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

Ibrahim Baba Goni, Richard G. Taylor, Guillaume Favreau, Mohammad Shamsudduha, Yahaya Nazoumou and Benjamin Ngounou Ngatcha

Department of Geology, University of Maiduguri, Maiduguri, Nigeria; Department of Geography, University College London, London, UK; Département Dynamiques internes et de surface des continents, IRD, CNRS, Grenoble INP, IGE, Université Grenoble Alpes, Grenoble, France; Institut de Recherche Pour le Développement (IRD), Niamey, Niger; Institute for Risk and Disaster Reduction, University College London, London, UK; Department of Geography, University of Sussex, Brighton, UK; Département de Géologie, Faculté des Sciences et Techniques, Université Abdou Moumouni de Niamey, Niamey, Niger; Faculty of Science, University of Ngaoundéré, Ngaoundéré, Cameroon

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 (δD, δ18O) from groundwater and rainfall. δ18O signatures in groundwater proximate to surface waters are enriched in 18O 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 (δD, δ18O) 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,
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.
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 $17 \times 10^6$ m³ 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), Descloières 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; Zaïri 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 km² (IAEA 2017) that extends from the humid tropics of the Central African 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 area 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 ($\text{^{18}O}, \text{^{2H}}$) 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 $\text{^{18}O}$ and $\text{^{2H}}$ 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 km² of north-eastern 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 days and partially confined by the clays (Fig. 2). Beacon Services Ltd. – Consultant 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 Descloiotres 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 rain gauges 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: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 ($^2$H:H) and oxygen-18 ($^{18}$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 1500 of NBS (National Bureau of Standards) Oxalic Acid I (SRM (Standard Reference Material) 4990B, OX-I) normalized to $^{14}$CVPDB98 (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 $\delta^{18}$H = (7.3 ± 0.2)$\delta^{18}$O + 5.5 ± 0.9‰ (Fig. 3(a)). Weighted mean stable isotope compositions of rainfall sampled at Maiduguri ($\delta^{18}$H = −19‰, $\delta^{18}$O = −3.3‰) and N’Djamena ($\delta^{18}$H = −19‰, $\delta^{18}$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 ($\delta^{18}$H = −21‰, $\delta^{18}$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 ($\delta^{18}$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* of rainfall relative to Vienna-SMOW (Standard Mean Ocean Water) in the SW Chad Basin; data for IAEA station at N’Djamena (11°51.88N, 13°13.25E; elevation: 294 mmsl) and IAEA station at Kano (11°51.88N, 13°13.25E; elevation: 420 mmsl) derive from monthly samples, whereas data for Jos (9°58.00N, 8°52.00E; elevation: 1173 mmsl) are (mostly) taken every 2 weeks, and data for Maiduguri (11°51.88N, 13°13.25E; elevation: 332 mmsl) and Garin Alkali (12°49.52N, 11°04.45E; elevation: 328 mmsl) derive from daily samples. mmsl: metres above mean sea level. Uncertainty expressed in linear-regression equations for LMWLs is solely mathematical.

| Station    | N  | Period         | LMWL            | $\delta^{18}$H | $\delta^{18}$O (%) | $\delta^{18}$H (%) |
|------------|----|----------------|-----------------|----------------|-------------------|-------------------|
| Garin Alkali  | 21 | 1998           | $\delta^{18}$H = (6.3 ± 0.4)$\delta^{18}$O + 9.9 ± 1.6‰ | 0.92 | −3.6 | −10 |
| Kano        | 33 | 1961–1973      | $\delta^{18}$H = (7.1 ± 0.4)$\delta^{18}$O + 4.4 ± 1.7‰ | 0.90 | −4.0 | −25 |
| Maiduguri   | 21 | 2001           | $\delta^{18}$H = (7.3 ± 0.2)$\delta^{18}$O + 5.5 ± 0.9‰ | 0.98 | −3.3 | −19 |
| Jos         | 15 | 1988–1989      | $\delta^{18}$H = (7.3 ± 0.2)$\delta^{18}$O + 5.5 ± 0.9‰ | 0.98 | −4.3 | −19 |
| N’Djamena   | 73 | 1964–1995      | $\delta^{18}$H = (6.3 ± 0.2)$\delta^{18}$O + 4.3 ± 0.7‰ | 0.95 | −3.6 | −19 |
| N’Djamena   | 20 | 2015–2018      | $\delta^{18}$H = (6.8 ± 0.2)$\delta^{18}$O + 5.6 ± 1.1‰ | 0.98 | −3.8 | −21 |
\[\delta^{18}O = -3.6\%\) and slightly more depleted in heavy isotopes
\[\delta^2H = -25\%\), \[\delta^{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 (\[\delta^{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 δ18O (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 δ18O 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 (18O) 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‰ (δ18O) and −49‰ to +14‰ (δ2H). Groundwater isotopic signatures regress along a non-equilibrium evaporation line (Fig. 3(b)): δ2H = (6.0 ± 0.1)−δ18O − 4.8 ± 0.6 (R² = 0.97). This line intersects the LMWL at Maiduguri and the global meteoric water line (GMWL) at δ18O = −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 (18O, 2H) 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, δ18O values in groundwater that are depleted in 18O relative to the weighted mean composition of rainfall (δ18O ≤ −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 δ2H ≤ −30‰ (see Supplementary material, Fig. S4). The δ18O 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. δ18O values between these two categories (−3.3 to −4.2‰; N = 26) show no clear bias in their geographical position within the SW LCB. δ18O values from wells in which groundwater was sampled below a depth of 30 m bgl are consistently depleted (≤ −4.3‰) in 18O (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
conservative tracer, chloride, is influenced by the flushing of accumulated salinity in vadose-zone profiles at low elevations (<300 m a.s.l.) 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 ($\delta^{18}O$, $\delta^2H$) 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 of Chad 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 palaeo-meteorological origins of confined groundwaters as defined by Madubuchi 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 δ18O 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. \(\delta^{18}O > -3.2\%_o; ^2H\) excess < +2\%o) 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 \(^{18}O\) (\(\delta^{18}O < -4.3\%o\)). 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 (\(\leq 5\) km) are enriched in the heavy isotope \((\delta^{18}O > -2.9\%o)\); and (2) deeper groundwater sources (> 30 m bgl) more remote from drainage channels (\(\geq 5\) km) are depleted in the in the heavy isotope \((\delta^{18}O < -4.3\%o)\).

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 ^34Cl 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 (\(\delta^{18}O > -2.9\%o\)) 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 Desclóitres et al. (2013) and the conclusions of Iisoro 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 \((\delta^{18}O < -4.3\%o)\) in which evaporative enrichment is much reduced, as rainfall infiltrates either directly through dune deposits or potentially indirectly via surf ace 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 \((\delta^2H - \delta^{18}O)\) 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‰ (δ18O) and −49‰ to +14‰ (δ2H), relative to Vienna-SMOW, yet regress along a non-equilibrium evaporation line (r² = 0.97) reflecting varying degrees of evaporative enrichment in heavy isotopes (18O, 2H) prior to recharge. δ18O signatures in shallow groundwater (<30 m below ground level) that are evaporatively enriched relative to the weighted mean δ18O 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. δ18O 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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ORCID

Ibrahim Baba Goni http://orcid.org/0000-0002-5961-0810
Richard G. Taylor http://orcid.org/0000-0002-9867-8033
Guillaume Favreau http://orcid.org/0000-0001-7358-9301
Mohammad Shamsuddhu http://orcid.org/0000-0002-9708-7223

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