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Groundwater recharge from heavy rainfall in the southwestern Lake Chad Basin: evidence from isotopic observations

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ABSTRACT
We examine groundwater recharge processes and their relationship to rainfall intensity in the semi-arid, southwestern Lake Chad Basin of Nigeria using a newly compiled database of stable isotope data (δ^2H, δ^{18}O) from groundwater and rainfall. δ^{18}O signatures in groundwater proximate to surface waters are enriched in ^{18}O relative to regional rainfall and trace focused groundwater recharge from evaporated waters via ephemeral river discharge and Lake Chad; groundwater remote from river channels is comparatively depleted and associated with diffuse recharge, often via sand dunes. Stable isotope ratios of O and H (δ^2H, δ^{18}O) in groundwater samples regress to a value along the local meteoric waterline that is depleted relative to weighted mean composition of rainfall, consistent with rainfall exceeding the 60th percentile of monthly precipitation intensity. The observed bias in groundwater recharge to heavy monthly rainfall suggests that the intensification of tropical rainfall under global warming favours groundwater recharge in this basin.

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1 Introduction

In tropical drylands where river flow is often episodic or seasonal, groundwater is commonly the only perennial source of freshwater sustaining vital ecosystems (Leblanc *et al.* 2006) and freshwater withdrawals for agricultural, domestic and industrial uses (Taylor *et al.* 2013a). In the semi-arid region of the Sahel in West Africa, for example, groundwater withdrawals are rising and projected to increase substantially over the next few decades as nations expand irrigated agriculture and access to safe water in pursuit of the United Nations (UN)'s Sustainable Development Goals 2 and 6 (e.g. World Bank 2017, Commission Climat pour la Région du Sahel (CCRS) 2018). The sustainability of such groundwater use is in question. Substantial increases in freshwater withdrawals associated with the expansion of irrigated agriculture in drylands (i.e. sub-humid to hyper-arid environments) have led to groundwater depletion not only in Africa (e.g. Leduc *et al.* 2007) but also globally (e.g. Wada *et al.* 2010, Konikow 2011, de Graaf *et al.* 2017).

1.1 Renewability of groundwater in tropical drylands under global change

Current understanding of the renewability of groundwater in tropical drylands is limited. Groundwater recharge and its relationship to rainfall commonly relies on evidence from large-scale models (e.g. Altchenko and Villholth 2015) or environmental tracers (e.g. Edmunds *et al.* 2002, Huneau *et al.* 2011) due to a dearth of in situ observations (e.g. piezometry). Representation of recharge processes in such large-scale models (e.g. Wada *et al.* 2012, Hanasaki *et al.* 2018) is commonly restricted to the direct infiltration of precipitation (i.e. diffuse recharge), and neglects focused groundwater recharge that occurs via seepage from surface drainage that includes lake and rivers as well as ephemeral ponds and stream discharges. The latter has, however, been shown to contribute substantially to groundwater replenishment in drylands (e.g. Scanlon *et al.* 2006, Dahan *et al.* 2008, Favreau *et al.* 2009, Villeneuve *et al.* 2015, Cuthbert *et al.* 2019, Acworth *et al.* 2021). Evidence from the few long-term piezometric observations that have been made in tropical semi-arid Africa also suggests that groundwater recharge, whether focused or diffuse, is strongly influenced by climate variability (e.g. Taylor *et al.* 2013b, Cuthbert *et al.* 2019, Kolusu *et al.* 2019) and land-use change (e.g. Favreau *et al.* 2009, Le Coz *et al.* 2013, Ibrahim *et al.* 2014).

Substantial uncertainty exists regarding the renewability of groundwater in tropical drylands under climate change. A key conclusion of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, Collins *et al.* 2013) – that global changes in precipitation (P) minus evapotranspiration (E) patterns ($P - E$) in response to anthropogenic warming can be described as "wet gets wetter,

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Supplemental data for this article can be accessed here.

dry gets drier," – has since been shown to be too simplistic (e.g. Byrne and O'Gorman 2015). $P - E$ responses to warming on land are smaller, less well understood, and complicated by the uncertain impact of the intensification of precipitation on terrestrial water budgets (Short Gianotti *et al.* 2020, Zhou *et al.* 2021). Understanding hydrological responses to climate change is especially challenging in large endorheic basins in Africa with a complex hydrology that varies from humid uplands to dryland termini; these include the Lake Chad Basin (LCB) as well as the Rivers Awash (Kebede *et al.* 2021) and Okavango (Wolski *et al.* 2014) basins. Historically, the LCB has responded to changes in climate at the global scale. Late Pleistocene deglaciation, for example, led to the emergence of a humid period during the mid-Holocene (~5 ka) when the level of Lake Chad reached its zenith (Armitage *et al.* 2015, IAEA (International Atomic Energy Agency) 2017, Pham-Duc *et al.* 2020). The intensification of tropical rainfall leading to fewer but heavier rainfall events is one clear climate change signal that has been observed both globally (e.g. Allan *et al.* 2010, Fischer and Knutti 2016) and in the Sahel (Taylor *et al.* 2017).

1.2 Groundwater recharge in the southwestern LCB

Shallow (<100 m below ground level, mbgl) groundwater within Quaternary sands of the southwestern (SW) LCB extends over southeastern Niger, northeastern Nigeria, northern Cameroon and Chad (Fig. 1). For decades, this shared transboundary aquifer has provided an invaluable, distributed source of freshwater for domestic and agropastoral purposes (Carter and Alkali 1996, Ngounou Ngatcha *et al.* 2005, IAEA 2017). Declining groundwater levels, observed in deep (>200 mbgl) confined aquifers (Ndubisi 1990, Edmunds *et al.* 1999, Goni *et al.* 2000, Maduabuchi 2005, Bouchez *et al.* 2015), have raised concerns about the sustainability of groundwater withdrawals, including those from the upper, most accessible horizon in the Chad Group of Quaternary sands (Fig. 2). The renewability of shallow groundwater in the SW LCB has long

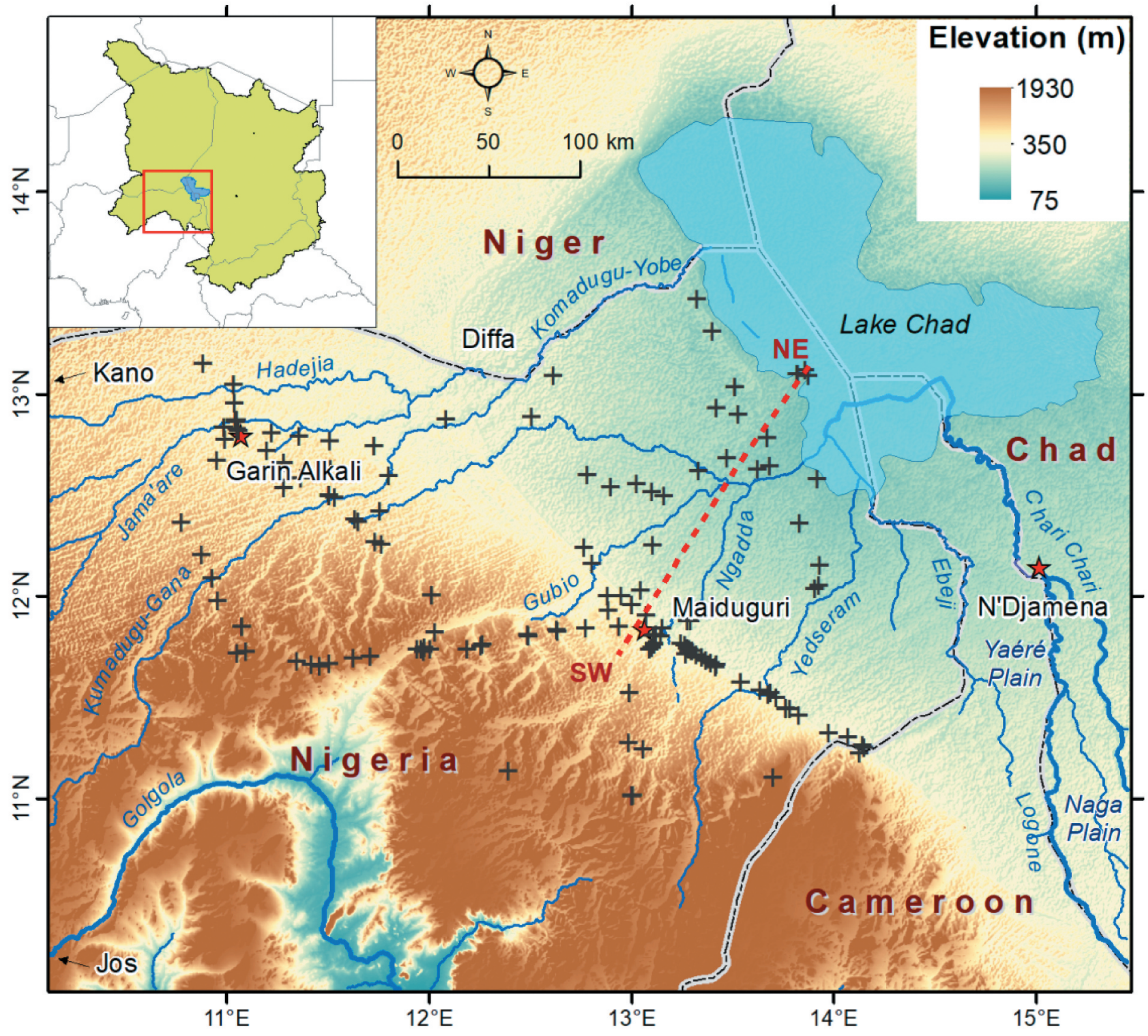

Figure 1. Map of the SW (southwestern) Chad Basin showing groundwater sampled sites and rainfall monitoring stations at Maiduguri and N'Djamena; inset map situates the Lake Chad Basin within the African continent; red dashed line roughly demarcates the geological cross-section of Fig. 2.

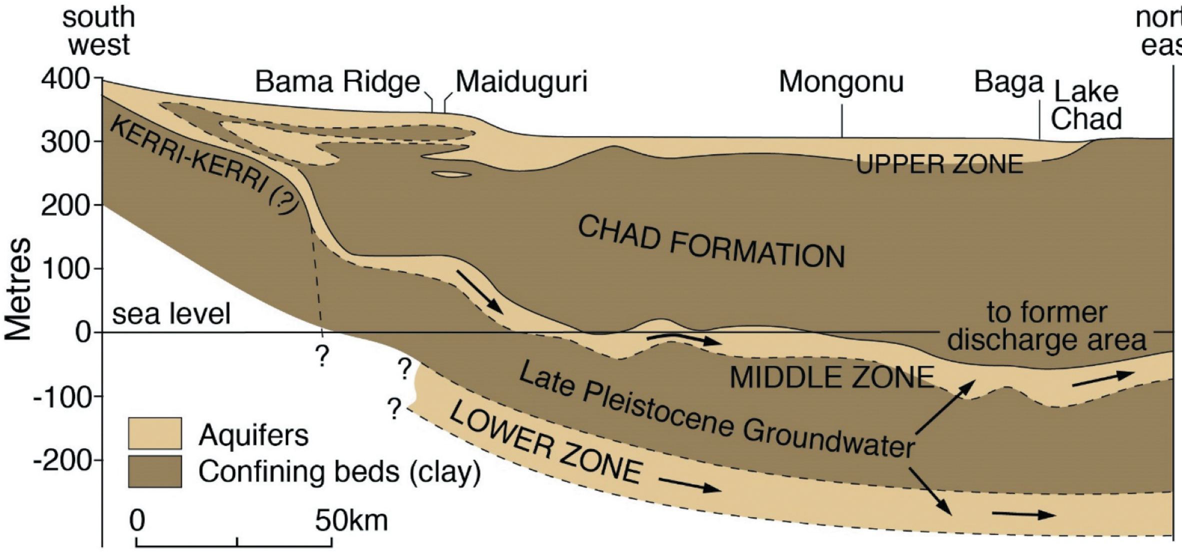

Figure 2. Geologic cross-section through the Chad Formation along a transect shown in Fig. 1, showing the three (Upper, Middle and Lower) primary aquifers in the SW Chad Basin (adapted from Goni (2006) and Miller (1968)).

been a focus of study (e.g. IWACO 1985, Carter 1994, Carter and Alkali 1996, Goes 1999, Edmunds *et al.* 2002, Goni 2006). Several studies (Carter 1994, Carter and Alkali 1996, Edmunds *et al.* 2002) showed groundwater-level rises in response to seasonal rainfall, and favourable comparisons between stable isotope ratios in modern rainfall and groundwater; each concluded that recharge is modern and, in places, diffuse. These studies challenged prevailing assumptions that high evapotranspiration and low rainfall in this semi-arid region prevented modern direct recharge (e.g. IWACO 1985). In sand dunes north of the Komadugu Yobe Basin (Fig. 1), Carter (1994) observed a mean annual water-table variation of 0.13 m in 11 piezometers during a 1-year period and estimated a mean spatial recharge rate of 49 mm. Edmunds *et al.* (2002) used a chloride mass-balance (CMB) method to derive similar mean recharge rates ranging from 14 to 49 mm·a^{-1} through the unsaturated zone of sand dunes in the same area.

The possibility of focused recharge in the SW LCB via leakage from ephemeral river flow was proposed by IWACO (1985) who roughly estimated lateral groundwater recharge along the entire length (286 km) of the River Yobe between Gashua and Lake Chad to be 17 × 10^6 m^3 per year. The simplicity of this assessment was subsequently challenged by Carter and Alkali (1996) who identified clay layers beneath the River Yobe floodplain inhibiting focused recharge near Gashua (Fig. 1). They noted further that (1) seasonal river flow can induce piezometric responses in the shallow confined aquifers that derive from compression (i.e. poroelastic response) and not, ostensibly, flow; and (2) sandy "windows" can occur locally through which focus recharge may take place. Downstream of the River Komadugu Yobe ~100 km from Lake Chad (Fig. 1), Descloitres *et al.* (2013) present regional-scale contours of hydraulic head in the shallow, permeable sand aquifer that confirm previous analyses (e.g. Miller 1968, Lake Chad Basin Commission (LCBC) 1973) of a steady decline in groundwater levels laterally away from the river channel, suggesting focused recharge via seepage from the river.

Evidence of both diffuse and focused recharge processes in the SW LCB has similarly been found in the lower Logone-Chari catchment in Cameroon (Ngounou Ngatcha *et al.* 2005, Bouchez *et al.* 2019). Adjacent to the lower reaches of the River Logone south of N'Djamena (Fig. 1), Vassolo *et al.* (2016) observe diffuse recharge in the Yaéré Plain, whereas focused recharge via floodwater inundations is thought to dominate in the Naga Plain, as is further suggested from geophysical and piezometric evidence near ephemeral streams at the border of the LCB in northern Cameroon (Kemgang *et al.* 2019). Focused recharge via seepage from Lake Chad and local ponds as well as perennial (Logone-Chari) and ephemeral (Komadugu Yobe) rivers is also indicated from measurements by Isiorho *et al.* (1996) and Leduc *et al.* (2000).

1.3 Study significance and aims

Current understanding of the impact of climate change on groundwater resources is limited in the SW LCB of Nigeria, where dependence on groundwater for the provision of domestic water supplies, livestock watering, and irrigation is substantial. A conspicuous dearth of long-term piezometric observations constrains investigation of the relationships between rainfall and recharge. Further, knowledge of recharge processes is restricted to local-scale studies. Here, we address both knowledge gaps through an examination of accumulated evidence from past studies analysing stable isotope ratios of O (^{18}O:^{16}O) and H (^{2}H:^{1}H) in groundwater and rainfall (e.g. LCBC 1973; Isiorho *et al.* 1996; Maduabuchi 2005; Goni 2006; Zairi 2008). Our examination of stable isotope tracers employs (1) the empirical "amount effect" (e.g. Jasechko 2019) to explore the effect of an observed impact of the intensification of rainfall under climate change; and (2) disequilibrium isotope effects from evaporation to infer recharge processes regionally across the SW LCB. For the latter, diffuse recharge through mainly aeolian sand dunes is expected to involve proportionately less evaporative enrichment relative to focused recharge that is derived from ephemeral or perennial river or lake waters.

2 Study area

2.1 Regional climatology and isotope hydrology

The LCB is the largest endorheic basin in Africa, with an area of 2 381 635 km^2 (IAEA 2017) that extends from the humid tropics of the Central Africa Republic at a latitude of 5°N to the hyper-arid sub-tropics of southeastern Algeria (Fig. 1, inset). The level of Lake Chad (basin terminus) has been subject to dramatic hydrological changes that have occurred over its basin area since the Late Pleistocene, when the lake disappeared during an arid phase in the tropics associated with the Last Glacial Maximum (~20 ka) (Williams 1975, Gasse 2000). The return of humid conditions following Late Pleistocene deglaciation created high lakestands (i.e. Lake Mega-Chad), which persisted through the Holocene to ~5 ka (Armitage *et al.* 2015, IAEA 2017). The level of Lake Chad has since largely declined with the increasing aridity in the northern part of the basin; fluctuations in lake levels have arisen primarily from variations in the lake's principal water supply from the River Logone-Chari (IAEA 2017; Pham-Duc *et al.* 2020). In the SW LCB during the 20th century, the Sahelian drought was marked by a 40% reduction in rainfall recorded at stations in Nigeria (Maiduguri 1915–1994; N'Guru: 1942–1988; and Potiskum: 1936–1990), similar to that observed at N'Djamena (Niel *et al.* 2005). Since 2000, there is evidence that the trend in the seasonally oscillating lake levels has stabilized (Pham-Duc *et al.* 2020).

The distribution in rainfall over west Africa and the SW LCB (Fig. 1) is controlled primarily by the African easterly jet and the Tropical easterly jet (Nicholson 2018). The latitude of the zone of maximum rainfall during northern hemisphere summer (June to September) changes both seasonally and from year to year (Grist and Nicholson 2001); dry-season rainfall (December to February) is negligible. The stable isotope composition of rainfall in the Sahel region is extremely variable, spatially and temporally, as a consequence of these atmospheric circulation patterns (Taupin *et al.* 2000, Tremoy *et al.* 2014). The source of precipitation for the Sahara-Sahel, including the SW LCB, is the Gulf of Guinea (Taupin *et al.* 2000). Re-evaporated water from land surfaces is nevertheless an important source of water vapour, as shown by the lack of continental effect and also a large deuterium excess at the beginning and the end of the rainy season (Taupin *et al.* 2000). The altitude effect, wherein precipitation falling at higher elevations becomes progressively depleted in heavy isotopes (^{18}O, ^{2}H) through Rayleigh distillation, can influence the stable isotope precipitation, especially in areas of high relief (Gonfiantini *et al.* 2001). As highlighted above, the amount of rainfall in a storm event also strongly influences stable isotope ratios in the tropics, as high-intensity rainfall is depleted in ^{18}O and ^{2}H relative to low-intensity rainfall (Jasechko and Taylor 2015, Jasechko 2019).

2.2 Hydrological setting

Surface drainage in the SW LCB is mostly ephemeral, with the exception of Rivers Komadugu Yobe and Ebeji (El-Beid) that drain directly into Lake Chad from the west and south, respectively (Fig. 1). Comparatively higher, seasonal rainfall occurs in headwater areas to the south and southwest of the SW Chad Basin, where the underlying geology is dominated by deeply weathered crystalline rocks (see Supplementary material, Fig. S1). The low permeability of lateritic residua of Fe and Al and accumulated clays (e.g. kaolinite) in saprolite in these areas can promote runoff generation supplying river discharges. The fleeting nature of these flows arises not only from seasonality in rainfall and high potential evapotranspiration but is also thought to result from leakage to the subsurface as these flows cross into the more permeable surface soils of the Chad Formation (Goes 1999). Drainage to the north of the SW Chad Basin is dominated by Rivers Hadejia and Jama'are, which combine downstream to form River Komadugu Yobe, which itself joins the River Komadugu Gana before discharging to Lake Chad (Fig. 1). To the south, Rivers Yedseram, Ngadda and Gubio drain in a northeastern direction whereas River Ebeji (El-Beid) forms part of the border between Nigeria and Cameroon (Fig. 1).

2.3 Geological setting

The LCB has been a structural depression since the early Cretaceous (Genik 1992), providing a locus of subsidence and sedimentation rather than erosion. The SW LCB to the west of Lake Chad (Fig. 1) occupies ~155 400 km^2 of northeastern Nigeria (Du Preez and Barber 1965) and is underlain by the Quaternary Chad Formation, the Tertiary Kerri-Kerri Formation, Cretaceous sedimentary rocks and crystalline basement complex rocks. Although all the arenaceous layers of formations in the basin are potential aquifers, the youngest of the sequences (the Chad Formation) contains the principal identified aquifers in the SW LCB (Fig. 2). This formation was deposited in or near ancestral Lake Chad during the late Tertiary and Quaternary, on an uneven surface. The Chad Formation dips gently east and northeast towards Lake Chad in conformity with the slope of the land surface. Except for a belt of alluvial deposits around the edge of the basin, the formation is of mainly lacustrine origin and consists of thick beds of clay intercalated with irregular beds of sand, silt, and sandy clay (Barber 1965, Miller 1968).

2.4 Hydrogeology

The Plio–Pleistocene Chad Formation and the younger overlying Quaternary sediments are the main source of groundwater in the study area. The Chad Formation is essentially an argillaceous sequence in which minor arenaceous horizons occur (Barber 1965), and the formation shows considerable lateral and vertical variability in lithology. Barber and Jones (1960) named three clearly defined arenaceous horizons of the Chad Formation as the Upper, Middle and Lower Zone aquifers (Fig. 2). The Lower and Middle Zones are confined, whereas the Upper Zone, of interest in the present paper, is mostly unconfined but locally semi-confined in places.

Upper Zone sands forming the Quaternary Aquifer (QA) are considered to be lake-margin, alluvial-fan or deltaic sediments related to sedimentation in and around Lake Chad, which has varied considerably in size throughout the

Quaternary (Durand 1995, Goes 1999). Clays are mainly lake deposits laid down under non-turbulent conditions and are most extensive near to the present-day lakeshore. Lithological logs from the area are highly variable. Around Maiduguri, the QA includes not only a surface zone of recent sands with an unconfined water table but also deeper sand layers of the Chad Formation that are complexly intercalated between clays and partially confined by the clays (Fig. 2). Beacon Services Ltd. – Consulint International S.r.l. (1979) further subdivided the Upper aquifer system into three zones in northeast Nigeria: an unconfined aquifer (A zone) and underlying B and C zones which are semi-confined or confined. Mean hydrogeological properties estimated by geophysics (TDEM: Time Domain Electromagnetic, MRS: Magnetic Resonance Sounding) of the upper A zone reported by Descloitres *et al.* (2013) suggest a transmissivity of ~6 × 10^3 m^2/day and a total porosity of between 20 and 25% in the Komadugu Yobe valley, whereas a flux rate of 1 × 10^3 m/day is estimated from hydrodynamic and chemical experiments (Isiorho *et al.* 1996) conducted near the Lake Chad shoreline.

3 Methodology

Stable isotope ratios of O (^{18}O:^{16}O) and H (^{2}H:^{1}H) in groundwater, surface waters, and rainfall are used to investigate relationships between rainfall and recharge and to trace recharge processes. The local meteoric water line at Maiduguri station (Table 1) was constructed from 28 samples of rainfall collected from raingauges by the local meteorological observer on a storm-event basis throughout the rainy season of 2001. Rainfall amount was measured at the end of each event, when samples were immediately stored in sealed Nalgene® bottles with minimum headspace to minimize evaporation. Stable isotope ratios of O and H in rainfall were also drawn from monthly samples following the IAEA/GNIP (2014) protocol at International Atomic Energy Agency (IAEA) stations in N'Djamena and Kano, and daily samples at Garin Alkali (Table 1). Weighted mean compositions of stable isotope ratios in rainfalls were computed by weighting the contribution of each sample to the mean composition by the relative amount of the rainfall (daily or monthly) to the total of all rainfall samples.

Groundwater samples (145) were filtered through a membrane of 0.45 µm or finer and stored in polythene bottles; specific sampling details are given in each of LCBC (1973), Isiorho *et al.* (1996), Goni (2006), and Zairi (2008), respectively. Analyses were primarily carried out on a VG 602E mass spectrometer following standard preparation techniques, namely the reaction of 10 µL water with heated zinc shot for ^{2}H:^{1}H and equilibration of 5 mL water with CO_2 of known isotopic composition for ^{18}O:^{16}O (Epstein and Mayeda 1953, Coleman *et al.* 1982). Stable isotope ratios are reported as per mille differences from Vienna- standard mean ocean water (SMOW) for deuterium (δ^{2}H) and oxygen-18 (δ^{18}O) with a precision of ± 2‰ and ± 0.2‰, respectively. A small subset of nine radiocarbon measurements, sampling and analytical details, given in LCBC (1973) and Zairi (2008), is used to identify modern- versus palaeo-groundwaters with depth in the Chad Formation. Values are expressed in percent modern carbon (pMC), which is a measurement of the deviation of the ^{14}C:^{12}C ratio of a sample from "modern," which is defined as 95% of the radiocarbon concentration (in AD 1950) of NBS (National Bureau of Standards) Oxalic Acid I (SRM (Standard Reference Material) 4990B, OX-I) normalized to $\delta^{13}C_{VPDB}$(Vienna Pee Dee Belemnite) = −19‰ (Olsson 1970). Major-ion hydrochemistry of a subset of groundwater locations sampled for stable isotope ratios was analysed using a Dionex DX-100 Ion Chromatograph at the Institute of Groundwater Ecology, GSF National Research Centre for Environment and Health, Neuherberg (Germany); only those samples (49) with a charge-balance error of less than 5% were employed.

4 Results

4.1 *Stable isotope ratios of O and H in rainwater*

Stable isotope ratios of O and H from 28 daily samples collected from individual daily rainfall events at Maiduguri Airport in 2001 regress along a local meteoric water line (LMWL) of $\delta^{2}H = (7.3 \pm 0.2)\cdot\delta^{18}O + 5.5 \pm 0.9‰$ (Fig. 3(a)). Weighted mean stable isotope compositions of rainfall sampled at Maiduguri (δ^{2}H = −19‰, δ^{18}O = −3.3‰) and N'Djamena (δ^{2}H = −19‰, δ^{18}O = −3.6‰) are very similar (Fig. 3(b), Table 1); the smaller (N = 20), discontinuous dataset of more recent (2015–2018) data from N'Djamena reveals weighted mean values (δ^{2}H = −21‰, δ^{18}O = −3.8‰) that are marginally more depleted in the heavy isotope and associated with a sampling bias to heavier mean monthly rainfall (111 mm) relative to the larger (N = 73), earlier (1964–1995) dataset (86 mm). Limited monthly records (33) from Kano (1961 to 1973) and daily data (21) from Garin Alkali in western areas of the Komadugu Yobe Basin (Fig. 1) have a weighted mean stable isotope composition that is similar (δ^{2}H = −10‰,

Table 1. Time series records of stable isotope ratios of O and H in precipitation, local meteoric waterlines derived from linear regression, and weighted mean stable isotope compositions[a] of rainfall relative to Vienna-SMOW (Standard Mean Ocean Water) in the SW Chad Basin; data for IAEA station at N'Djamena (11°51.88'N, 13°13.25'E, elevation: 294 mamsl) and IAEA station at Kano (11°51.88'N, 13°13.25'E, elevation: 420 mamsl) derive from monthly samples, whereas data for Jos (9°58.00'N, 8°52.00'E, elevation: 1173 mamsl) are (mostly) taken every 2 weeks, and data for Maiduguri (11°51.88'N, 13°13.25'E, elevation: 332 mamsl) and Garin Alkali (12°49.52'N, 11°04.45'E, elevation: 328 mamsl) derive from daily samples. mamsl: metres above mean sea level. Uncertainty expressed in linear-regression equations for LMWLs is solely mathematical.

Station	N	Period	LMWL	r^2	$\delta^{18}O^a$ (‰)	$\delta^{2}H^a$ (‰)
Garin Alkali	21	1998	$\delta^{2}H = (6.3 \pm 0.4)\cdot\delta^{18}O + 9.9 \pm 1.6‰$	0.92	−3.6	−10
Kano	33	1961–1973	$\delta^{2}H = (7.1 \pm 0.4)\cdot\delta^{18}O + 4.4 \pm 1.7‰$	0.90	−4.0	−25
Maiduguri	21	2001	$\delta^{2}H = (7.3 \pm 0.2)\cdot\delta^{18}O + 5.5 \pm 0.9‰$	0.98	−3.3	−19
Jos	15	1988–1989			−4.3	
N'Djamena	73	1964–1995	$\delta^{2}H = (6.3 \pm 0.2)\cdot\delta^{18}O + 4.3 \pm 0.7‰$	0.95	−3.6	−19
N'Djamena	20	2015–2018	$\delta^{2}H = (6.8 \pm 0.2)\cdot\delta^{18}O + 5.6 \pm 1.1‰$	0.98	−3.8	−21

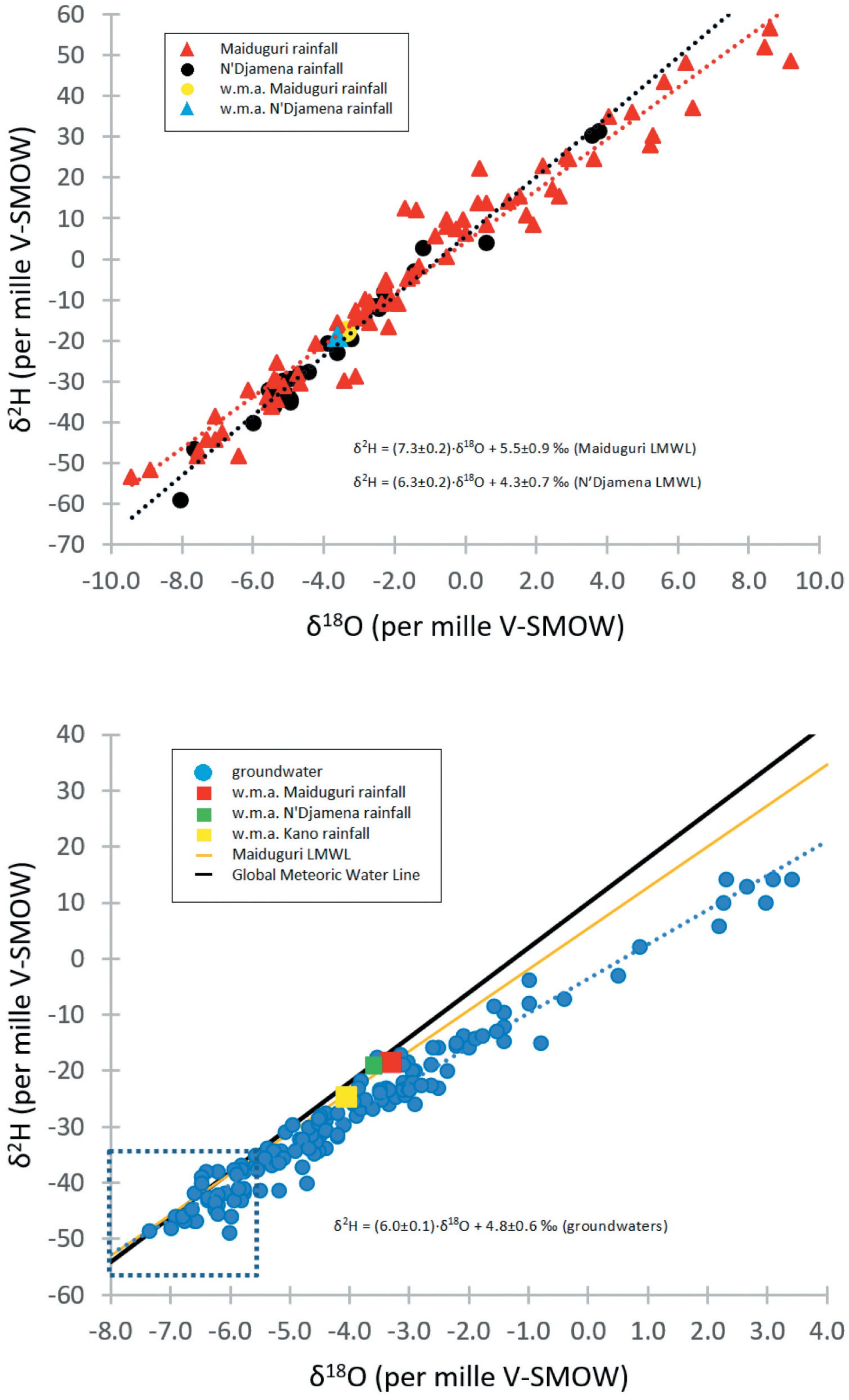

Figure 3. (a) Local meteoric water lines (LMWL) at Maiduguri (Nigeria) based on daily precipitation data collected in 2001, and at N'Djamena based on 73 monthly samples from 1964 to 1995; linear regression statistics and weighted mean compositions are also reported in Table 1; (b) stable isotope ratios of O and H for groundwaters in the SW Chad Basin plotted with respect to the global meteoric water line, Maiduguri LMWL and weighted mean stable isotope compositions at Maiduguri and IAEA stations at N'Djamena and Kano.

δ^{18}O = −3.6‰) and slightly more depleted in heavy isotopes (δ^2H = −25‰, δ^{18}O = −4.0‰) relative to observations at Maiduguri and N'Djamena (Fig. 3(b)); limited seasonal data (1988–1989) from different locations on the Jos Plateau on the southwest boundary of the LCB (Fig. 1) also show a range of weighted mean average compositions (δ^{18}O = −3.7 to 4.8‰) that are slightly depleted in their heavy isotopes (Mbonu and Travi 1994) (Table 1).

Collectively, these observations indicate that the influence of the altitude effect over the range in elevation (284 to 518 mamsl) of sampled groundwater (Fig. 1) is minimal, <0.3‰ for $\delta^{18}O$ (see Supplementary material, Fig. S2), and consistent with regional evaluations of the altitude effect (see e.g. eq. (9) in Gonfiantini *et al.* 2001). The largest and longest rainfall time series of $\delta^{18}O$ data in the Chad Basin at N'Djamena is plotted against progressively more intensive monthly rainfalls (i.e. higher percentile) in Fig. 4 following the approach of Jasechko and Taylor (2015). Consistent with evidence from 10 other IAEA stations across tropical Africa as well as the limited time series record at Kano (see Supplementary material, Fig. S3), the dataset for N'Djamena clearly demonstrates that the mean heavy isotope (^{18}O) content of monthly rainfall becomes progressively depleted (by 2‰) as observations are selected for more intensive (higher percentile) monthly rainfalls.

4.2 Stable isotope ratios of O and H in groundwater

In the SW LCB, stable isotope ratios of O and H in 145 groundwater samples (see Supplementary material, Table S1) drawn almost entirely from the QA (see Supplementary material, Fig. S1) reveal a wide range of values, from −7.4‰ to +3.4‰ ($\delta^{18}O$) and −49‰ to +14‰ ($\delta^{2}H$). Groundwater isotopic signatures regress along a non-equilibrium evaporation line (Fig. 3(b)): $\delta^{2}H = (6.0 \pm 0.1)\cdot\delta^{18}O - 4.8 \pm 0.6$ ($R^2 = 0.97$). This line intersects the LMWL at Maiduguri and the global meteoric water line (GMWL) at $\delta^{18}O = -7.9‰$ (−5.5 to −12‰) and −7.4‰ (−6.8 to −8.1‰), respectively; values in parentheses account for statistical uncertainty in linear regression (defined by the blue-dotted box in Fig. 3(b)). Both intersections are substantially more depleted in heavy isotopes (^{18}O, ^{2}H) than the weighted mean isotopic composition of rainfall observed regionally (Table 1). Radiocarbon data (Fig. 5) for groundwater sampled from shallow wells (<30 m bgl) remote from river channels range from 100 to 120 pMC; values exceeding 100 arise from the employed reference of 1950 (see Methodology). Groundwater sampled from depths deeper than 30 m bgl exhibit lower proportions of modern carbon, ranging from 79 to 98 pMC at depths of 35 to 55 m bgl, and 17 pMC at 85 m bgl.

Across the SW LCB, $\delta^{18}O$ values in groundwater that are depleted in ^{18}O relative to the weighted mean composition of rainfall ($\delta^{18}O \leq -4.3‰$; N = 75) are commonly although not exclusively observed in headwater areas. These depleted signatures in groundwater are remote from perennial and ephemeral surface waters (Fig. 6) and consistent with a deuterium excess of ≥ +5‰ and $\delta^{2}H \leq -30‰$ (see Supplementary material, Fig. S4). The $\delta^{18}O$ values in groundwater, which are enriched in the heavy isotope relative to the weighted mean composition of rainfall in the SW Chad Basin (≥ −3.2‰; N = 44) with a deuterium excess of ≤ +3‰, are more commonly observed proximate to perennial and ephemeral surface drainage including Lake Chad. $\delta^{18}O$ values between these two categories (−3.3 to −4.2‰; N = 26) show no clear bias in their geographical position within the SW LCB. $\delta^{18}O$ values from wells in which groundwater was sampled below a depth of 30 m bgl are consistently depleted (≤-4.3‰) in ^{18}O (Fig. 5). No obvious contrasts in observations are evident from stable isotope ratios recorded in groundwater sampled in 1967 and 1968 compared to more recent observations from 1991 to 2005 (see Supplementary material, Fig. S1). Available hydrochemical data (see Supplementary material, Table S2) do not permit an independent measure of evaporative influences on the stable isotope ratios of sampled groundwaters. The

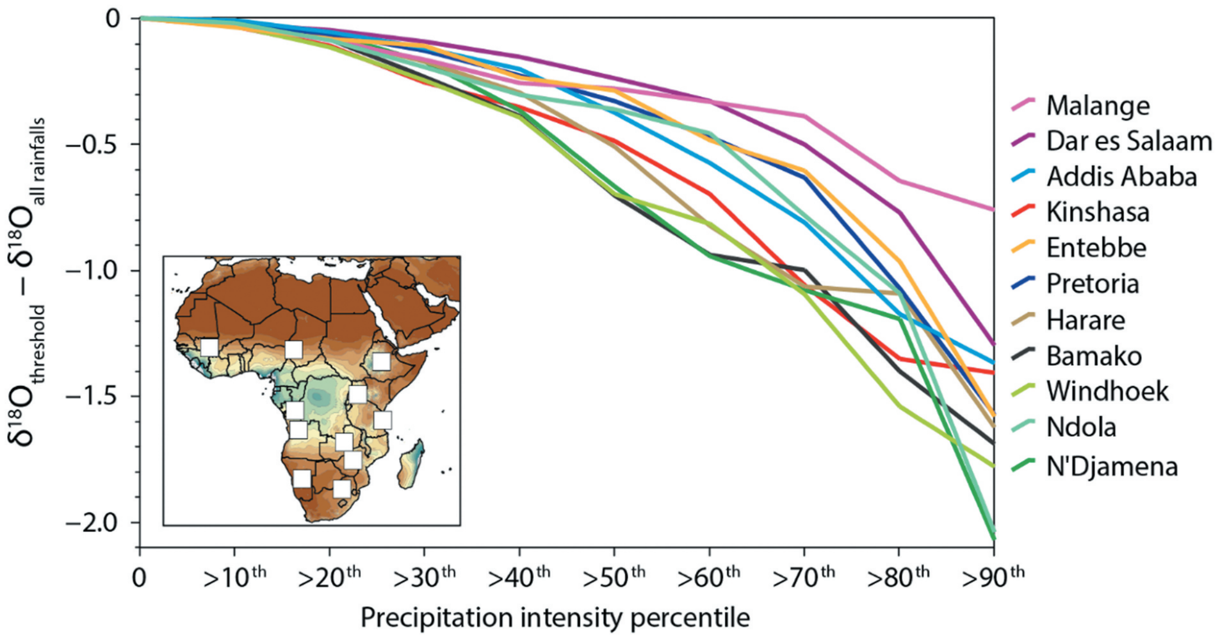

Figure 4. Long-term amount-weighted precipitation $\delta^{18}O$ versus precipitation exceeding intensity thresholds at 11 IAEA stations in tropical Africa including N'Djamena (N = 73); inset map of Africa shows the location of the 11 IAEA stations; "0" indicates weighted mean precipitation with progressive sampling of monthly rainfall exceeding intensity percentiles.

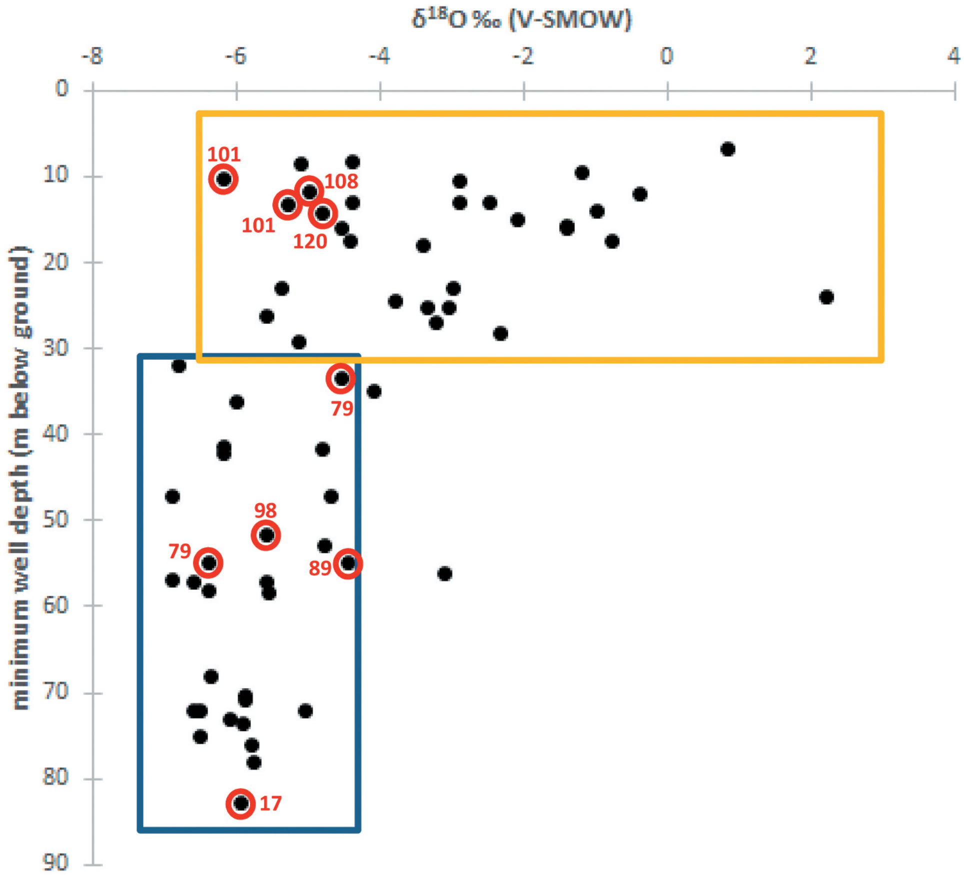

Figure 5. Cross-plot of $\delta^{18}O$ values in sampled groundwater in the SW Chad Basin versus minimum sample depth (i.e. static water levels in sampled wells without knowledge of absolute well or screen depths); observations circled in red report radiocarbon in terms of percent modern carbon (pMC).

conservative tracer, chloride, is influenced by the flushing of accumulated salinity in vadose-zone profiles at low elevations (<300 mamsl) proximate (<100 km) to Lake Chad (Isiorho *et al.* 1996, Zairi 2008) and faecal contamination around Maiduguri (see Supplementary material, Figs S5 and S6).

5 Discussion

5.1 Rainfall-recharge relationships

Long-term (1964–1995) monthly records of stable isotope ratios of O and H in rainfall at N'Djamena (N = 74) demonstrate the amount effect, in which the stable isotope composition of monthly rainfall becomes progressively depleted in heavy isotopes (^{18}O, ^{2}H) as observations are selected for more intensive monthly rainfalls (Fig. 4). This evidence is consistent with more limited time series records (N = 33) in the LCB at Kano (1961–1973; see Supplementary material, Fig. S3) and 10 other IAEA stations across tropical Africa (Fig. 4). Stable isotope ratios in groundwater from the QA in the SW LCB regress to a composition that is considerably more depleted in ^{18}O and ^{2}H than the weighted mean composition of rainfall at N'Djamena and Maiduguri. As such, they trace groundwater recharge to result disproportionately during months of heavy rainfall exceeding the ~60th percentile (i.e. ~0.7‰ or more depleted than the weighted mean composition, Fig. 4). Tracing groundwater recharge to a threshold of a specific monthly rainfall intensity percentile is complicated by uncertainty in linear regression statistics; the designated 60th percentile of monthly rainfall incorporates this uncertainty and represents a minimum threshold. The influence of the altitude effect (<0.3‰) is comparatively minor (see Supplementary material, Fig. S7). Similar deductions of a bias in groundwater recharge to months of heavy rainfall in tropical drylands have been reached from stable isotope tracers in Senegal (Faye *et al.* 2019) (Fig. 2) and southern Africa (Jasechko 2019) (Fig. 5(c)). Of note is that sampled groundwaters from the QA of Chad (IAEA 2017, fig. 32) and Niger (Leduc *et al.* 2000) (Fig. 2) in the LCB also regress to a rainfall composition on the LMWL that is depleted in heavy isotopes relative to the weighted mean composition of monthly rainfall at N'Djamena.

Limited radiocarbon measurements (9) confirm that shallow (<30 m bgl) groundwater in the QA (Upper A zone) of the Chad Formation is modern (post-1950s according to ^{14}C content); an increasing proportion of older groundwater, albeit replenished by modern meteoric waters (according to palaeometeoric origins of confined groundwaters as defined by Maduabuchi *et al.* 2006), is suggested at depths exceeding 30 m bgl. It is important to note that carbonate minerals occur in Lake Chad aquifer sediments (Durand *et al.* 1984). Because the Chad Formation is continental and Quaternary in age, it is not possible to correct for dead carbon using a fixed value as the $\delta^{13}C$ signature of the continental carbonates is both unknown and expected to be highly variable. The presence of ^{14}C itself indicates a component of modern recharge.

5.2 Evidence of recharge process

The large range in stable isotope ratios of O and H in groundwater samples from the QA in the SW LCB (−7.4‰ to +3.4‰

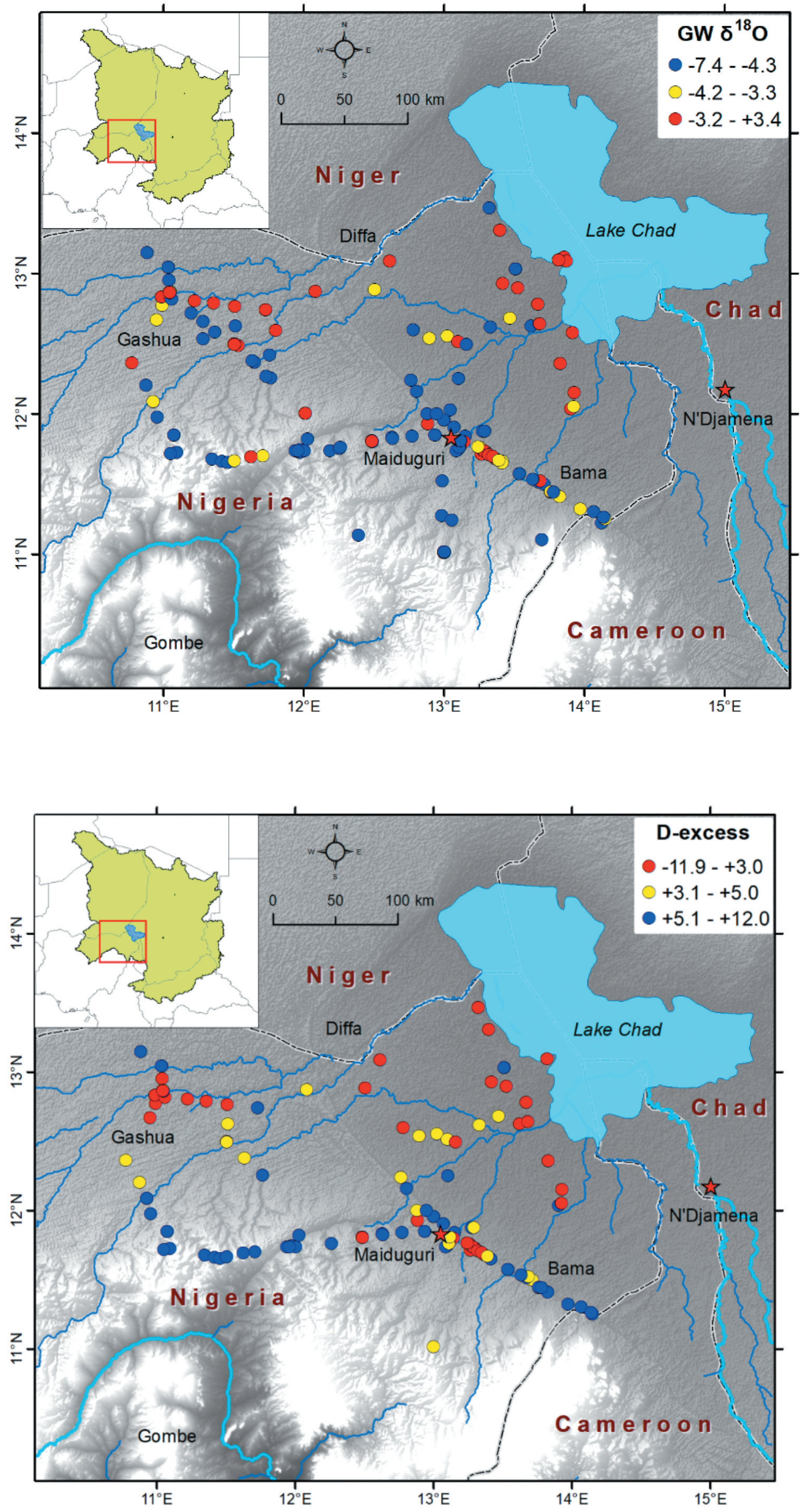

Figure 6. Map of surface drainage in the SW Chad Basin using the HydroSHEDS database (Ouellet Dallaire *et al.* 2019) – light/dark blue lines denote "medium/small" river channels as defined by the GloRic database (v. 1.0) of HydroSHEDS. (a) Blue/yellow/red circles denote different $\delta^{18}O$ ranges for 145 groundwater samples; and (b) blue/yellow/red circles denote different ranges in values of deuterium excess for 145 groundwater samples.

V-SMOW) reflects varying degrees of evaporative enrichment that provide insight into recharge processes. Substantial enrichment in heavy isotope content relative to the weighted mean composition (e.g. $\delta^{18}O > -3.2‰$; ^2H excess < +2‰) is expected to trace residency at the surface as part of ephemeral or perennial surface drainage. Evaporative enrichment of this order is not generally expected in the soil zone of arenaceous deposits of the QA but may occur locally where clays impede drainage and provide confining conditions. This basic conceptual model is largely consistent with the observed distribution in stable isotope ratios in groundwater (Fig. 5, also see Supplementary material, Fig. S3) whereby groundwater enriched in heavy isotopes through evaporation is often proximate to surface drainage including the River Komadugu Yobe and Lake Chad.

Variations in $\delta^{18}O$ in groundwater with minimum sampling depth (Fig. 5) are revealing. Substantial enrichment in heavy isotope content of groundwater through evaporation is restricted to shallow depths < 30 m bgl; groundwater sampled at deeper depths is more consistently depleted in ^{18}O ($\delta^{18}O < -4.3‰$). Although site information for many groundwater samples is limited (see Supplementary material, Table S1), a transect near Gashua of depth measurements that includes the sites adjacent to, and more remote from, the rivers Hadeja and Jama'are (see Supplementary material, Fig. S8) highlights the following: (1) shallow groundwater sources (< 20 m bgl) close to drainage channels (□ 5 km) are enriched in the heavy isotope ($\delta^{18}O > -2.9‰$); and (2) deeper groundwater sources (> 30 m bgl) more remote from drainage channels (□ 5 km) are depleted in the in the heavy isotope ($\delta^{18}O < -4.3‰$).

The emerging conceptual model of groundwater recharge in the SW LCB traced by stable isotope ratios in rainfall and groundwater is one in which recharge occurs by both diffuse and focused pathways, consistent with recent evidence derived from ^{36}Cl tracers in Logone-Chari catchment of Cameroon (Bouchez *et al.* 2019). Focused groundwater recharge is denoted primarily but not exclusively by isotopic values enriched in the heavy isotopes ($\delta^{18}O > -2.9‰$) through evaporation (Zairi 2008), and occurs via leakage from river channels and Lake Chad to shallow groundwater where favourable (permeable) conditions for drainage persist. This deduction is consistent with regional piezometric contours reported by Descloitres *et al.* (2013) and the conclusions of Isiorho *et al.* (1996) who reported flow from Lake Chad to shallow groundwater in the SW Chad Basin that was estimated to influence groundwater sources up to 15 to 20 km from the lake's shoreline. Diffuse groundwater recharge is generally traced by isotopic ratios depleted in heavy isotopes ($\delta^{18}O < -4.3‰$) in which evaporative enrichment is much reduced, as rainfall infiltrates either directly through dune deposits or potentially indirectly via surface runoff infiltrating close (e.g. within a few hundred metres) to the origin of the rainfall, as noted by Favreau *et al.* (2002) in the Niger Basin. Limited evaporative enrichment of groundwater associated with diffuse recharge in this dryland environment is attributed to the role of soil macropores and preferential flowpaths that enable rapid transmission to water tables through the unsaturated zone bypassing soil matrices (Beven and Germann 2013), as has been observed in Burkina Faso (Mathieu and Bariac 1996), Tanzania (Taylor *et al.* 2013b) and Uganda (Taylor and Howard 1999). Diffuse recharge is traced more commonly in headwater regions of the SW LCB to the south and southwest (Fig. 6), remote from regional drainage features (River Komadugu Yobe, Lake Chad). Here, where rainfall is relatively higher, the underlying geology (e.g. weathered granite soils) just outside of dune deposits (see Supplementary material, Fig. S1) can impede infiltration and generate runoff. Resultant ephemeral flows can drain into sedimentary areas and recharge the QA, consistent with Kemgang *et al.* (2019). These hydrological dynamics underscore the complexities of recharge pathways in the SW LCB and the range of influences on stable isotope ratios in sampled groundwater.

5.3 Threshold-dependent hydrological responses and climate change

We trace the stable isotope composition of groundwater in the QA of the SW LCB to heavy monthly rainfall exceeding, at minimum, the 60th percentile (~90 mm). This association mirrors evidence from Jasechko and Taylor (2015) linking groundwater at 14 of 15 IAEA stations across the tropics to monthly rainfalls exceeding the 70th percentile. The bias to heavy rainfall in the SW LCB applies to groundwater derived from both diffuse and focused recharge as stable isotope ratios of O and H in groundwater regress ($r^2 = 0.97$) along an evaporative slope of 6 (δ^2H vs. $\delta^{18}O$) to a composition depleted in heavy isotopes relative to the observed weighted mean composition of rainfall in the SW LCB (Table 1); furthermore, there is evidence from stable isotope studies in Niger (Leduc *et al.* 2000) and Chad (IAEA 2017) that this bias in groundwater recharge to heavy monthly rainfall occurs more widely in the LCB. In practice, diffuse and focused groundwater recharge can result from events or a sequence of events on a weekly to daily or even hourly time frame so that the bias in stable isotope composition to months of heavy rainfall represents periods when such events occur. The noted dependence upon heavy rainfalls nevertheless highlights the importance of moisture surpluses exceeding thresholds required to (1) generate surface discharges supplying focused groundwater recharge; and (2) enable rapid infiltration of diffuse recharge via preferential pathways bypassing soil matrices, as has been observed across Sub-Saharan Africa from long-term piezometric records (Cuthbert *et al.* 2019).

Quantification of the impacts of climate change on groundwater recharge in drylands remains highly uncertain due to uncertainty in the direction and magnitude of precipitation projections from general circulation models and the inability of large-scale models (e.g. global hydrological models, land surface models) to represent focused recharge (Taylor *et al.* 2013b, Cuthbert *et al.* 2019). One consistent, observed impact of climate change is the intensification of precipitation (Fischer and Knutti 2016, Taylor *et al.* 2017; Myhre *et al.* 2019) that is particularly acute in the tropics (Allan *et al.* 2010) and results in fewer light rainfalls and more frequent heavy rainfalls. The consequences of this changing distribution of rainfall events include reduced soil moisture, more frequent and intense floods as well as more persistent and frequent droughts (Yin *et al.* 2018). The observed bias in groundwater recharge to heavy monthly rainfalls traced by stable isotope ratios in the SW LCB suggests that the intensification of rainfall brought about by global warming may favour groundwater recharge as thresholds to generate diffuse or focused recharge may be expected to be exceeded more frequently. A key outstanding question is whether recharge increases associated with intensification of rainfall outweigh the impact of rising potential evapotranspiration.

6 Conclusions

In the southwestern (SW) Lake Chad Basin (LCB) of semi-arid northeastern Nigeria, a newly compiled database of stable isotope ratios of O and H in 145 groundwater sources and rainfall from three locations (N'Djamena, Chad; Maiduguri and Kano, Nigeria) trace, for the first time, a bias in groundwater recharge to heavy monthly rainfalls, exceeding the 60th percentile observed at the IAEA station in N'Djamena. Stable isotope ratios in sampled groundwater sources vary considerably, from −7.4‰ to +3.4‰ (δ^{18}O) and −49‰ to +14‰ (δ^{2}H), relative to Vienna-SMOW, yet regress along a non-equilibrium evaporation line (r^2 = 0.97) reflecting varying degrees of evaporative enrichment in heavy isotopes (^{18}O, ^{2}H) prior to recharge. δ^{18}O signatures in shallow groundwater (<30 m below ground level) that are evaporatively enriched relative to the weighted mean δ^{18}O composition of precipitation (−3.3‰ at Maiduguri, −3.6‰ at N'Djamena) range from −3.2 to +3.4‰ and trace focused recharge via leakage from river channels and Lake Chad. δ^{18}O values in groundwater sources that are comparatively depleted in heavy isotopes (−4.3 to −7.4‰) are typically found on interfluves, remote from surface waters, and reflect diffuse, rain-fed recharge via dune systems, particularly in the south and southwestern headwater areas of the SW LCB in Nigeria. We recognize not only the existence of focused and diffuse recharge pathways in this semi-arid environment but also the complexity of recharge pathways within these general designations that can occur as a function of other controlling factors such as geology to explain the wide range in observed stable isotope ratios in sampled groundwater. The observed bias in groundwater recharge in the SW LCB to heavy monthly rainfall, associated with both diffuse and focused pathways, suggests that the progressive intensification of tropical rainfall under climate change favours groundwater recharge in this basin.

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References

Acworth, R.I., *et al.*, 2021. Runoff and focused groundwater-recharge response to flooding rains in the arid zone of Australia. *Hydrogeology Journal*, 29 (2), 737–764. doi:10.1007/s10040-020-02284-x.

Allan, R.P., *et al.*, 2010. Current changes in tropical precipitation. *Environmental Research Letters*, 5 (2), 025205. doi:10.1088/1748-9326/5/2/025205.

Altchenko, Y. and Villholth, K.G., 2015. Mapping irrigation potential from renewable groundwater in Africa – a quantitative hydrological approach. *Hydrology and Earth System Sciences*, 19 (2), 1055–1067. doi:10.5194/hess-19-1055-2015.

Armitage, S.J., Bristow, C.S., and Drake, N.A., 2015. West African monsoon dynamics inferred from abrupt fluctuations of Lake Mega-Chad. *Proceedings of the National Academy of Sciences*, 112 (28), 8543–8548. doi:10.1073/pnas.1417655112.

Barber, W., 1965. Pressure water in the Chad Formation of Bornu and Dikwa emirates, north-eastern Nigeria. *Bulletin of the Geological Survev of Nigeria*, 35, 138.

Barber, W. and Jones, D.G., 1960. The geology and hydrology of Maiduguri, Bornu province. (Unpublished records) Geological Survey of Nigeria.

Beacon Services Ltd. – Consulint International S.r.l., 1979. Maiduguri water supply, Hydrogeological report Vol. 1, Hydrogeology and future exploitation of groundwater. Borno State Water Board, Nigeria, 158p.

Beven, K. and Germann, P., 2013. Macropores and water flow in soils revisited. *Water Resources Resources*, 49, 3071–3092.

Bouchez, C., *et al.*, 2015. Investigation of Cl-36 distribution: towards a new estimation of groundwater residence times in the confined aquifer of the LCB? *Procedia Earth and Planetary Science*, 13, 147–150. doi:10.1016/j.proeps.2015.07.035

Bouchez, C., *et al.*, 2019. Water transit time and active recharge in the Sahel inferred by bomb-produced ^{36}Cl. *Nature Scientific Reports*, 9 (1), 7465. doi:10.1038/s41598-019-43514-x.

Byrne, M.P. and O'Gorman, P.A., 2015. The response of precipitation minus evapotranspiration to climate warming: why the 'wet-get-wetter, dry-get-drier' scaling does not hold over land. *Journal of Climate*, 28 (20), 8078–8092. doi:10.1175/JCLI-D-15-0369.1.

Carter, R.C., 1994. The groundwater hydrology of the Manga Grassland, north east Nigeria; importance to agricultural development strategy for the area. *Quarterly Journal of Engineering Geology and Hydrogeology*, 27, 73–83. doi:10.1144/GSL.QJEGH.1994.027.0S.08

Carter, R.C. and Alkali, A.G., 1996. Shallow groundwater in the northeast arid zone of Nigeria. *Quarterly Journal of Engineering Geology and Hydrogeology*, 29 (4), 341–355. doi:10.1144/GSL.QJEGH.1996.029.P4.07.

Coleman, M.L., *et al.*, 1982. Reduction of water with zinc for hydrogen isotope analysis. *Analytical Chemistry*, 54 (6), 993–995. doi:10.1021/ac00243a035.

Collins, M., *et al.*, 2013. Long-term climate change: projections, commitments and irreversibility. *In*: T.F. Stocker, *et al.*, eds. *Climate change 2013: the physical science basis. Contribution of working group i to the fifth assessment report of the intergovernmental panel on climate change.* Cambridge, UK and New York, NY, USA: Cambridge University Press, 1029–1136.

Commission Climat pour la Région du Sahel (CCRS), 2018. Plan d'Investissement climat pour la Region du Sahel 2018–2030. Available from: https://chm.cbd.int/api/v2013/documents/7BB42009-D66B-EC5F-BBF4-34A450687056/attachments/Rapport%20final%20PIC-RS-Version%20finale%20%20u%2025%20oct%202018%20(1).pdf [Accessed 28 Jan 2020].

Cuthbert, M.O., *et al.*, 2019. Observed controls on resilience of groundwater to climate variability in sub-Saharan Africa. *Nature*, 572, 230–234. doi:10.1038/s41586-019-1441-7

Dahan, O., *et al.*, 2008. Dynamics of flood water infiltration and ground water recharge in hyperarid desert. *Ground Water*, 46 (3), 450–461. doi:10.1111/j.1745-6584.2007.00414.x.

de Graaf, I.E.M., *et al.*, 2017. A global-scale two layer transient groundwater model: development and application to groundwater depletion. *Advances in Water Resources*, 102, 53–67. doi:10.1016/j.advwatres.2017.01.011

Descloitres, M., *et al.*, 2013. Investigation of groundwater resources in the Komadugu Yobe valley (Lake Chad Basin, Niger) using MRS and TDEM methods. *Journal of African Earth Sciences*, 87, 71–85. doi:10.1016/j.jafrearsci.2013.07.006

Du Preez, J.W. and Barber, W., 1965. The distribution and chemical quality of groundwater in Northern Nigeria. *Bulletin of the Geological Survev of Nigeria*, 36, 93.

Durand, A., *et al.*, 1984. Le Nord-ouest du lac Tchad au Quaternaire: étude de paléoenvironnements alluviaux, éoliens, palustres et lacustres. *Paleoecology of Africa*, 16, 215–243.

Durand, A., 1995. Sédiments quaternaires et changements climatiques au Sahel central (Niger et Tchad). *African Geosciences Review*, 2 (3–4), 323–614.

Edmunds, W.M., *et al.*, 2002. Spatial and temporal distribution of groundwater recharge in northern Nigeria. *Hydrogeology Journal*, 10 (1), 205–215. doi:10.1007/s10040-001-0179-z.

Edmunds, W.M., Fellman, E., and Goni, I.B., 1999. Lakes, groundwater and palaeohydrology in the Sahel of NE Nigeria: evidence from hydrogeochemistry. *Journal of the Geological Society of London*, 156 (2), 345–355. doi:10.1144/gsjgs.156.2.0345.

Epstein, S. and Mayeda, T.K., 1953. Variations of the 18O/16O ratio in natural waters. *Geochimica et Cosmochimica Acta*, 4 (5), 213–224. doi:10.1016/0016-7037(53)90051-9.

Favreau, G., *et al.*, 2002. Estimate of recharge of a rising water table in semi-arid Niger from ^{3}H and ^{14}C modeling. *Groundwater*, 40 (2), 144–151. doi:10.1111/j.1745-6584.2002.tb02499.x.

Favreau, G., *et al.*, 2009. Land clearing, climate variability, and water resources increase in semiarid southwest Niger: a review. *Water Resources Research*, 45 (7), W00A16. doi:10.1029/2007WR006785.

Faye, S.C., *et al.*, 2019. Tracing natural groundwater recharge to the Thiaroye aquifer of Dakar, Senegal. *Hydrogeology Journal*, 27 (3), 1067–1080. doi:10.1007/s10040-018-01923-8.

Fischer, E. and Knutti, R., 2016. Observed heavy precipitation increase confirms theory and early models. *Nature Climate Change*, 6 (11), 986–991. doi:10.1038/nclimate3110.

Gasse, F., 2000. Hydrological changes in the African tropics since the Last Glacial Maximum. *Quaternary Science Reviews*, 19 (1–5), 189–211. doi:10.1016/S0277-3791(99)00061-X.

Genik, G.J., 1992. Regional framework, structural and petroleum aspects of rift basins in Niger, Chad and the Central African Republic (C.A.R.). *Tectonophysics*, 213 (1–2), 169–185. doi:10.1016/0040-1951(92)90257-7.

Goes, B.J.M., 1999. Estimate of shallow groundwater recharge in the Hadejia–Nguru Wetlands, semi-arid northeastern Nigeria. *Hydrogeology Journal*, 7 (3), 294–304. doi:10.1007/s100400050203.

Gonfiantini, R., *et al.*, 2001. The altitude effect on the isotopic composition of tropical rains. *Chemical Geology*, 181 (1–4), 147–167. doi:10.1016/S0009-2541(01)00279-0.

Goni, I.B., 2006. Tracing stable isotope values from meteoric water to groundwater in the southwestern part of the Chad basin. *Hydrogeology Journal*, 14 (5), 742–752. doi:10.1007/s10040-005-0469-y.

Goni, I.B., Kachallah, M., and Aji, M.M., 2000. Another look at the piezometric head declines in Middle zone aquifer of the Chad Formation in the Southwestern Chad basin. *Borno Journal of Geology*, 1&2 (2), 51–64. doi:10.1016/0006-2944(75)90147-7.

Grist, J.P. and Nicholson, S.E., 2001. A Study of the Dynamic Factors Influencing the Rainfall Variability in the West African Sahel. *Journal of Climate*, 14 (7), 1337–1339. doi:10.1175/1520-0442(2001)014<1337:ASOTDF>2.0.CO;2.

Hanasaki, N., *et al.*, 2018. A global hydrological simulation to specify the sources of water used by humans. *Hydrology and Earth System Sciences*, 22 (1), 789–817. doi:10.5194/hess-22-789-2018.

Huneau, F., *et al.*, 2011. Flow pattern and residence time of groundwater within the south-eastern Taoudeni sedimentary basin (Burkina Faso, Mali). *Journal of Hydrology*, 409 (1–2), 423–439. doi:10.1016/j.jhydrol.2011.08.043.

IAEA (International Atomic Energy Agency), 2017. 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. Vienna: IAEA, p. 47.

IAEA/GNIP, 2014. IAEA/GNIP precipitation sampling guide, v2.02. *IAEA*. Available from: www.iaea.org/water [Accessed 28 Jan 2020].

Ibrahim, M., *et al.*, 2014. Long-term increase in diffuse groundwater recharge following expansion of rainfed cultivation in the Sahel, West Africa. *Hydrogeology Journal*, 22 (6), 1293–1305. doi:10.1007/s10040-014-1143-z.

Isiorho, S.A., Matisoff, G., and When, K.S., 1996. Seepage relationships between Lake Chad and the Chad aquifers. *Ground Water*, 34 (5), 819–826. doi:10.1111/j.1745-6584.1996.tb02076.x.

IWACO, 1985. Study of the water resources in the Komadougou-Yobe Basin. Technical Report No.5: Groundwater Resources. Nigeria - Niger Joint Commission for Cooperation Niamey, Niger.

Jasechko, S., 2019. Global isotope hydrogeology - review. *Reviews in Geophysics*, 57 (3), 835–965.

Jasechko, S. and Taylor, R.G., 2015. Intensive rainfall recharges tropical groundwaters. *Environmental Research Letters*, 10 (12), 124015. doi:10.1088/1748-9326/10/12/124015.

Kebede, S., *et al.*, 2021. Regional-scale interactions between groundwater and surface water under changing aridity: evidence from the River Awash Basin, Ethiopia. *Hydrological Sciences Journal*, 66 (3), 450–463. doi:10.1080/02626667.2021.1874613.

Kemgang, D.T., *et al.*, 2019. Contribution of time domain electromagnetic and magnetic resonance soundings to groundwater assessment at the margin of Lake Chad Basin, Cameroon. *Journal of Applied Geophysics*, 170, 103840. doi:10.1016/j.jappgeo.2019.103840

Kolusu, S.R., *et al.*, 2019. The El Niño event of 2015–16: climate anomalies and their impact on groundwater resources in East and Southern Africa. *Hydrology and Earth System Sciences*, 23 (3), 1751–1762. doi:10.5194/hess-23-1751-2019.

Konikow, L.F., 2011. Contribution of global groundwater depletion since 1900 to sea-level rise. *Geophysical Research Letters*, 38 (17), L17401. doi:10.1029/2011GL048604.

Lake Chad Basin Commission (LCBC), 1973. Survey of the water resources of the Chad Basin for development purposes. FAO Technical Report, No. 5, Vol. 1 – Hydrogeological Study.

Le Coz, M., Favreau, G., and Ousmane, S.D., 2013. Modeling increased groundwater recharge due to change from rainfed to irrigated cropping in a semiarid region. *Vadose Zone Journal*, 12 (2), 2–12. doi:10.2136/vzj2012.0148.

Leblanc, M., *et al.*, 2006. Remote sensing for groundwater modelling in large semiarid areas: lake Chad Basin, Africa. *Hydrogeology Journal*, 15 (1), 97–100. doi:10.1007/s10040-006-0126-0.

Leduc, C., *et al.*, 2000. Recharge of the Quaternary water table in the northwestern Lake Chad basin (southeastern Niger) estimated from isotopes. *Comptes rendus de l'Académie des Sciences IIa*, 330, 355–361.

Leduc, C., *et al.*, 2007. Impacts of hydrological changes in the Mediterranean zone: environmental modifications and rural development in the Merguellil catchment, central Tunisia. *Hydrological Sciences Journal*, 52 (6), 1162–1178. doi:10.1623/hysj.52.6.1162.

Maduabuchi, C., 2005. Isotope-based investigations in the Chad Basin Aquifers – IAEA TC Project NIR/8/006. Published by the Department of Hydrology and Hydrogeology, Federal Ministry of Water Resources, Abuja. Vol. 2, p. 77.

Maduabuchi, C., Faye, S., and Maloszewski, P., 2006. Isotope evidence of palaeorecharge and palaeoclimate in the deep confined aquifers of the Chad Basin, NE Nigeria. *Science of the Total Environment*, 370 (2–3), 467–479. doi:10.1016/j.scitotenv.2006.08.015.

Mathieu, R. and Bariac, T., 1996. An isotopic study (^{2}H and ^{18}O) on water movements in clayey soils under semi-arid climate. *Water Resources Research*, 32, 779–789.

Mbonu, M. and Travi, Y., 1994. Labelling of precipitation by stable isotopes (^{18}O, ^{2}H) over the Jos Plateau and the surrounding plains (North-Central Nigeria). *Journal of African Earth Sciences*, 19 (1–2), 91–98. doi:10.1016/0899-5362(94)90041-8.

Miller, R.E., 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. USGS Water Supply Paper 1757-1, p. 48.

Myhre, G., *et al.*, 2019. Frequency of extreme precipitation increases extensively with event rareness under global warming. *Nature Scientific Reports*, 9 (1), 16063. doi:10.1038/s41598-019-52277-4.

Ndubisi, O.L., 1990. Managing groundwater resources of the Lake Chad Basin in Nigeria. Proc. 1st Binnual Nat. Hydrogy Symp. Maiduguri. pp. 429–436.

Ngounou Ngatcha, B., *et al.*, 2005 April. Climate variability and impacts on an alluvial aquifer in a semiarid climate, the Logone-Chari plain (south of Lake Chad). In: Regional Hydrological Impacts of Climatic Change—Impact Assessment and Decision Making. Proceedings of symposium S6 held during the Seventh IAHS Scientific Assembly at Foz do Iguaçu, Brazil, IAHS Publ. 295, 94–100.

Nicholson, S.E., 2018. The ITCZ and the seasonal cycle over equatorial Africa. *Bulletin of the American Meteorological Society*, 99 (2), 337–348. doi:10.1175/BAMS-D-16-0287.1.

Niel, H., Leduc, C., and Dieulin, C., 2005. Caractérisation de la variabilité spatiale et temporelle des précipitations annuelles sur le bassin du Lac Tchad au cours du 20ème siècle. *Hydrological Sciences Journal*, 50 (2), 223–243. doi:10.1623/hysj.50.2.223.61800.

Olsson, I.U., 1970. The use of Oxalic acid as a Standard. In I.U. Olsson (ed.), Radiocarbon Variations and Absolute Chronology, Nobel Symposium, 12th Proc, John Wiley & Sons, New York, p. 17.

Ouellet Dallaire, C., *et al.*, 2019. A multidisciplinary framework to derive global river reach classifications at high spatial resolution. *Environmental Research Letters*, 14 (2), 024003. doi:10.1088/1748-9326/aad8e9.

Pham-Duc, B., *et al.*, 2020. The Lake Chad hydrology under current climate change. *Scientific Reports*, 10 (1), 5498. doi:10.1038/s41598-020-62417-w.

Scanlon, B.R., *et al.*, 2006. Global synthesis of groundwater recharge in semiarid and arid regions. *Hydrological Processes*, 20 (15), 3335–3370. doi:10.1002/hyp.6335.

Short Gianotti, D.J., *et al.*, 2020. Terrestrial evaporation and moisture drainage in a warmer climate. *Geophysical Research Letters*, 47 (5), e2019GL086498. doi:10.1029/2019GL086498.

Taupin, J.-D., *et al.*, 2000. Rainfall characteristics (δ18O, δ2H, T and ΔH r) in western Africa: regional scale and influence of irrigated areas. *Journal of Geophysical Research - Atmospheres*, 105 (D9), 11911–11924. doi:10.1029/1999JD901032.

Taylor, C.M., *et al.*, 2017. Frequency of extreme Sahelian storms tripled since 1982 in satellite observations. *Nature*, 544 (7651), 475–478. doi:10.1038/nature22069.

Taylor, R.G., *et al.*, 2013a. Groundwater and climate change. *Nature Climate Change*, 3 (4), 322–329. doi:10.1038/nclimate1744.

Taylor, R.G., *et al.*, 2013b. Evidence of the dependence of groundwater resources on extreme rainfall in east Africa. *Nature Climate Change*, 3 (4), 374–378. doi:10.1038/nclimate1731.

Taylor, R.G. and Howard, K.W.F., 1999. The influence of tectonic setting on the hydrological characteristics of deeply weathered terrains: evidence from Uganda. *Journal of Hydrology*, 218 (1–2), 44–71. doi:10.1016/S0022-1694(99)00024-4.

Tremoy, G., *et al.*, 2014. Clustering mesoscale convective systems with laser-based water vapor 18 O monitoring in Niamey (Niger). *Journal of Geophysical Research: Atmospheres*, 119 (9), 5079–5103. doi:10.1002/2013JD020968.

Vassolo, S., *et al.*, 2016. Groundwater - surface water interaction in the lower logone floodplain: "sustainable water management of the lake Chad Basin" project activities - report No. 10. Hannover-N'Djamena: BGR-CBLT. Available from: http://www.bgr.bund.de/lcbc [Accessed 28 Jan 2020].

Villeneuve, S., *et al.*, 2015. Groundwater recharge via infiltration through an ephemeral riverbed, central Australia. *Journal of Arid Environments*, 117, 47–58. doi:10.1016/j.jaridenv.2015.02.009

Wada, Y., *et al.*, 2010. Global depletion of groundwater resources. *Geophysical Research Letters*, 37 (20), L20402. doi:10.1029/2010GL044571.

Wada, Y., van Beek, L.P.H., and Bierkens, M.F.P., 2012. Non-sustainable groundwater sustaining irrigation: a global assessment. *Water Resources Research*, 48 (6), W00L06. doi:10.1029/2011WR010562.

Williams, M.A.J., 1975. Late Pleistocene tropical aridity synchronous in both hemispheres? *Nature*, 253 (5493), 617–618. doi:10.1038/253617a0.

Wolski, P., *et al.*, 2014. Attribution of floods in the Okavango basin, Southern Africa. *Journal of Hydrology*, 511, 350–358. doi:10.1016/j.jhydrol.2014.01.055

World Bank, 2017. *A wake up call: nigeria water supply, sanitation, and hygiene poverty diagnostic*. Washington DC: WASH Poverty Diagnostic, World Bank, 142.

Yin, J., *et al.*, 2018. Large increase in global storm runoff extremes driven by climate and anthropogenic changes. *Nature Communications*, 9 (1), 4389. doi:10.1038/s41467-018-06765-2.

Zairi, R., 2008. Etude hydrodynamique et géochimique de la nappe phréatique dans la région du Kadzell (Niger) et la région du Bornou (Nigéria), Bassin du Lac Tchad. PhD thesis, University of Montpellier 2, France.

Zhou, S., *et al.*, 2021. Soil moisture–atmosphere feedbacks mitigate declining water availability in drylands. *Nature Climate Change*, 11 (1), 38–44. doi:10.1038/s41558-020-00945-z.