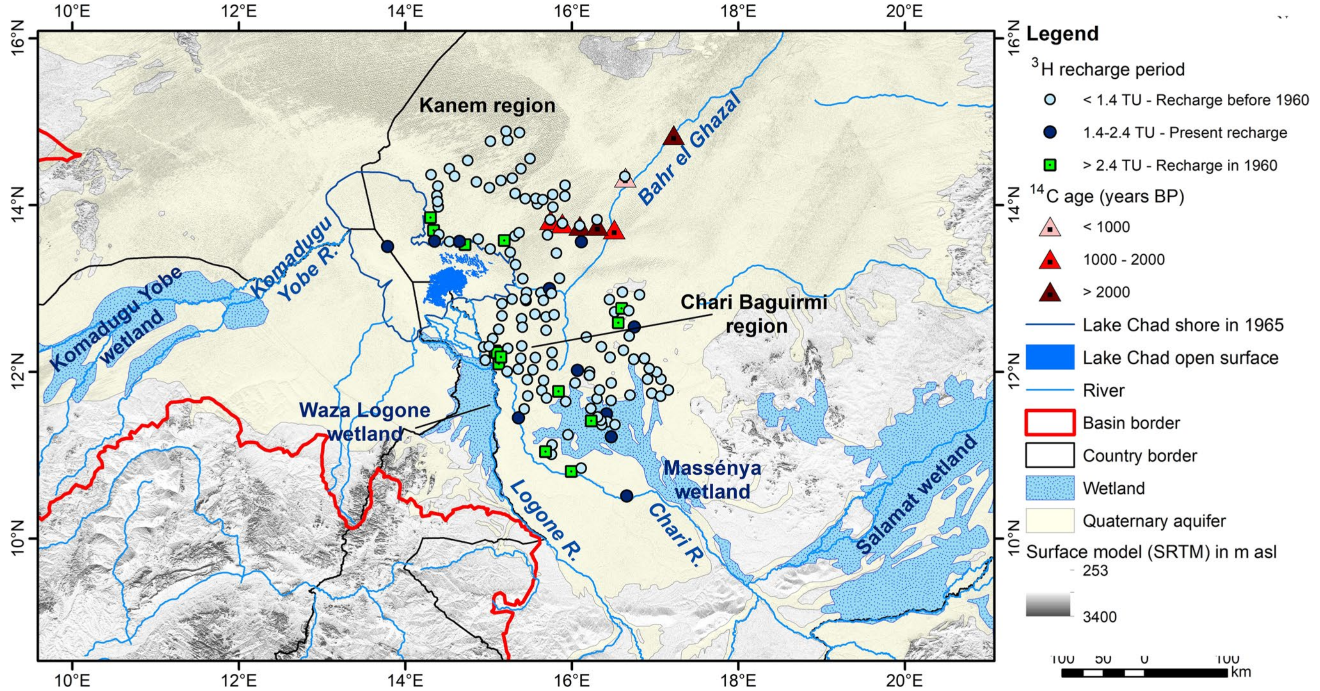

Fig. 7 Distribution of groundwater age in the LCB based on ^{14}C and ^{3}H results

groundwater, d-excess varies from –37 to 12‰ with a median of 1‰ and an average of 3‰. Because the lowest d-excess values in groundwater are much lower than in precipitation or Chari River, it can be concluded that ponds or wetlands, where large evaporation is possible, also produce recharge.

Table 4 Summary of recharge mechanisms in the LCB

Region	Recharge type	Source of recharge	Recharge mechanism	Groundwater age
Kanem	Diffuse	Precipitation	Infiltration of rainfall water along interdunal valleys with evaporation	Recharged before 1960 or mixed (very old and present)
Chari Baguirmi	Focused	Lake Chad	Lateral inflow of heavily evaporated lake water along the southern rim	No dating
	Diffuse	Precipitation	Direct rainfall infiltration with evaporation	Recharged before 1960 or mixed (very old and present)
Komadugu Yobe wetland	Focused	Komadugu	Lateral inflow of river water during high water without evaporation	Recharged before 1960 or mixed (very old and present)
	Diffuse	Wetland	Infiltration of evaporated ponding water (heavily evaporated in the west)	No dating
Salamat wetland	Focused	River	Lateral inflow of river water during high water without evaporation	Recharged before 1960 or mixed (very old and present)
	Diffuse	Wetland	Infiltration of evaporated ponding water (heavily evaporated along the borders)	No dating
Waza Logone wetland	Diffuse	Wetland	Infiltration of evaporated ponding water	Recharged before 1960 or mixed (very old and present)
	Focused	Logone and Chari	Lateral inflow from river water during high water without evaporation	Recharged before 1960 or mixed (very old and present)
Southern Quaternary rim (in Chad)	Diffuse	Precipitation	Direct rainfall infiltration without evaporation	Recharged before 1960 or mixed (very old and present)
	Focused	Logone and Chari	Lateral inflow from river water during high water without evaporation	Recharged before 1960 or mixed (very old and present)
Northern part of Lake Chad	Focused	Lake water	Infiltration of heavily evaporated lake water	Recharged before 1960 or mixed (very old and present)
Bahr el Ghazal	Focused	River	Infiltration of heavily evaporated river water	Very old groundwater (500–4,150 years BP)

The d-excess distribution for the LCB (Fig. 6) shows direct recharge without evaporation at the southern rim of the Quaternary aquifer (blue dots) meaning that direct recharge from precipitation without or only little evaporation effects takes place here. Values of d-excess close to 10‰ appear also along the rivers; thus, they only recharge the Quaternary aquifer during high water levels, when river water is composed mainly of precipitation water. Groundwater in the northern pool of Lake Chad, as well as along the lake's shore and the Bahr el Ghazal, show very negative d-excess values (red dots), which confirms the fact that here recharge is produced by heavily evaporated water.

Tritium measurements from 142 samples in Kanem and the Chari Baguirmi region as well as seven ^{14}C analyses were available to evaluate the time of recharge (Fig. 7). Most of the samples show very low tritium values (<1.5 TU, light blue dots) demonstrating that recharge occurred mainly before the bomb peak in the 1960s. However, samples along the Lake Chad shore show recharge from 55 years ago ($^{3}H > 2.5$ TU, green squares) produced by lateral inflow from the lake at its "normal" state and confirm finding from Mahamat Nour et al. (2022). Lake Chad in the 1960s has been defined as "normal" (Lemoalle et al. 2012) and is characterised by water levels between 281 and 282 m above mean sea level (amsl), an extension of ~20,000 km^2, numerous dune islands, and occasional marshy vegetation on the shores (Lemoalle et al. 2012). According to tritium results, the present recharge by precipitation (values between 1.5 and 2.5 TU, dark blue dots) takes place in some locations scattered throughout the LCB (Fig. 6). Carbon-14 values along the Bahr el Ghazal estimate

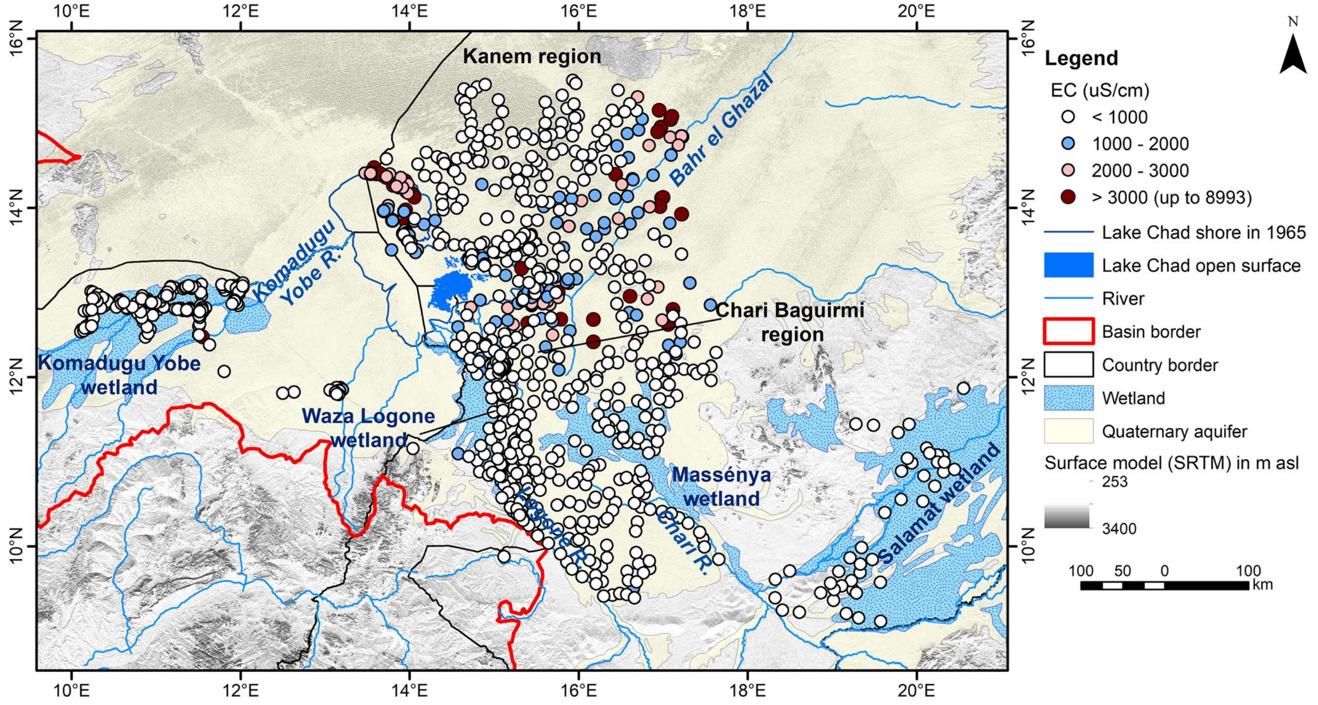

Fig. 8 Distribution of electrical conductivity (EC) in groundwater in the LCB

groundwater ages between 600 and 4,150 years (Fig. 7). These values confirm findings from Bouchez et al. (2019), who reported premodern recharge for this area.

In summary, water isotopes allow for defining recharge mechanisms within the LCB. Results are presented in Table 4.

Chemical composition

The chemical composition of groundwater also reflects the recharge areas in a semiarid climate. Newly recharged groundwater is characterised by low values of EC, because precipitation shows generally low values of EC. In N'Djamena, 12 values of EC in precipitation have been recorded for May to July 2020. Values vary from 16 to 48 µS/cm with an average of 27 µS/cm.

Electrical conductivity was measured in 1,263 groundwater samples in the LCB. Values vary largely from 31 to 8,993 µS/cm with an average of 689 µS/cm (Fig. 8). Altogether, 1,046 (83%) of the values show an EC value below 1,000 µS/cm and thus reflect the general low groundwater mineralization of the Quaternary aquifer. High values of EC (>2,000 µS/cm) occur in the northern part and southern rim of Lake Chad, along the Bahr el Ghazal, and in the northern part of the Chari Baguirmi.

Sulphate concentration in 1,267 groundwater samples throughout the LCB vary from below the detection limit to 4,403 mg/L with an average of 98.5 mg/L. A large number of samples (1,197 samples, 94.4 %) have values below the WHO (2022) guideline of 500 mg/L. Samples with sulphate concentrations above the WHO limit also show high EC values.

It is possible to distinguish two different trends of EC–SO_4. The increasing trend of low slope corresponds to the northern part of Lake Chad, where large values of EC do not correlate with sulphate concentration (Fig. 9a) but are the result of high chloride concentrations (Fig. 9b) due to evaporation. In this area, recharge is caused by lake water that experiences large evaporation before percolation. The steeper trend (Fig. 9a) belongs to the boreholes along the Bahr el Ghazal, where EC correlates with high sulphate concentrations that occur in the area. Eugster and Maglione (1979) postulated that sulphate could originate from oxidation of sulphides or organic matter trapped in clays deposited by the Mega Lake Chad (10,000–2,000 years BP). Seven groundwater samples along the Bahr el Ghazal area were dated by means of ^{14}C. Calculated ages vary between 600 and 4,150 years with an average age of 2,176 years confirming that groundwater in the Bahr el Ghazal was recharged at the time of the Mega Lake Chad occurrence. This area does not receive recharge presently and is less affected by evaporation, which is depicted by a lower correlation between EC and Cl (Fig. 9b).

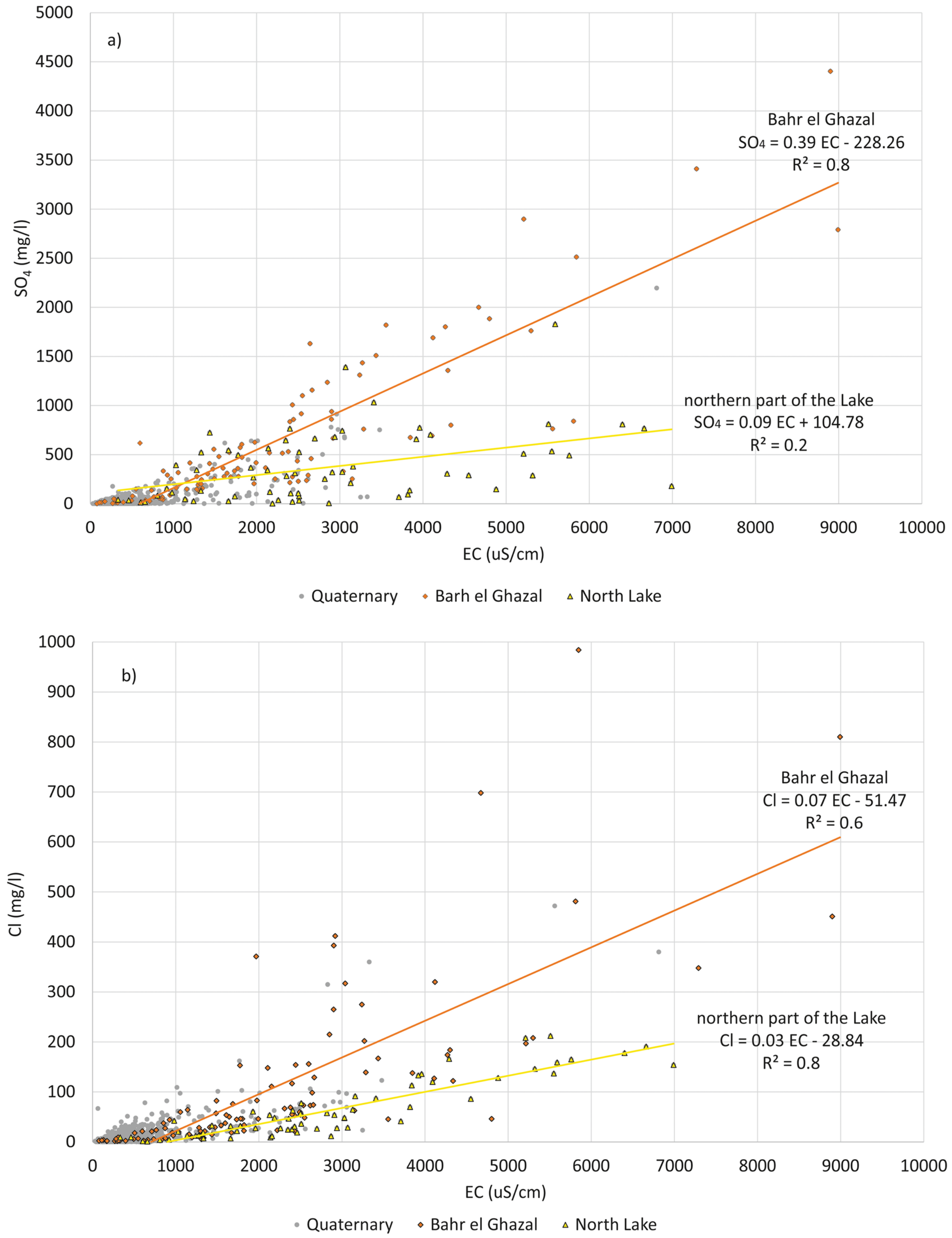

Fig. 9 Relationship between electrical conductivity (EC) and **a** sulphate and **b** chloride, for groundwater in the LCB

Conclusions

The combination of isotope and chemical analyses of groundwater allows one to delineate areas of recharge in the LCB and to determine the age of the groundwater. Actual diffuse recharge occurs in the Kanem dunes. Although precipitation in the area is very low, recharge does occur because of the concentration of rainwater along the interdunal valleys. The Chari Baguirmi area in central Chad, the wetlands of Salamat in south Chad, and Komadugu Yobe at the border between Nigeria and Niger also experience recent diffuse recharge from precipitation. However, in these areas focused recharge during floods prevails, when the rivers transport mainly rainfall. Tewolde et al. (2019) estimated diffuse mean annual groundwater recharge in the range of 3–19 mm and focussed recharge of 111 mm for Salamat wetlands.

The Waza Logone area is characterised by slightly enriched groundwater, which is the result of recharge with surface water that has experienced some evaporation. Here recharge has been estimated between 117 and 163 mm/annum (Tewolde et al. 2019). Heavily ^{2}H- and ^{18}O-enriched groundwater is found in the northern part of Lake Chad as well as along the lake's shore, where recharge is caused by lake water that severely evaporates before percolating. However, present recharge seems to be very low. Tewolde et al. (2019) estimated annual recharge between 0.6 and 0.8 mm/annum.

Groundwater along the Bahr el Ghazal is ^{2}H and ^{18}O-depleted with large negative values of d-excess, which points to a recharge with evaporated surface water. Groundwater also presents large contents of sulphate probably due to oxidation of sulphides or from organic matter trapped in clays deposited by the Mega Lake Chad (10,000–2,000 years BP). Measurement of ^{14}C translates into groundwater ages varying between 600 and 4,150 years, which is defined as premodern by Bouchez et al. (2019).

In general, groundwater of the Quaternary aquifer has low electrical conductivity (EC), which is an indication of recently recharged water. Values above 2,000 µS/cm are only present in the northern part and the southern rim of Lake Chad, the northern part of Chari Baguirmi, and along Bahr el Ghazal. The high EC values in the northern part and southern rim of Lake Chad are evaporation-induced and correlate with chloride. However, the elevated values along the Bahr el Ghazal correlate with SO_4, which could originate from oxidation of sulphides or organic matter trapped in clays deposited by the Mega Lake Chad.

Recommendations to water resource managers

Although recharge occurs in most of the LCB, protection of the wetlands is urgently needed. The largest amount of recharge takes place in these wetland areas and they should be managed to maintain quantity and quality. It is highly recommended to avoid installation of dams or other engineering structures that could lead to their desiccation. If this occurs, not only recharge would reduce substantially in the basin, but also biodiversity would reduce significantly. Furthermore, actions should be taken to avoid pollution, e.g. misuse of fertilisers or lack of effluent treatment facilities in towns and villages.

Use of groundwater along the Bahr el Ghazal could be of concern because of the high content of salts, especially sulphate. It is recommended not to install any wells for water supply before ensuring the good quality of groundwater.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

Abderamane H, Razak M, Vassolo S (2012) Hydrochemical and isotopic characterization of the groundwater in the Chari-Baguirmi depression, Republic Chad. Environ Earth Sci 69:2337–2350. https://doi.org/10.1007/s12665-012-2063-7

Adelana SMA, Olasehinde PL, Vrbka PA (2006) Quantitative estimation of groundwater recharge in part of the Sokoto Basin, Nigeria. J Environ Hydrol 14(5):1–14

Adomako D, Maloszewski P, Stumpp C, Osae S, Akit TT (2010) Estimating groundwater recharge from water isotopes (δ2H, δ18O) depth profiles in the Densu River basin, Ghana. Hydrol Sci J 55(8):1405–1416. https://doi.org/10.1080/02626667.2010.527847

Allison GB, Hughes MW (1983) The use of natural tracers as indicators of soil-water movement in a temperate semi-arid region. J Hydrol 60:157–173

Arad A, Kafri U (1975) Geochemistry of groundwaters in the Chad basin. J Hydrol 25:105–107

Ashton PJ (2002) Avoiding conflicts over Africa's water resources. Royal Academy of Sciences. AMBIO: J Human Environ 31(3):236–242. https://doi.org/10.1579/0044-7447-31.3.236

Barber W (1965) Pressure water in the Chad Formation of Bornu and Dikwa Emirates, north-eastern Nigeria. Bulletin No. 35, Geological Survey of Nigeria, Ministry of Mines and Power, Abuja, Nigeria

Barnes CJ, Allison GB (1988) Tracing water movement in the unsaturated zone using stable isotopes of hydrogen and oxygen. J Hydrol 100:143–176

Barnes CJ, Allison GB, Hughes MW (1989) Temperature gradient effects on stable isotope and chloride profiles in dry soils. J Hydrol 112:69–87

Bello M, Ketchemen-Tandia B, Nlend B, Huneau F, Fouepe A, Fantong WY, Ngo Boum-Nkot S, Garel E, Celle-Jeanton H (2019) Shallow groundwater quality evolution after 20 years of exploitation in the southern Lake Chad: hydrochemistry and stable isotopes survey in the far north of Cameroon. Environ Earth Sci 78:479

Bershaw J (2018) Controls on deuterium excess across Asia. Geosciences 8(7):257. https://doi.org/10.3390/gesciences8070257

Beyer M, Gaj M, Hamutoko JT, Koeniger P, Wanke H, Himmelsbach T (2015) Estimation of groundwater recharge via deuterium labelling in the semi-arid Cuvelai-Etosha Basin, Namibia. Isotopes Environ Stud 51(4):533–552. https://doi.org/10.1080/10256016.2015.1076407

Bon AF, Abderamane H, Mboudou GE, Doua SA, Banakeng LA, Boyomo SBB, Piih SL, Damo BW (2020) Parametrization of groundwater quality of the Quaternary aquifer in N'Djamena (Chad), Lake Chad Basin: application of numerical and multivariate analyses. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-020-10622-5

Bonsor HC, Shamsudduha M, Marchant BP, MacDonald AM, Taylor RG (2018) Seasonal and decadal groundwater changes in African sedimentary aquifers using GRACE products and LSMs. Remote Sens 10:904. https://doi.org/10.3390/rs10060904

Boronina A, Favreau G, Coudrain A, Dieulin C, Zairi R (2005) Data scarcity in the large semiarid Lake Chad basin: incorporation environmental tracers as a priori information for groundwater modelling. In: Proceedings of ModelCARE, fifth conference on Calibration and Reliability in Groundwater Modelling: From Uncertainty to Decision Making. The Hague, June 2005

Bouchez C, Deschamps P, Goncalves J, Hamelin B, Nour AM, Vallet-Coulomb C, Sylvestre F (2019) Water transit time and active recharge in the Sahel inferred by bomb-produced 36Cl. Sci Rep 9:7465. https://doi.org/10.1038/s41598-019-43514-x

Bura B, Goni IB, Sheriff BM, Gazali AK (2018) Occurrence and distribution of fluoride in groundwater of Chad formation aquifers in Borno state, Nigeria. Int J Hydro 2(4):528–537. https://doi.org/10.15406/ijh.2018.02.00121

Candela L, Elorza FJ, Tamoh K, Jiménez-Martínez J, Aureli A (2014) Groundwater modelling with limited data sets: the Chari-Logone area (Lake Chad Basin, Chad). Hydrol Process 28:3714–3727

Carter RC, Morgulis ED, Dottridge J, Agbo JU (1994) Groundwater modelling with limited data: a case study in a semi-arid dunefield of Northeast Nigeria. Q J Eng Geol Hydrogeol 27:85–94. https://doi.org/10.1144/GSL.QJEGH.1994.027.0S.09

Clark I, Fritz P (1997) Environmental isotopes in hydrogeology. Lewis, Boca Raton, FL, 328 pp

Döll P, Flörke M (2005) Global-Scale estimation of diffuse groundwater recharge: model tuning to local data for semi-arid and arid regions and assessment of climate change impact. Frankfurt Hydrology Paper 03, Frankfurt University, Frankfurt

Durant A, Mathieu P (1980) Le quaternaire supérieur sur la rive sud du lac Tchad [The Upper Quaternary on the southern shore of Lake Chad]. Cahier ORSTOM sér Géolo XI(2):180–203

Eberschweiler C (1993a) Suivi et gestion de ressources en eau souterraine dans le bassin du la Tchad: pré-modélisation des systèmes aquifères, évaluation des ressources et simulations d'exploitation [Monitoring and management of groundwater resources in the Lake Chad Basin: pre-modeling of aquifer systems, resources assessment, and exploitation simulations]. Rapport intermédiaire no. 2, BRGM/CBLT, Orleans, France, 73 pp

Eberschweiler C (1993b) Monitoring and management of groundwater resources in the Lake Chad Basin: mapping of aquifers, water resources management. Final report, BRGM/CBLT, Orleans, France, 67 pp

Edmunds WM, Tyler SW (2002) Unsaturated zones as archives of past climates: toward a new proxy for continental regions. Hydrogeol J 10:216–228

Edmunds WM, Fellman E, Goni IB (1999) Lakes, groundwater and palaeohydrology in the Sahel of NE Nigeria: evidence from hydrogeochemistry. J Geol Soc London 156(2):345–355

Edmunds WM, Fellman E, Goni IB, Prudhomme C (2002) Spatial and temporal distribution of groundwater recharge in northern Nigeria. Hydrogeol J 10(1):205–215

Eugster HP, Maglione G (1979) Brines and evaporates of the Lake Chad basin, Africa. Geochim Cosmochim Acta 43:973–981

Fantong WY, Satake H, Ayonghe SN, Suh EC, Adelana SMA, Fantong EBS, Banseka HS, Gwanfogbe CD, Woincham LN, Uehara Y, Zhang J (2010) Geochemical provenance and spatial distribution of fluoride in groundwater of Mayo Tsanaga River Basin, Far North Region, Cameroon: implications for incidence of fluorosis and optimal consumption dose. Environ Geochem Health 32:147–163. https://doi.org/10.1007/s10653-009-9271-4

Favreau G, Leduc C, Marlin C, Dray M, Taupin J-D, Massault M, Le Gall La Salle C, Babic M (2002) Estimate of recharge of a rising water table in semiarid Niger from ^{3}H and ^{14}C modeling. Ground Water 40(2):144–151

Florea L, Bird B, Lau JK, Wang L, Lei Y, Yao T, Thompson LG (2017) Stable isotopes of river and groundwater along altitudinal gradients in the High Himalayas and the Eastern Nyainqetanghla Mountains. J Hydrol: Region Stud 14:37–48. https://doi.org/10.1016/j.ejrh.2017.10.003

Fritz P, Fontes JCh (1980) Handbook of environmental isotope geochemistry, vol 1: the terrestrial environment, A. Elsevier, Amsterdam, The Netherlands, 545 pp

Gaj M, Beyer M, Koeniger P, Wanke H, Hamutoko J, Himmelsbach T (2016) In situ unsaturated zone water stable isotope (^{2}H and ^{18}O) measurements in semi-arid environments: a soil water balance. Hydrol Earth Syst Sci 20(2):715–731

Gaye CB, Edmunds WM (1996) Groundwater recharge estimation using chloride, stable isotopes and tritium profiles in the sands of northwestern Senegal. Environ Geol 27:246–251

Geerken R, Vassolo S, Bila M (2011) Impacts of climate variability and population pressure on water resources in the Lake Chad Basin. BRG, Berlin

Genthon P, Hector B, Luxereau A, Descloitres M, Abdou H, Hinderer J, Bakalowicz M (2015) Groundwater recharge by Sahelian rivers: consequences for agricultural development—example from the lower Komadugu Yobe River (eastern Niger, Lake Chad Basin). Environ Earth Sci 74:1291–1302

Goes BJM, Zabudum AN (1999) Hydrology of the Hadejia-Jama'are-Yobe River Basin: 1996-1997. Hadejia-Nguru Wetlands Conservation Project, Nigeria, IUCN, Gland

Goni I, Travi Y, Edmunds WM (2005) Estimating groundwater recharge from modelling unsaturated zone chloride profiles in the Nigerian sector of the Chad Basin. J Min Geol 41(1):123–130. https://doi.org/10.4314/jmg.v41i1.18836

Goni IB, Sheriff BM, Kolo AM, Ibrahim MB (2019) Assessment of nitrate concentrations in the shallow groundwater aquifer of Maiduguri and environs, northeastern Nigeria. Sci African 4. https://doi.org/10.1016/j.sciaf.2019.e00089

Goni IB, Taylor RG, Favreau G, Shamsudduha M, Nazoumou Y, Ngouno Ngatcha B (2021) Groundwater recharge from heavy rainfall in the southwestern Lake Chad Basin: evidence from isotopic observations. Hydrol Sci J 66(8):1359–1371. https://doi.org/10.1080/02626667.2021.1937630

Hall NMJ, Peyrillé P (2006) Dynamics of the West African Monsoon. J Phys IV 139:81–99. https://doi.org/10.1051/jp4:2006139007

Huneau F (2017) Lake Chad Basin. In: Integrated and sustainable management of shared aquifer systems and basins of the Sahel region. Report of the IAEA-supported regional technical cooperation project RAF/7/011. https://www.iaea.org/sites/default/files/raf7011_lake_chad_basin.pdf. Accessed August 2023

Isiorho SA, Matisoff G, When KS (1996) Seepage relationships between Lake Chad and the Chad aquifers. Ground Water 34(5):819–826

Lang J, Kogbe C, Alidou S, Alzouma KA, Bellion G, Dubois D, Durnad A, Guiraud R, Houessou A, de Klasz I, Romann E, Salard-Cheboldaeff M, Trichet J (1990) The Continental Terminal in West Africa. J African Earth Sci 10(1/2):79–99

LCBC (2016) Report on the state of the Lake Chad Basin ecosystem. Lake Chad Basin Commission/Gesellschaft für internationale Zusammenarbeit, Bonn, Germany

Leblanc M (1997) Modélisation numérique de la nappe quaternaire du Manga (Niger sud-oriental) [Numerical modeling of the Manga Quaternary aquifer (south-eastern Niger)]. Mémoire Hydrogéologie et Environment, Université d'Avignon et des Pays du Vaucluse et ORSTOM de Montpelier, France, 87 pp

Leblanc M, Razack M, Dagorne D, Mofor L, Jones C (2003) Application of Meteosat thermal data to map soil infiltrability in the central part of the Lake Chad basin, Africa. Geophys Res Lett 30(19):1998. https://doi.org/10.1029/2003GL018094

Leblanc M, Favreau G, Tweed S, Leduc C, Razack M, Mofor L (2007) Remote sensing for groundwater modelling in large semiarid areas: Lake Chad Basin, Africa. Hydrogeol J 15(1):97–100. https://doi.org/10.1007/s10040-006-0126-0

Leduc C, Sabljak S, Taupin J-D, Marlin C, Favreau G (2000) Estimation de la recharge de la nappe quaternaire dans le Nord-Ouest du bassin du lac Tchad (Niger oriental) à partir de mesures isotopiques [Estimation of the recharge to the Quaternary aquifer in the north-east of the Lake Chad basin (eastern Niger) based on isotopic measurements]. Earth Planet Sci 330:355–361

Lemoalle J, Bader J-C, Leblanc M, Sedick A (2012) Recent changes in Lake Chad: observations, simulations and management options (1973–2011). Glob Planet Change 80–81:247–254. https://doi.org/10.1016/j.gloplacha.2011.07.004

Mahamat Nour A (2019) Fonctionnement hydrologique, chimique et isotopique du principal affluent du lac Tchad: le système Chari-Logone [Hydrological, chemical, and isotopic functioning of the main tributary to the Lake Chad: the Chari-Logone system). PhD Thesis, Aix–Marseille Université, Marseille, France

Mahamat Nour A, Huneau F, Mahamat Ali A, Mahamat Saleh H, Ngo Boum-Nkot S, Nlend B, Djebebe-Ndjiguim CL, Foto E, Sanoussi R, Araguas-Araguas L, Vystavna Y (2022) Shallow Quaternary groundwater in the Lake Chad basin is resilient to climate change but requires sustainable management strategy: results of isotopic investigation. Sci Total Environ 851:158152. https://doi.org/10.1016/j.scitotenv.2022.158152

Massuel S (2001) Modélisation hydrodynamique de la nappe phréatique quaternaire du bassin du lac Tchad [Hydrodynamic modeling of the Quaternary aquifer in the Lake Chad Basin]. Thesis, l'Université de Montpellier II et à l'Université d'Avignon, France

Miller RE, Johnston RH, Olowu JAI, Uzoma JU (1968) Ground-water hydrology of the Chad Basin in Bornu and Dikwa Emirates, northeastern Nigeria, with special emphasis on the flow life of the artesian system. Geological Survey Water-Supply Paper 1757-I, Geological Survey of Nigeria, Abuja, Nigeria, and USAID, Washington, DC

Mohan C, Western AW, Wei Y, Saft M (2018) Predicting groundwater recharge for varying land cover and climatic conditions: a global meta-data study. Hydrol Earth Syst Sci 22:2689–2703. https://doi.org/10.5194/hess-22-2689-2018

Moussa A, Moussa I, Abderamane H, Schuster M, Mackaye HT, Andossa L, Ahounta D, Duringer P, Vignaud P (2013) Synthèse des dépôts sédimentaires continentaux d'âge Miocène et Pliocène du bassin du Lac Tchad: proposition de nouvelles coupes géologiques à travers le bassin [Synthesis of continental sedimentary deposits of Miocene and Pliocene age in the Lake Chad basin: proposal of new geological cross-sections across the basin]. Rev Sci Tchad Dec. volume:22–33

Ndubuisi OL (2007) Assessment of groundwater recharge in semi-arid region of northern-Nigeria: using soil moisture deficit method. J Eng Appl Sci 2(9):1377–1382

Neukum C, Rieckh H, Ndedje-Allah Ronelngar M, Daira D (2017) Groundwater chemistry and quality of the northern Lake Chad region, Republic of Chad. Report no. 11. BGR/CBLT, N'Djamena, Chad

Ngounou Ngatcha B, Daïra D (2010) Nitrate pollution in groundwater in two selected areas from Cameroon and Chad in the Lake Chad basin. Water Policy 12(5):722-733. https://doi.org/10.2166/wp.2010.017

Ngounou Ngatcha B, Mudry J, Sarrot RJ (2007) Groundwater recharge from rainfall in the southern border of Lake Chad in Cameroon. World Appl Sci J 2(2):125–131

Njitchoua R, Fontes C, Zuppi GM, Aranyossy JF, Naah E (1995) Use of chemical and isotopic tracers in studying recharge processes of the upper Cretaceous aquifer of Garoua basin, northern Cameroon. Application of Tracers in Arid Zone Hydrology, IAHS Publ. no. 232, IAHS, Wallingford, England

Nkiaka E, Nawaz NR, Lovett JC (2018) Effect of single and multi-site calibration techniques on hydrological model performance, parameter estimation and predictive uncertainty: a case study in the Logone catchment. Stoch Environ Res Risk Assess 32:1665–1682

Olivry J-C, Chouret A, Vuillaume G, Lemoalle J, Bricquet J-P (1996) Hydrologie du lac Tchad [Hydrology of the Lake Chad]. Monographie hydrologique 12, ORSTOM, Paris

Peel MC, Finlayson BL, McMahon TA (2007) Updated world map of the Köppen-Geiger climate classification. Hydrol Earth Syst Sci 11:1633–1644

Richey AS, Thomas BF, Lo MH, Famiglietti JS, Swenson S, Rodell M (2015a) Uncertainty in global groundwater storage estimates in a total groundwater stress framework. Water Resour Res 51:5198–5216. https://doi.org/10.1002/2015WR017351

Richey AS, Thomas BF, Lo MH, Reager JT, Famiglietti JS, Voss K, Swenson S, Rodell M (2015b) Quantifying renewable groundwater stress with GRACE. Water Resour Res 51:5217–5238

Rizzo J (2015) A shrinking lake and a rising insurgency. In: The State of Environmental Migration 2015: a review of 2014. The Hugo Observatory, Université de Liège, Liège, The Netherlands, pp 13–29

Scanlon BR, Keese KE, Flint AL, Flint LE, Gaye CB, Edmunds MW, Simmers I (2006) Global synthesis of groundwater recharge in semiarid and arid regions. Hydrol Process 20:3335–3370

Schneider JL, Wolff JP (1992) Carte géologique et cartes hydrogéologiques de la République du Tchad [Geological and hydrogeological maps of the Republic of Chad]. Mémoire explicatif, vol 2. Document no. 209, BRGM, Orleans, France

Tewolde DO, Koeniger P, Beyer M, Neukum C, Groeschke M, Ronelngar M, Rieckh H, Vassolo S (2019) Soil water balance in the Lake Chad Basin using stable isotopes and chloride of soil profiles. Isotopes Environ Health Stud. https://doi.org/10.1080/10256016.2019.1647194

UNESCO (1969) Study of water resources in the Chad basin. Technical Report. UNESCO/UNDP Special Fund Project. Serial no. 1600/BMS.RD/SCE, UNESCO, Paris, 165 pp

Vaquero G, Siavashani NS, García-Martínez D, Elorza FJ, Bila M, Candela L, Serrat-Capdevilla A (2021) The Lake Chad transboundary aquifer: estimation of groundwater fluxes through international borders from regional numerical modelling. J Hydrol: Reg Stud 38:100935

Vassolo S, Daïra D (2012) Lake Chad: sustainable water management. Report no. 4. BGR, Berlin

White F (1983) The vegetation of Africa. ORSTOM/UNESCO. https://doi.org/10.5281/zenodo.293797. Accessed August 2023

WHO (2022) Guidelines for drinking-water quality: fourth edition incorporation the first and second addenda. World Health Organisation. (electronic version)

Zagana E, Obeidat M, Kuells C, Udluft P (2007a) Chloride, hydrochemical and isotope methods of groundwater recharge estimation in eastern Mediterranean areas: a case study in Jordan. Hydrol Process 21:2112–2123

Zagana E, Kuells C, Udluft P, Constantinou C (2007b) Methods of groundwater recharge estimation in eastern Mediterranean: a water balance model application in Greece, Cyprus and Jordan. Hydrol Process 21:2405–2414. https://doi.org/10.1002/hyp.6392

Zairi R (2008) Étude géochimique et hydrodynamique de la nappe libre du bassin du Lac Tchad dans les régions de Diffa (Niger oriental) et du Bournou (nord-est du Nigéria) [Geochemical and hydrodynamic study of the unconfined aquifer in the Lake Chad basin for the regions Diffa (eastern Niger) and Bournou (north-eastern Nigeria)]. Thesis, Université Montpellier II, France

Zhou T, Šimůnek J, Braud I (2021) Adapting HYDRUS 1D to simulate transport of soil water isotopes with evaporation fractionation. Environ Modell Software 143. https://doi.org/10.1016/j.envsoft.2021.105118