# Tracing stable isotope values from meteoric water to groundwater in the southwestern part of the Chad basin

**I. B. Goni**

**Abstract** The southwestern Chad basin is a semi-arid region with annual rainfall that is generally less than 500 mm and over 2,000 mm of evapotranspiration. Surface water in rivers is seasonal, and therefore groundwater is the perennial source of water supply for domestic and other purposes. Stable isotope has been measured for rainwater, surface water and groundwater samples in this region. The stable isotope data have been used to understand the interrelationships between the rainwater, surface water, shallow and deep groundwater of this region. This is being used in a qualitative sense to demonstrate present day recharge to the groundwater. Stable isotope in rainwater for the region has an average value of –4‰ $\delta^{18}$O and –20‰ $\delta^{2}$H. Surface water samples from rivers and Lake Chad fall on the evaporation line of this average value. The Upper Zone aquifer water samples show stable isotope signal with a wide range of values indicating the complex character of the aquifer Zone with three distinguishable units. The wide range of values is attributable to waters from individual unit and/or mixture of waters of different units. The Middle and Lower aquifers Zones' waters show similar stable isotopes values, probably indicating similarity in timing and/or mechanism of recharge. These are palaeowaters probably recharged under a climate that is different from today. The Upper Zone aquifer is presently being recharged as some of its waters show stable isotope compositions similar to those of average rainfall waters of the region.

**Résumé** Le Sud-Ouest du bassin du Tchad est une région semi-aride, caractérisée par une pluviométrie annuelle généralement inférieure à 500 mm et une évapotranspiration supérieure à 2000 mm. Les eaux de surface, dans les rivières, sont saisonnières, et dés lors l'eau souterraine est par excellence la ressource d'eau pérenne, pour, entre autres, l'usage domestique. Les isotopes stables ont été mesurés dans des échantillons d'eau de pluie, d'eaux de surfaces et d'eaux souterraines de la région. Les mesures d'isotopes stables ont été utilisées pour comprendre la relation entre les eaux de pluie, les eaux de surface, les eaux souterraines de surface et profondes. Ceci a été utilisé d'une manière qualitative, pour évaluer la recharge actuelle de l'eau souterraine. Les isotopes stables de l'eau de pluie sur la région ont une valeur moyenne de −4‰ $\delta^{18}$0 et −20‰ $\delta^{2}$H. Les eaux de surface des rivières et du Lac Tchad se trouvent sur la ligne d'évaporation résultant de cette valeur moyenne. La partie supérieure de l'aquifère présente un signal hétérogène en isotope stable, ce qui évoque le caractère complexe de la zone aquifère, avec trois unités distinguables. La plus part des valeurs sont attribuées à des eaux provenant des unités individuelles, et/ou à un mélange de ces différentes unités. Les zones aquifères intermédiaires et plus profondes montrent des valeurs en isotopes stables similaires, indiquant des similitudes probables sur la durée et le mécanisme de recharge. Ce sont probablement des paléo-eaux souterraines marquées par la recharge à l'époque où les climats étaient différents de maintenant. La zone supérieure de l'aquifère est présentement rechargée, comme le montre le signal isotopique de certains échantillons, similaire au signal des eaux de pluies régionales.

**Resumen** La cuenca suroeste de Chad es una región semiárida con lluvia anual generalmente menos de 500 mm y por encima de 2,000 mm de evapotranspiración. El agua superficial en los ríos es estacional y por lo tanto el agua subterránea es la fuente perenne de abastecimiento de agua para uso doméstico y otros propósitos. Se han medido isótopos estables en agua de lluvia, agua superficial y muestras de agua subterránea en esta región. Los datos de isótopos estables se han utilizado para entender las interrelaciones entre el agua de lluvia, agua superficial, y agua subterránea somera y profunda de esta región. Esto se ha utilizado en un sentido cualitativo para demostrar la recarga actual a el agua subterránea. Los isótopos estables en agua de lluvia para la región tienen un valor promedio de –4‰ $\delta^{18}$0 y –20‰ $\delta^{2}$. Las muestras de agua superficial de los ríos y el Lago Chad caen sobre la línea de evaporación de este valor promedio. Las muestras de agua del acuífero de la Zona Superior muestran señales

Received: 25 January 2005 / Accepted: 3 June 2005
Published online: 18 November 2005



I. B. Goni (✉)
Department of Geology, University of Maiduguri,
P.M.B. 1069, Maiduguri, Borno State, Nigeria
e-mail: ibgoni@yahoo.com
Tel.: +234-8036372676
Fax: +234-76-390817

 DOI 10.1007/s10040-005-0469-y

de isótopos estables con un amplio rango de valores indicando el carácter complejo de la zona acuífera que tiene tres unidades distinguibles. El amplio rango de valores se atribuye a aguas provenientes de unidades individuales y/o mezcla de agua de diferentes unidades. Las aguas de la zona Media e Inferior de los acuíferos muestran valores similares de isótopos estables, indicando probablemente similitud en tiempo y/o mecanismo de recarga. Estas son paleoaguas probablemente recargadas bajo un clima que es diferente al actual. El acuífero de la Zona Superior está siendo recargado actualmente ya que algunas de sus aguas muestran composiciones de isótopos estables similares a las de agua de lluvia promedio de la región.

**Keywords** Stable isotope · Rainwater · Groundwater recharge · Chad basin

## Introduction

The stable isotopes, deuterium ($^2$H) and oxygen-18 ($^{18}$O), and the radioactive isotope, tritium ($^3$H), are rare components of the water molecule $H_2O$, and can offer a broad range of possibilities for studying processes within the water cycle. Stable isotope data from these components of the hydrologic cycle can provide useful information on the relationship between rainwater and groundwater and among waters from different aquifers. Stable isotopes may also be used for estimating recharge rates directly according to techniques described by Saxena and Dressie (1984) and Allison et al. (1984).

The study area lies in the southwestern part of the Chad basin, west of Lake Chad (Fig. 1). It is in a semi-arid region with an average annual rainfall of about 500 mm and an evapotranspiration that is generally over 2,000 mm. Apart from the Lake Chad, surface water in this area is intermittent and thus groundwater is the perennial source of water supply for domestic and other purposes. Recent studies (Offodile 1972; Oteze and Fayose 1988; Ndubisi 1990; Olugboye 1995; Goni et al. 2000; Goni 2002) have shown that groundwater levels in the shallow water table aquifer and in the deep artesian aquifers in this area are rapidly declining, with rates estimated at 1.1 and 2.5 m/year, respectively, (Ndubisi 1990). This has raised questions on the overall sustainability of the groundwater resources. Little work has been carried out to assess the total water balance, and recharge and abstraction rates are poorly defined. Although, there is an indication of modern recharge in the area, the amount and distribution are not well known, neither are the relationships between the modern hydrological cycle and groundwater in storage.

For a sustainable management of groundwater resources in this area, especially from the context of supply planning, there is the need for an understanding of the renewal rate, thus information about replenishment of the groundwater becomes fundamental. The main control is the balance between the rates of recharge and that of discharge, and these fundamentals are not clearly understood in this area, and indeed in most semi-arid and arid regions. In this study, an attempt is made to trace stable isotope signal from rainwater to groundwater and in the different aquifers in order to demonstrate whether or not present day recharge is taking place in a qualitative sense.

## Climatological setting

The rainfall distribution over the southwestern part of the Chad basin and indeed over western Africa is determined by the position of the meteorological equator and its two associated structures, the ITF (Inter Tropical Front) and the ITCZ (Inter Tropical Convergence Zone). The ITCZ rarely exerts its influence over continental areas north of 12°N latitude, the southern boundary of the Sahel. Thus Sahelian rainfall depends almost exclusively on the position and structure of the ITF, and is mostly of convective origin, either from isolated cumulo-nimbus clouds or from cloud formations, often evolving in the form of squall lines. Such squall lines are a feature of the Sahelian rainy season and they move in a general east/southeast to west/southwest direction (Lebel et al. 1992).

The present climatic regime in this area is simple, consisting of a long dry season (October–May) and a shorter rainy season (June–September), which is related to seasonal winds. During the winter months the cool, dry, dust-laden “harmattam” blows from the Sahara in the north, bringing low humidity, cool temperatures that at night go below 10°C. In the summer months, temperatures may be as high as 48°C and in these months moisture-laden winds blown from the Gulf of Guinea in the south, bring higher humidity and rains. These monsoon rains in general show high spatial (Fig. 2) and temporal variability over the area. The rainfall at the Maiduguri station for the 2001 season was 711 mm, very much similar to the long-term average and thus some 33% higher than the average for the Sahel drought period (Goni 2002). In 2003 the annual rainfall for the Maiduguri station was 670 mm. Potential evaporation is high in this area with an annual average of about 2,300 mm.

## Hydrogeological setting of the area

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 Chad Formation shows considerable lateral and vertical variability in lithology. Barber and Jones (1960) have named three clearly defined arenaceous horizons of the Chad Formation as the Upper, Middle and Lower Zones aquifer (Fig. 3). The Lower and Middle Zones are confined, whereas the Upper Zone of interest in the present study, ranges from confined to semi-confined and unconfined in places. The Upper Zone sands are considered to be lake margin, alluvial fans or deltaic sediments related to sedimentation in and around Lake Chad, which has varied considerably in

 DOI 10.1007/s10040-005-0469-y

**Fig. 1** Map of the Chad basin showing the study area on the southwestern part (Modified from Schneider 1989; scale not shown)

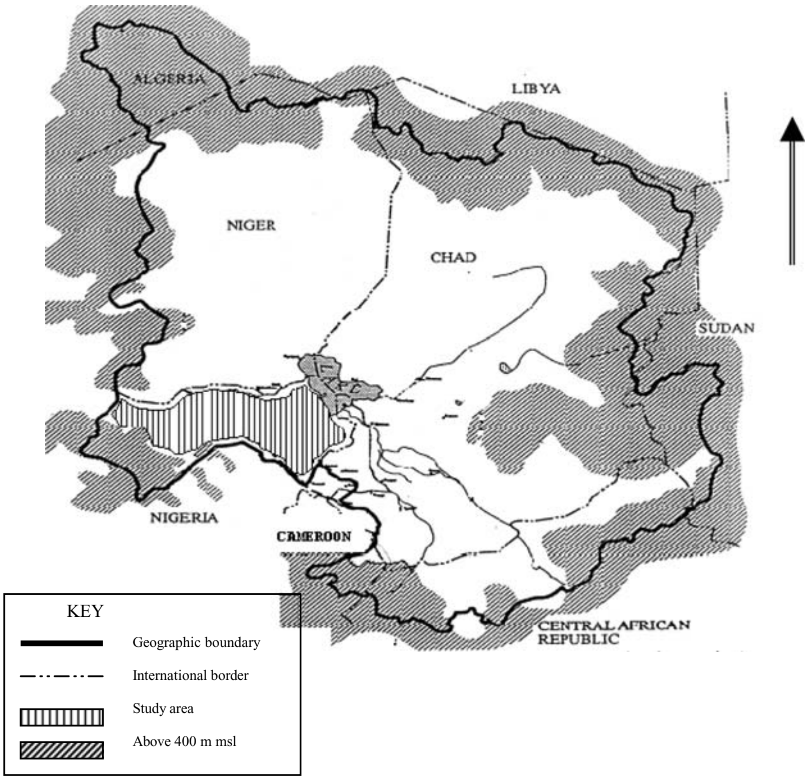



**Fig. 2** Map of the study area showing meteorological stations, isohyets of mean annual rainfall, and some major towns

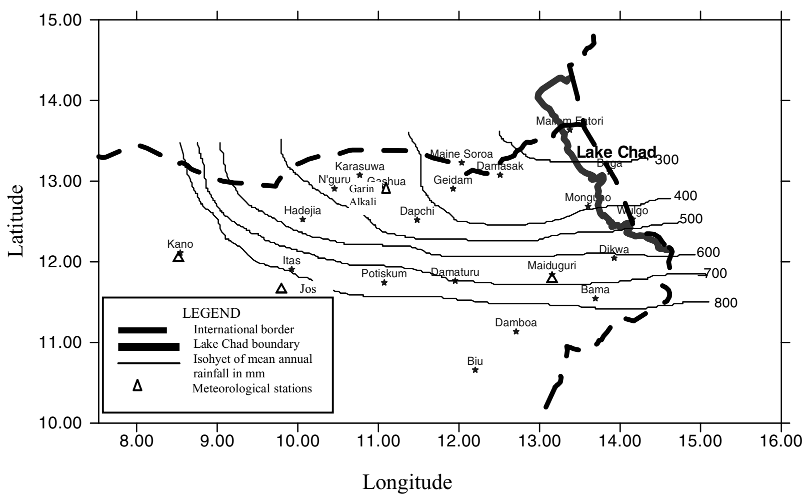
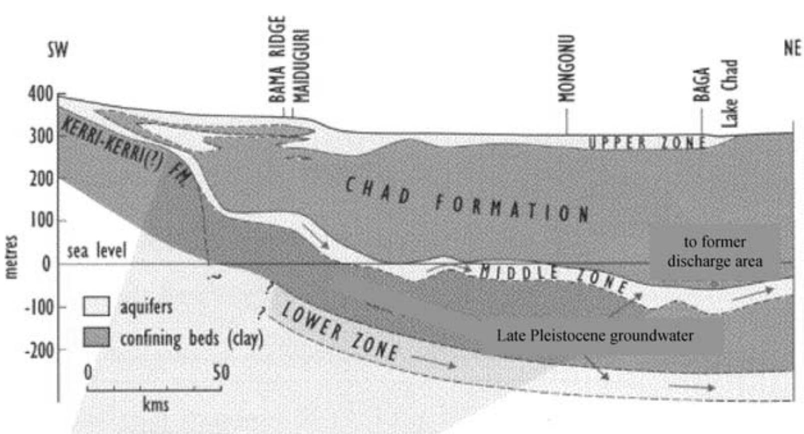



**Fig. 3** Geologic cross section through the Chad Formation showing the Upper, Middle and Lower Zones aquifer




 DOI 10.1007/s10040-005-0469-y

size throughout the Quaternary (Durand 1995). The clays are mainly lake deposits laid down under non-turbulent conditions and are most extensive near to the present day lake shore.

The lithological logs from the area are highly variable and it is currently not possible to present a stratigraphy of the near surface formations. Around Maiduguri (type locality of the Chad Formation) the Upper Zone aquifer includes not only a surface zone of recent sands with an unconfined water table but deeper layers of sands of Chad Formation, complexly intercalated between clays, and partially confined by the clays. Beacon Services Ltd. (1979) further subdivided the Upper Zone aquifer into three units, an upper A unit under water table conditions and underlying B and C units which are semi-confined and/or confined. Water table is generally at a depth of 20 m.

## Methodology

Samples of rainfall were collected from rain gauges by local meteorological observers at two sites in the south-western Chad basin (Fig. 2)—at Garin Alkali (12°48.97′N, 11°03.07′E) and Maiduguri (11°51.88′N, 13°13.25′E)—on a storm event basis throughout the rainy seasons of 1997 and 2001, respectively. Rainfall amount is measured at the end of each event and sample immediately poured into a Nalgene® bottle to minimise evaporation. Samples of surface water from rivers and Lake Chad were collected by dipping sample bottles into the water body directly and sealing it immediately afterwards.

Groundwater samples were collected mostly from pumping boreholes and some from dug wells tapping the three aquifers. The boreholes are usually deep (over 50 m) and screened in the lower part of an aquifer. For the confined aquifers, borehole depths range between 250 and 350 m and 450 and 650 m, respectively, for the Middle and Lower Zones aquifers. Where multiple aquifers are encountered in a borehole, the lower aquifer is usually screened. Therefore, the possibility of mixing of water during sampling is only likely in the boreholes tapping the Upper Zone aquifer, where waters from the three units (A, B and C) may mix because of their complex relations, especially outside the type locality. The dug wells range in depth between 20 and 40 m and about 2 m in diameter. Depth to water is, on average, about 20 m.

Polythene (LDPE) bottles were used for the sampling, which are properly sealed and all samples were sent to either British Geological Survey, UK or GSF Germany laboratories for the analysis of stable isotopes (oxygen-18 and deuterium). The isotope analysis was carried out on a VG 602E mass spectrometer following standard preparation techniques, namely the reaction of 10 µl water with heated zinc shot $\delta^2$H and equilibration of 5 ml water with $CO_2$ of known isotopic composition $\delta^{18}$O. Precision is ±2‰ for deuterium and ±0.2‰ for oxygen-18.

## Results and discussion

### *Rainwater*

The isotope chemistry of rainfall in the Sahel region is extremely variable, both geographically and temporally, responding to atmospheric circulation patterns. The source of precipitation for the Sahara-Sahel, including the southwestern part of the Chad basin, is the Gulf of Guinea (Taupin et al. 2000). However re-evaporated water from the continent is an important source of water vapour as shown by the lack of continental effect and also a large deuterium excess at the beginning and end of the rainy season (Taupin et al. 1997, 2000). Although temperature is an important factor controlling the variation in the isotopic content of rainfall, it has been shown (e.g., Fontes 1976) that there is often no clear relationship between temperatures measured on the ground and the isotopic composition of tropical rains, indicating that other processes must be involved. As storms develop, convection leads to low condensation temperatures at the height of the vertical cloud development (Fontes et al. 1993; Taupin et al. 1995). Thus, rains in the study area and elsewhere at the peak of the season in August are the most depleted in the heavier isotopes (Mbonu and Travi 1994; Taupin et al. 1997). The amount of rainfall in a storm event can also affect the isotopic signature. The relative humidity of the air column is also very important. Rains of less than 5 mm have been shown to be heavier as a result of evaporation leading to loss of the lighter isotopes as rain droplets fall through drier air (Gat 1980). Thus the extreme climatic and meteorological situations found in tropical monsoon regions can produce very different isotopic signatures for individual rain episodes.

Weighted mean stable isotope data in rainfall from stations at: Maiduguri in 2001 and Garin Alkali in May–July 1997 (the present study); Kano in 1963–1973 ((Global Networks of Isotopes in Precipitation (GNIP database) of the International Atomic Energy Agency (IAEA)); and Jos in 1989 (Mbonu and Travi 1994). These are shown in Fig. 4. It was noted that the weighted mean for the Garin Alkali

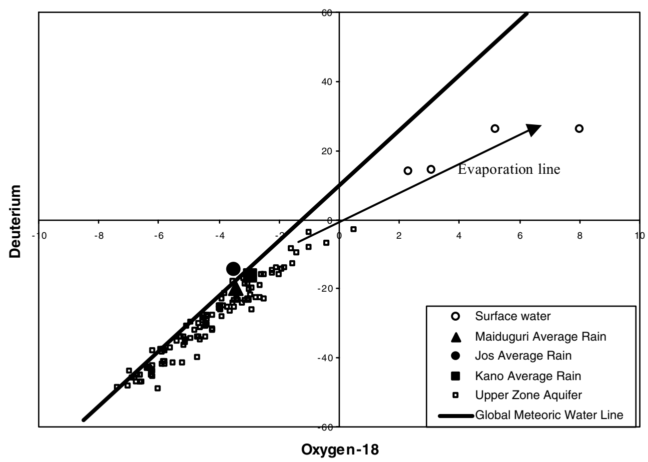



**Fig. 4** Stable isotope contents for rainfall (weighted mean) from stations in northern Nigeria, surface water and Upper Zone aquifer groundwater. *Arrow* shows the evaporation line

 DOI 10.1007/s10040-005-0469-y

site (−3.6‰ $\delta^{18}$O and −10.4‰ $\delta^{2}$H) was slightly more enriched when compared to the mean for the other stations, which is attributable to the exclusion of the rains of July and August that are usually more intense and thus more depleted. Also, the Garin Alkali and Jos mean data plot above the global meteoric water line (Fig. 4), indicating the importance of recycled water vapour under low humidity conditions in contributing to the rainfall (Clark and Fritz 1997). The characterisation of the isotopic composition of the rainfall is significant in tracing the origin of the groundwater since, in general, recharging water may correspond to a composition close to the weighted mean values (Goni et al. 2001). Therefore, for the purpose of tracing the present day signal in the groundwater, weighted mean ranges of −4‰ to −3‰ $\delta^{18}$O and −40‰ to −20‰ $\delta^{2}$H are appropriate and are used in this study.

Oxygen-18 data (Table 1) show that the lake water is as expected: evaporated with approximately 5‰ $\delta^{18}$O. The Komadougou Yobe river water range from −1.6‰ to +2.5‰ $\delta^{18}$O (Table 1). Also, river Yedseram farther south exhibits more depleted values (−3.3‰ $\delta^{18}$O) compared to river Ngadda (−0.39‰ $\delta^{18}$O) that is relatively farther north. In general, the stable isotope content of the surface water show that it is evaporated, plotting off the Global Meteoric Water Line (GMWL) along the evaporation line (Fig. 4).

## Groundwater

The stable isotopes (deuterium and oxygen-18) are part of the water molecule and thus can play an important role in the study of groundwater. They can be used to trace the origin of water, the mode of recharge, determination of relative age (as old waters can be distinguished from present day recharged waters) and therefore recharge in a qualitative sense. Unlike in temperate regions, the isotopic composition of groundwater in arid regions can be considerably modified from the local precipitation (Clark and Fritz 1997). This is caused by the strong isotopic enrichment during evaporation. Despite the strong evaporation in arid regions, it is possible to have present day recharged waters with isotope contents close to the mean composition of precipitation. This has been observed in central Africa (Mathieu and Bariac 1996) where soil profiles show the typical evaporative isotope enrichments, yet little to no enrichment is observed in the groundwater. This has been attributed to macropores and preferential flow channels in the unsaturated zone, permitting the fast movement of water to the water table with very limited mixing with the enriched water found in the upper parts of the profile. What is significant here is tracing the stable isotope signal of rainfall in groundwater in order to demonstrate present day recharge.

Stable isotope compositions of water from the three aquifer zones in the southwestern part of the Chad basin are presented in Tables 2, 3 and 4. These data show that the Upper Zone aquifer has a wide range of composition with values from −7‰ to +3‰ $\delta^{18}$O and −50‰ to +14‰ $\delta^{2}$H (Table 2). Plot of stable isotope data on a delta diagram (Fig. 4) shows that some samples plot in the same region as those of the confined aquifers' groundwater. Some other samples plot in the same region as those of average present day rainfall. Yet another set is the data that plot between the two regions, indicating mixing of the two types of waters.

Water from the Middle and Lower Zones aquifers tends to have relatively smaller range of values −7‰ to −5‰ $\delta^{18}$O and −50‰ to −30‰ $\delta^{2}$H (Tables 3, 4). There is no apparent difference between compositions of water in the Middle Zone aquifer and those of the Lower Zone aquifer, perhaps indicating similarities in mechanism and timing of recharge. Edmunds et al. (1998) have studied the confined aquifers of the area using the activity of $^{14}$C and observed

**Table 1** Surface water data

| Location | Latitude | Longitude | pH | EC (uS/cm) | $T$ (°C) | $\delta^{18}$O | $\delta^{2}$H |
|---|---|---|---|---|---|---|---|
| River water Garin Gwanna | 12°49.89′ | 10°59.33′ | 8.11 | | | 8 | 26 |
| Yobe R. (Gashua) | 12°52.15′ | 11°03.00′ | 7 | 143 | 30.9 | −4.1 | |
| Lake Alo | 11°43.46′ | 13°17.12′ | | 173.5 | 32.3 | 5.27 | 23.6 |
| River Yobe at MF | | | 7.62 | 108.3 | 28.6 | | |
| Komadougou Yobe | 13°32.00′ | 13°10.00′ | | <140 | | 2.59 | |
| Komadougou Yobe | 13°06.00′ | 12°29.50′ | | | | −1.64 | |
| Komadougou Yobe | 13°32.00′ | 13°10.00′ | | <140 | 23.5 | −0.46 | |
| Komadougou Yobe | 13°42.00′ | 13°19.00′ | | <140 | 19.2 | 1.6 | |
| River Tilde | 10°03.00′ | 09°00.00′ | | | 20.5 | −1.24 | |
| River Ngadda | 11°14.00′ | 13°09.17′ | | 140 | 28.2 | −0.39 | |
| River Yedseram | 11°15.00′ | 13°20.34′ | | <140 | | −3.3 | |
| River Yantage | 11°08.00′ | 13°30.17′ | | | | −3.75 | |
| Lake Chad | 13°43.00′ | 13°40.00′ | | 310 | 17.9 | 5.17 | |
| Lake Chad (At 5 m depth) | 13°43.00′ | 13°40.00′ | | 325 | 17.8 | 5.25 | |
| Lake Chad | 13°40.00′ | 13°33.00′ | | 380 | 19.5 | 6.16 | |
| Lake Chad | 13°36.00′ | 13°28.00′ | | 320 | 20 | 5.17 | |
| Lake Chad | 13°08.73′ | 13°50.13′ | | 299 | 36.8 | 4.84 | 23.5 |
| Lake Bisugu | 12°33.34′ | 11°46.00′ | | <140 | 25 | −0.39 | −16.3 |

 DOI 10.1007/s10040-005-0469-y

**Table 2** Upper Zone aquifer data

| Location | Latitude | Longitude | pH | EC (uS/cm) | T (°C) | $\delta^{18}O$ | $\delta^{2}H$ | $^{14}C$ (pmC) | $\delta^{13}C$ |
|---|---|---|---|---|---|---|---|---|---|
| Molai Hospital | N13°05.97′ | E11°44.65′ | 6.2 | | 32.3 | −5.06 | −31 | 52.59 | −13.9 |
| Konduga | N13°25.41′ | E11°39.59′ | 6.19 | | 33.9 | −6.96 | −44 | 7.63 | −11.4 |
| Bazamri 5 Km N Konduga | | | | | | −3.93 | −26 | 74.1 | −12.1 |
| Kajiri | N13°45.64′ | E11°26.66′ | 6.25 | | 29.3 | −4.44 | −30 | 64.76 | −13.2 |
| Bama South BOSADP | N13°42.77′ | E11°29.81′ | 6.74 | | 31.9 | −4.43 | −31 | 74.27 | −11.8 |
| Kawuri | N13°42.27′ | E11°34.41′ | 5.59 | | 30.3 | −5.86 | −42 | 20.21 | −6.8 |
| Bama South BOSADP | N13°40.55′ | E11°30.88′ | 6.85 | | 33.1 | −6.36 | −43 | | −13.7 |
| Maid Biu RD | | | 6.49 | | 31.2 | −5.79 | −38 | 56.71 | −14.4 |
| Maid Girls School | | | 6.38 | | 31.0 | −5.78 | −42 | | |
| Dikwa BOSADP | N13°54.35′ | E12°02.17′ | 7.03 | | 30.5 | −3.02 | −19 | 77.38 | −11.5 |
| Garin Semiye | N13°29.45′ | E11°53.43′ | 6.99 | | 31.5 | −5.3 | −34 | | |
| Maimalari | | | 6.28 | | 30.2 | −5.77 | −41 | 18.63 | −15.5 |
| Mainari | N11°02.23′ | E12°57.30′ | 6.83 | | 29.7 | −4.42 | −34 | 49.89 | −13.2 |
| Jajubari | N10°59.40′ | E12°46.34′ | 6.87 | | 30.2 | −4.21 | −32 | 30.46 | −14.1 |
| Garin Gwamna | N10°59.33′ | E12°49.89′ | 7.46 | | 25.6 | −0.41 | −7 | | |
| Kurtari | N12°04.94′ | E12°52.44′ | 7.2 | | | −2.5 | −16 | | |
| Layi | N12°53.73′ | E12°32.29′ | 7.7 | | | −3.9 | −28 | | |
| Close to Damasak | N13°01.56′ | E12°33.33′ | 8.31 | | | −3.4 | −23 | | |
| Damasak | N13°05.96′ | E12°30.83′ | 8.08 | | 29.1 | −2.9 | −20 | | |
| Minari | N13°30.56′ | E13°02.04′ | 8.26 | | | 0.5 | −3 | | |
| Mallam Fatori | | | 8.3 | | | −6 | −49 | | |
| Chadi Kakari | N13°23.97′ | E13°18.46′ | 8.72 | | | 2.3 | 14 | | |
| Ngamdu | N11°45.86′ | E12°15.24′ | 6.54 | | 32.2 | −6.2 | −44 | | |
| North of Damaturi | N12°01.61′ | E11°49.32′ | 7.58 | | 32.9 | −6.9 | −46 | | |
| Garin Gwamna 2 | N10°59.33′ | E12°49.89′ | 8.33 | | | −1 | −8 | | |
| Karasuwa | | | 5.96 | | 26.0 | −5.1 | −35 | | |
| Garin Mamadu | N13°08.93′ | E10°52.98′ | 7.72 | | | −4.4 | −28 | | |
| Mainari | | | 7.88 | | | −4.4 | −29 | | |
| Maimalari 2 | | | 7.92 | | | −6.2 | −38 | | |
| Geidam | N12°52.98′ | E11°55.66′ | 5.43 | | 31.0 | −2.1 | −14 | | |
| Kirgimtilo | | | 8.33 | | | −3.2 | −24 | | |
| Garin Alkali | N12°49.45′ | E11°03.00′ | | | | −2.5 | −23 | | |
| Dogou Markai | N12°43.00′ | E11°12.00′ | | | | −4.7 | −40 | | |
| Garin Boka | N12°39.45′ | E11°17.00′ | | | | −5.6 | −37 | | |
| Ingweljabi | N12°32.00′ | E11°17.00′ | | | | −6.6 | −47 | | |
| Jambam | N12°29.15′ | E11°32.00′ | | | | −2.9 | −26 | | |
| Geidam | N12°53.40′ | E11°56.00′ | | | | −4.7 | −34 | | −13.1 |
| Dala Alamdari | N11°48.15′ | E13°08.57′ | 8.4 | 145 | 32.5 | 3.09 | 14 | | |
| Kangaderi | N11°46.00′ | E13°06.64′ | 6.7 | 117 | 31.2 | −4.61 | −35 | | |
| Molai Bariki | N11°45.72′ | E13°06.74′ | 6.37 | 149 | 30.4 | −4.93 | −34 | | |
| Mai Bukarti | N11°44.33′ | E13°05.38′ | 6.71 | 146 | 31.2 | −5.17 | −34 | | |
| Banki (Wajare) | N11°15.03′ | E14°08.94′ | 6.47 | 382 | 30.8 | −3.82 | −22 | | |
| Compr. Health Centre Banki | N11°15.68′ | E14°08.38′ | 7.42 | 565 | 29.4 | −4.48 | −29 | | |
| Banki (Walasa Jaudiri) | N11°18.24′ | E14°04.17′ | 7.31 | 782 | 30.3 | −5.25 | −34 | | |
| Dareljamal | N11°19.35′ | E13°58.45′ | 6.93 | 716 | 31.5 | −3.87 | −25 | | |
| Mangari | N11°24.66′ | E13°49.43′ | 6.61 | 235 | 31.0 | −3.97 | −26 | | |
| Sadori | N11°26.48′ | E13°46.98′ | 6.51 | 244 | 31.3 | −4.41 | −28 | | |
| Kajeri | N11°26.86′ | E13°45.65′ | 6.69 | 374 | 29.7 | −3.93 | −25 | | |
| Bama | N11°31.41′ | E13°41.15′ | 6.73 | 467 | 31.1 | −2.59 | −16 | | |
| Ngauramari | N11°31.92′ | E13°38.04′ | 6.6 | 236 | 30.0 | −4.49 | −28 | | |
| Kawuri | N11°34.36′ | E13°32.34′ | 6.75 | 845 | 30.5 | −3.92 | −25 | | |
| Kawuri | N11°34.44′ | E13°32.23′ | 6.32 | 160 | 30.5 | −5.85 | −41 | | |


DOI 10.1007/s10040-005-0469-y

**Table 2** Continued

| Location | Latitude | Longitude | pH | EC (uS/cm) | T (°C) | δ18O | δ2H | 14C (pmC) | δ13C |
|---|---|---|---|---|---|---|---|---|---|
| Bingeri | N11°40.92′ | E13°21.94′ | 6.21 | 124 | 32.3 | −2.64 | −19 | | |
| Malari | N11°41.84′ | E13°20.86′ | 6.21 | 116 | 30.8 | −2.00 | −16 | | |
| Dalori | N11°5.46′ | E13°15.91′ | 7.28 | 208 | 30.5 | −3.47 | −25 | | |
| Dala Alamdari | N11°48.26′ | E13°06.54′ | 6.3 | 158 | 29.9 | −3.36 | −23 | | |
| Sharaton Bridge | N11°48.54′ | E13°07.24′ | 6.38 | 170 | 30.5 | −4.42 | −31 | | |
| Chabbal | N11°57.32′ | E13°00.11′ | 7.36 | 701 | 31.0 | −4.62 | −31 | | |
| Hoyo | N12°00.05′ | E12°56.94′ | 7.28 | 403 | 31.4 | −4.62 | −31 | | |
| Chabbal | N11°54.29′ | E13°04.24′ | 7.37 | 402 | 33.8 | −6.24 | −45 | | |
| Kofa | N11°45.81′ | E13°14.53′ | 7.15 | 244 | 30.6 | −3.64 | −27 | | |
| Dalori (Family Support Farm) | N11°44.52′ | E13°16.49′ | 6.72 | 192 | 32.1 | −3.73 | −25 | | |
| Kalari | N11°44.19′ | E13°16.99′ | 7.16 | 373 | 29.9 | −2.97 | −20 | | |
| Kalari | N11°44.16′ | E13°17.04′ | 6.53 | 8460 | 29.7 | −2.20 | −16 | | |
| Awa-Isari | N11°42.75′ | E13°15.97′ | 7.48 | 1925 | 29.1 | −1.89 | −14 | | |
| Amarwa | N11°43.65′ | E13°17.94′ | 6.32 | 117 | 31.1 | −1.79 | −14 | | |
| Amarwa | N11°43.74′ | E13°17.84′ | 6.66 | 712 | 29.9 | −1.52 | −13 | | |
| Kimeri | N11°42.63′ | E13°19.19′ | 6.53 | 176 | 31.0 | −2.21 | −15 | | |
| Moshmari | N11°40.11′ | E13°23.53′ | 6.46 | 116 | 30.4 | −3.50 | −23 | | |
| Konduga | N11°38.91′ | E13°25.00′ | 6.62 | 451 | 29.7 | −3.93 | −26 | | |
| Galemeri | N11°52.62′ | E13°16.65′ | 7.13 | 906 | 31.4 | −5.13 | −36 | | |
| Yari | N11°52.67′ | E13°17.61′ | 7.22 | 888 | 31.7 | −5.17 | −36 | | |
| Gajigana | N12°15.16′ | E13°06.21′ | 6.56 | 642 | 36.1 | −6.27 | −43 | | |
| Auno | N11°50.90′ | E12°56.12′ | 6.6 | 657 | 30.1 | −6.35 | −43 | | |
| Auno | N11°50.86′ | E12°56.20′ | 6.84 | 775 | 32.7 | −6.20 | −42 | | |
| Jakana | N11°50.57′ | E12°46.46′ | 6.57 | 937 | 32.3 | −6.68 | −45 | | |
| Mainok | N11°49.99′ | E12°37.79′ | 5.72 | 160 | 30.8 | −6.56 | −47 | | |
| Mainok | N11°49.61′ | E12°37.98′ | 6.06 | 262 | 31.3 | −5.83 | −38 | | |
| Beni Sheikh | N11°48.45′ | E12°29.27′ | 6.32 | 250 | 32.7 | −6.74 | −47 | | |
| Beni Sheikh | N11°48.37′ | E12°29.08′ | 7.15 | 60 | 33.3 | −1.42 | −10 | | |
| Ngamdu | N11°45.67′ | E12°15.76′ | 6.86 | 225 | 29.6 | −6.26 | −43 | | |
| J.I. Ben-Kalio Estate Damaturu | N11°44.19′ | E12°00.30′ | 5.99 | 134 | 33.0 | −6.78 | −46 | | |
| Damaturu (Sabon-pegi) | N11°44.81′ | E11°58.46′ | 6.02 | 185 | 34.1 | −7.00 | −48 | | |
| Police Barrack Damaturu | N11°44.33′ | E11°57.71′ | 5.81 | 157 | 34.0 | −6.63 | −45 | | |
| 250 Estate Damaturu | N11°44.23′ | E11°56.47′ | 5.83 | 139 | 31.0 | −4.66 | −30 | | |
| Mile Biyar (Fune L.G.A.) | N11°42.16′ | E11°42.45′ | 5.47 | 38 | 27.7 | −3.53 | −18 | | |
| Ngelzarma | N11°41.53′ | E11°37.46′ | 4.75 | 217 | 28.2 | −3.16 | −17 | | |
| Sabon Garin Idi Barde | N11°39.87′ | E11°30.33′ | 5.38 | 102 | 28.9 | −4.00 | −25 | | |
| Gununu (Fune L.G.A.) | N11°39.30′ | E11°27.38′ | 5.36 | 58 | 30.5 | −5.94 | −37 | | |
| Dogon Kuka | N11°39.79′ | E11°25.17′ | 5.13 | 55 | 31.2 | −5.41 | −35 | | |
| Damagum | N11°40.57′ | E11°20.65′ | 6.01 | 162 | 29.4 | −5.89 | −38 | | |
| State Hotel Potiskum | N11°43.02′ | E11°03.06′ | 5.27 | 68 | 29.4 | −4.51 | −29 | | |
| Potiskum (Indiski) | N11°43.56′ | E11°05.66′ | 5.9 | 137 | 29.8 | −4.95 | −30 | | |
| Sabon Garin Nangere | N11°51.05′ | E11°04.54′ | 7.31 | 446 | 32.2 | −7.37 | −49 | | |
| Sabon Garin Nangere | N11°51.05′ | E11°04.54′ | 6.88 | 509 | 28.4 | −4.82 | −32 | | |
| Dawasa | N11°58.65′ | E10°57.29′ | 6.56 | 364 | 29.1 | −4.51 | −29 | | |
| Garin Mai Taru | N12°05.26′ | E10°55.71′ | 6.77 | 26 | 27.4 | −3.87 | −23 | | |
| Garin Mai Taru | N12°05.37′ | E10°55.68′ | 6.33 | 65 | 29.9 | −4.21 | −28 | | |
| Budua | N12°12.16′ | E10°52.54′ | 6.47 | 159 | 31.3 | −4.40 | −30 | | |
| Jakusko | N12°21.87′ | E10°46.55′ | 6.77 | 165 | 28.7 | −1.00 | −4 | | |
| Garin Mallam | N12°40.11′ | E10°57.08′ | 6.64 | 298 | 31.3 | −4.22 | −32 | | |
| Garin Alkali (Masaba L.G.A.) | N12°49.15′ | E11°03.42′ | 6.88 | 262 | 32.1 | −5.51 | −42 | | |

 DOI 10.1007/s10040-005-0469-y

**Table 2** Continued

| Location | Latitude | Longitude | pH | EC (uS/cm) | T (°C) | $\delta^{18}O$ | $\delta^{2}H$ | $^{14}C$ (pmC) | $\delta^{13}C$ |
|---|---|---|---|---|---|---|---|---|---|
| Gashua | N12°51.71′ | E11°02.70′ | 7.37 | 55 | 28.7 | −3.11 | −19 | | |
| Gashua | N12°51.82′ | E11°02.63′ | 6.1 | 164 | 30.5 | −3.12 | −23 | | |
| Central Mosque Gashua | N12°52.08′ | E11°02.61′ | 6.36 | 206 | 31.0 | −5.20 | −41 | | |
| Emir palace Gashua | N12°52.08′ | E11°02.77′ | 6.13 | 566 | 29.0 | −3.52 | −24 | | |
| Garun Dole | N12°48.32′ | E11°13.45′ | 6.89 | 267 | 30.5 | −3.04 | −23 | | |
| Kankere | N12°47.51′ | E11°21.59′ | 6.55 | 134 | 31.3 | −2.96 | −22 | | |
| Bayamari | N12°46.05′ | E11°30.47′ | 6.42 | 139 | 31.4 | −2.98 | −24 | | |
| Bukarti | N12°37.69′ | E11°30.87′ | 6.5 | 166 | 31.6 | −6.20 | −46 | | |
| Dapchi | N12°29.82′ | E11°30.32′ | 6.57 | 141 | 32.0 | −2.63 | −22 | | |
| Dapchi | N12°29.82′ | E11°30.34′ | 6.56 | 217 | 30.4 | −2.78 | −23 | | |
| Dapchi | N12°29.62′ | E11°30.42′ | 6.9 | 51 | 30.1 | −1.57 | −8 | | |
| Kaliari | N12°22.85′ | E11°38.06′ | 6.77 | 167 | 31.2 | −4.67 | −34 | | |

**Table 3** Middle Zone aquifer data

| Location | Latitude | Longitude | pH | EC (uS/cm) | T (°C) | $\delta^{18}O$ | $\delta^{2}H$ | $^{14}C$ (pmC) | $\delta^{13}C$ |
|---|---|---|---|---|---|---|---|---|---|
| Bramandiri | N13°06.75′ | E11°59.31′ | 6.11 | | 38.8 | −6 | −40 | 4.99 | −14 |
| Mafa Town | | | 6.63 | | 37.6 | −5.64 | −35 | | |
| Umarari | N13°22.70′ | E11°52.83′ | 6.39 | | 36.2 | −5.15 | −31 | 3.84 | −16 |
| Logomani West | N14°00.87′ | E12°11.08′ | 6.43 | | 38.5 | −6.02 | −43 | 5 | −16.1 |
| Ngala West | N14°09.88′ | E12°21.48′ | 6.68 | | 39.1 | −6.27 | −47 | 3.55 | −15.5 |
| Missuni | N14°04.51′ | E12°16.13′ | 6.53 | | 38.7 | −6.2 | −45 | 5.12 | −16.4 |
| Gajibo | N13°59.35′ | E12°06.53′ | 6.38 | | 38.2 | −6 | −44 | 4.22 | −11.9 |
| Kuduge | N13°57.90′ | E12°01.54′ | 6.45 | | 38.7 | −5.84 | −43 | 2.8 | −11 |
| Mafa Ngubdori | N13°37.65′ | E11°56.13′ | 6.23 | | 38.6 | −5.51 | −40 | 5.39 | −14 |
| Maid Damboa RD 2 | N13°07.80′ | E11°47.87′ | 6.47 | | 36.0 | −6.68 | −42 | | |
| Maid Lagos ST | | | 6.43 | | 35.4 | −5 | −34 | 18.78 | −12.1 |
| Kaje | N13°54.61′ | E12°08.92′ | 6.34 | | 38.3 | −6.62 | −40 | | |
| Old Marte | N13°49.68′ | E12°21.91′ | 6.51 | | 38.5 | −5.93 | −41 | 2.44 | −14.6 |
| Kirinowa | N13°55.67′ | E12°25.65′ | 6.77 | | 38.5 | −5.85 | −42 | 2.62 | −16 |
| Kirinowa West | N13°53.27′ | E12°20.03′ | 6.89 | | 38.4 | −5.9 | −31 | | |
| New Marte CBDA | | | 7.91 | | 38.4 | −6.9 | −48 | | |
| Dikwa | N13°54.05′ | E12°02.46′ | 6.21 | | 38.3 | −6.02 | −45 | 2.66 | −10.9 |
| Magumeri | N12°06.85′ | E12°49.94′ | 8.1 | | 39.8 | −6.4 | −43 | | |
| Kareram | N12°11.49′ | E12°47.01′ | 5.51 | | 36.6 | −6.5 | −45 | | |
| Gubio | N12°29.94′ | E12°47.33′ | 6.04 | | 37.5 | −6.8 | −45 | | |
| Madamari | N12°17.33′ | E12°47.67′ | 5.81 | | 39.0 | −6.7 | −45 | | |
| Gubio 2 | N12°28.75′ | E12°47.50′ | 5.51 | | 37.0 | −6.8 | −47 | | |
| Karimboa | N13°19.34′ | E12°44.42′ | 8.04 | | 36.1 | −5.9 | −45 | | |
| Gashagar | N13°22.50′ | E12°47.67′ | 8.26 | | | −6.1 | −47 | | |
| Foguwa | N13°29.65′ | E12°59.58′ | 8.25 | | | −5.8 | −47 | | |
| Kanama | N13°17.46′ | E13°20.67′ | 8.2 | | 38.1 | −6 | −47 | | |
| Konduga | N11°39.01′ | E13°24.74′ | 6.16 | 238 | 35.7 | −6.27 | −44 | | |
| Jetete | N12°02.37′ | E12°54.47′ | 6.6 | 694 | 34.7 | −6.28 | −43 | | |
| Magumeri | N12°06.87′ | E12°49.42′ | 6.43 | 490 | 36.3 | −6.63 | −46 | | |
| Muna Kori | N11°51.93′ | E13°14.42′ | 6.28 | 636 | 37.2 | −5.94 | −40 | | |
| Limanti | N11°52.87′ | E13°22.27′ | 6.4 | 1174 | 36.5 | −4.81 | −33 | | |
| Gubio Junction | N11°54.12′ | E13°05.90′ | 7.05 | 345 | 37.2 | −6.27 | −44 | | |
| Tungushe | N12°01.78′ | E13°03.70′ | 6.64 | 646 | 35.4 | −5.85 | −41 | | |
| Tungushe | N12°02.22′ | E13°04.24′ | 6.28 | 749 | 36.7 | −5.78 | −40 | | |
| Karnowa | N11°08.34′ | E13°04.44′ | 6.44 | 611 | 38.7 | −6.10 | −39 | | |


DOI 10.1007/s10040-005-0469-y

**Table 4** Lower Zone aquifer data

| Location | Latitude | Longitude | pH | EC (uS/cm) | *T* (°C) | $\delta^{18}O$ | $\delta^{2}H$ | $^{14}C$ (pmC) | $\delta^{13}C$ |
|---|---|---|---|---|---|---|---|---|---|
| UNIMAID | | | 6.58 | | 46.4 | −6.53 | −42 | | |
| NNPC Gaji Gana | N13°07.12′ | E12°15.15′ | 6.48 | | 41.1 | −6.38 | −41 | 5.29 | −12.7 |
| Gajiram | N13°12.88′ | E12°29.64′ | 6.55 | | 41.9 | −6.56 | −42 | 6.28 | −15.1 |
| Maid Baga RD | N13°05.89′ | E11°54.12′ | 7.07 | | 47.2 | −6.3 | −40 | 8.16 | −12.8 |
| Touba | N13°08.53′ | E12°08.98′ | 6.44 | | 41.9 | −5.91 | −40 | 4.03 | −14.3 |
| Baga | N13°49.15′ | E13°05.59′ | 6.4 | | 41.3 | −6.77 | −40 | 3.09 | −14.3 |
| Kekeno | N13°40.13′ | E12°47.53′ | 6.78 | | 40.2 | −6.75 | −45 | 4.47 | −13.9 |
| Maid Damboa RD | N13°08.17′ | E11°49.03′ | 6.46 | | 45.8 | −6.41 | −42 | 6.42 | −10.4 |
| Damakulli | N13°22.96′ | E12°16.41′ | 6.24 | | 42.1 | −5.4 | −37 | 3.33 | −14.3 |
| Bidu | N13°27.04′ | E12°20.71′ | 6.37 | | 44.0 | −5.82 | −38 | 2.92 | −14.3 |
| Logomani CBDA | N14°01.13′ | E12°12.50′ | 7.43 | | 44.9 | −6.92 | −50 | 3.88 | −17 |
| Wulgo | N14°10.70′ | E12°29.11′ | 6.53 | | 40.4 | −6.22 | −43 | 2.59 | −15.3 |
| Kukawa | N13°35.15′ | E12°55.61′ | 6.62 | | 44.2 | −6.89 | −44 | 5.41 | −14 |
| Cross Kauwa | N13°40.38′ | E12°56.65′ | 6.47 | | 43.8 | −7.08 | −45 | | |
| Monguno South | N13°34.89′ | E12°41.21′ | 6.64 | | 40.6 | −7.03 | −47 | 3.79 | −13.8 |
| Mairari | N13°26.36′ | E12°40.98′ | 6.73 | | 42.7 | −6.86 | −45 | 4.56 | −12.9 |
| Jagalta | N13°19.06′ | E12°36.28′ | 6.49 | | 41.7 | −6.18 | −44 | 3.85 | −13.2 |
| Zari | N13°05.27′ | E12°44.27′ | 5.55 | | 41.2 | −5.5 | −42 | | |
| Gudumbali | N12°56.61′ | E13°10.44′ | 6.09 | | 41.4 | −6.1 | −44 | | |
| Garanda | N13°00.10′ | E12°59.10′ | 6.25 | | 39.9 | −6.2 | −45 | | |
| Ngam | N13°29.70′ | E12°56.92′ | 8.4 | | 40.6 | −5.8 | −46 | | |
| Arege | N13°29.38′ | E13°19.65′ | 6.2 | | 41.0 | −6.1 | −46 | | |
| Gajigana | N11°14.86′ | E13°06.32′ | 6.87 | 408 | 47.2 | −6.47 | −46 | | |

that timing is rather uniform within the Middle Zone aquifer water at between 2.6 and 5.4 percent modern carbon (pmC) (Table 3); ignoring the abnormal 18.8 (pmC) for location "Maid Lagos ST." However, a higher value of 8.2 (pmC) (Table 4) is found in the Lower Zone aquifer, which they attribute to possibly a slightly higher transmissivity of the zone. A basis for deriving groundwater age is the chemistry of the TDIC combined with the $\delta^{13}C$ values (Edmunds et al. 1998).

The sediments of the Chad basin aquifers are derived from the alkaline geochemical province of the Jos plateau and contain highly weatherable silicate minerals, consuming biogenic $CO_2$ and producing $HCO_3$ and base metal cations in the recharge area. If this were the case, the $\delta^{13}C$ values of TDIC would remain depleted (−17‰ to −19‰), and no correction of the major radiocarbon activities would be required (Fontes 1983). In the southwestern Chad basin, a mean $\delta^{13}C$ value of −14‰ implies some addition of an enriched carbon source, most likely trace carbonate from the lacustrine sediments (Edmunds et al. 1998). The Pearson model (Evans et al. 1979) was used to obtain corrected ages for the Middle Zone aquifer lying in a relatively narrow range of 18.6–24 ka B.P. and for the Lower Zone aquifer having a value of 23.5 ka B.P. at depth (Edmunds et al. 1998). Therefore, the Middle and Lower aquifer Zones contain waters that were recharged around the same time, some 20 ka B.P.

Groundwater from the confined aquifers (Middle and Lower Zones) tends to plot quite characteristically, with depleted $\delta^{18}O$ and deuterium (Fig. 5). This may be as a result of climate change, indicating that the confined aquifers' groundwater was recharged under a climate that is probably different from today. Clark and Fritz (1997) have observed many deep artesian groundwaters from arid regions that have been confirmed by $^{14}C$ dating to contain palaeowater are characterised by depletion in $\delta^{18}O$ and $\delta^{2}H$ with respect to modern waters. Edmunds et al. (1998) have used stable isotope and noble gas data to demonstrate that the confined aquifers' groundwater of the southwestern part of the Chad basin was recharged during climate that is wetter and some 6°C cooler respectively than present. The clustering of the data points on the GMWL also indicate that the effect of

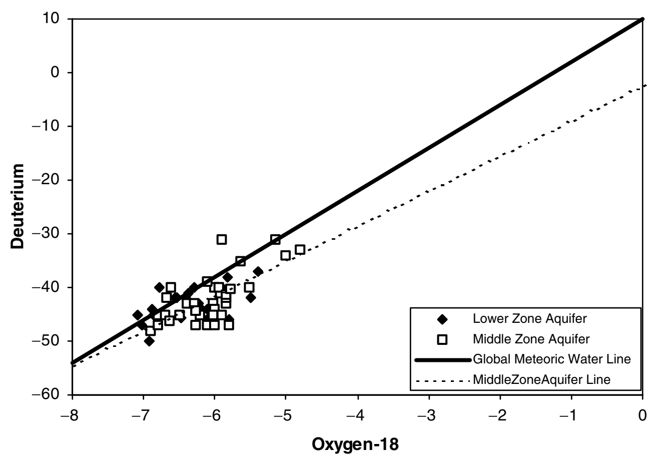



**Fig. 5** Stable isotope contents of aquifer waters from the Middle and Lower Zones

 DOI 10.1007/s10040-005-0469-y

evaporation is minimal, perhaps because of rapid infiltration, but also may be due to prevailing climatic conditions (Goni 2002). Another explanation may be that waters in these aquifer zones have had time to become homogenised by flow, diffusion and dispersion.

## Inter-relationships

Stable isotope data have been used to understand the inter-relationships between the rainwater and groundwater from the aquifers in the southwestern part of the Chad basin. The mean stable isotope data (Fig. 4) from the three stations (Maiduguri, Kano and Jos) with complete rainfall tend to plot within the same zone as those of unevaporated groundwater from the Upper Zone aquifer, presumably the A unit. This indicates that present day rainfall is recharging the A unit of the Upper Zone aquifer, which is generally an unconfined water table aquifer. Depth to this unit is extremely variable ranging from 10 to 70 m and may be locally semi-confined. Some Upper Zone aquifer groundwater shows evidence of evaporation with data plotting along evaporation line (Fig. 4). This may result from evaporated surface water infiltrating along river channels, and/or recharge from some evaporated lighter rains in the northern part. The mean long-term annual average rainfall reduces to less than 400 mm/a in the northern part close to the Niger border. Beacon Services Ltd. (1979) has demonstrated that considerable recharge is taking place to this unit via river channels.

The B unit of the Upper Zone aquifer is semi-confined to confined at an average depth of 40–70 m, with variable thickness. Some water samples from the Upper Zone aquifer plot between depleted and relatively enriched stable isotopes (Fig. 4), which are probably from the B unit. This is because the B unit may contain a complex mixture of water with stable isotopes exhibiting signals that are between present day rainfall and palaeowater. Beacon Services Ltd. (1979) estimate about 120 l/s is leaking from the A unit water table, while infiltration from rainfall is estimated at 80 l/s, accounting for the present day signal. Also, because the underlying aquifers are under pressure, water from these zones may rise and probably reach the B unit, because the piezometric heads in boreholes in the deeper confined aquifers are metres above the ground surface.

The C unit of the Upper Zone aquifer is confined, although it may be semi-confined locally. Depth to this unit averages about 90 m and the thickness is less than 5 m. Some water samples from the Upper Zone aquifer are depleted in stable isotopes and plot in the same region as those of the Middle and Lower Zones aquifer (Figs. 4, 5). These Upper Zone aquifer samples are interpreted as coming from the C unit, because it is the unit that is confined and thus less likely to be recharged when compared to the other units (A and B). The C unit is likely to contain palaeowater probably recharged at the same time as the Middle and Lower Zones aquifer on account of their stable isotope similarities. Already the Middle and Lower Zones aquifers have been shown to contain palaeowaters.

The stable isotopes' data show a wide range of values ( $\delta^2$H from –50 to +14 and $\delta^{18}$O from –7 to +3) from the Upper Zone aquifer, which underscores the complexities of the zone and indicates possible differences in mechanisms of recharge and timing.

The Middle and Lower Zones aquifers contain waters that have stable isotope compositions, which differ from present day precipitation. Some parts of the Upper Zone aquifer also exhibit composition that is different from present day rainfall. Therefore these aquifer zones contain waters that were recharged at a different period and probably have not been coupled to the present day hydrological cycle on the basis of their stable isotope contents. However, based on stratigraphic information some amount of recharge may be taking place at the southern and southwestern parts where they crop out. Overall, it is possible that recharge is taking place, but transmissivity of the zones is very low and thus present day recharge water has not reached the sampled points.

Groundwater in this region is the perennial source of water supply and in the last two decades there has been a continuous decline in head, both of the water table and the piezometric head of confined aquifers. The confined aquifers do not receive present day recharge judging at least from the stable isotope data and therefore abstraction from them amounts to mining. The Upper Zone aquifer is recharged presently, but the fact the water levels in wells tapping this zone are declining calls for concern. With increasing population in the region there will be a corresponding increase in demands for groundwater, being the only perennial source. For a sustainable exploitation of groundwater in this region, there is an urgent need for an accurate assessment of the renewal rate and abstraction limited to this renewable resource.

## Conclusion

Stable isotope data have been used to trace the flow of meteoric water to groundwater in the southwestern part of the Chad basin. The Upper aquifer Zone's water shows a wide range of stable isotopes values. The Middle and Lower aquifers Zones' waters show similar stable isotopes values, perhaps indicating common evolution. These aquifers zones probably contain palaeowaters, which were recharged during periods that are wetter and climates that are cooler than at present. Water from the Middle and Lower Zones have similar compositions with no apparent difference, which was attributed to similarities in mechanism and timing of recharge. Waters from most parts of the Middle and Lower Zones aquifers have not been coupled to the present day hydrological cycle.

**Acknowledgements** Data for this work were obtained under the Technical Co-operation Programme of the IAEA Vienna; project reference NIR/8/006 and NERC (National Environment Research Council) UK funded SAHEL project. I am grateful to Cheikh Gaye the scientific officer of the project for his assistance. I am equally grateful to the Principal Investigators of the SAHEL project W.M.

 DOI 10.1007/s10040-005-0469-y

Edmunds and F.A Street-Perrott. Many thanks are due to Mal. Musa Aji and Mr. Ekene Ani of Geology department, University of Maiduguri and GIBKAM Consult Nig. Ltd., respectively, for their contributions during the fieldwork. Analyses of the samples were carried out in GSF laboratory in Germany. I would like to thank Mal. Modu Sulum and Mr. Chris Maduabuchi for their roles in the project. I appreciate comments on the manuscript by Mal. Zarma of Geology department, University of Maiduguri. I am grateful to the anonymous reviewers for their interest and critical review.

## References

Allison GB, Barnes CJ, Hughes MW, Leancy FWJ (1984) Effect of climate and vegetation on Oxygen-18 and deuterium profiles in soils. In: Proc Int Symp on Isotope Hydrology in Water Resources Development. IAEA-SM-27020, Isotope Hydrology, 1983. IAEA Vienna, pp 105–124

Barber W (1965) Pressure water in the Chad Formation of Bornu and Dikwa emirates, north-eastern Nigeria. Geol Surv Nigeria Bull 35

Barber W, Jones DC (1960) The geology and hydrogeology of the Maiduguri, Borno Province. Geol Surv Nigeria, pp 520–521

Beacon Services Ltd.—Consulint International (1979) Maiduguri water supply, Hydrogeological report, vol 1, Hydrogeology and future exploitation of groundwater. Consulint Int. S.r.l., 158 pp

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

Durand A (1995) Quaternary sediments and climates in the central Sahel. Afr Geosci Rev 2:323–614

Edmunds WM, Fellman E, Baba Goni I, McNeill G, Harkness DD (1998) Groundwater, palaeoclimate and palaeorecharge in the SW Chad basin, Borno State, Nigeria. In: Isotope techniques in the study of past and current environmental changes in the hydrosphere and the atmosphere. IAEA, Vienna, pp 693–707

Evans GV, Otlet RL, Downing RA, Monkhouse RA, Rae G (1979) Some problems in the interpretation of isotope measurements in United Kingdom aquifers. In: Proc Int Symp Neuherberg. Isotope Hydrology, IAEA, Vienna, pp 679–708

Fontes JCh (1976) Isotopes du milieu et cycles des eaux naturelles: quelques aspects [Some aspects of mean isotopes and natural water cycles]. These de Doctorat d'etat, Universite Paris VI

Fontes JC (1983) Dating of groundwater. In: Guidebook on nuclear techniques in hydrology 1983, Tech Rep Ser 91. IAEA, Vienna, pp 285–317

Fontes JC, Gasse F, Andrews JN (1993) Climatic conditions of Holocene groundwater recharge in the Sahel Zone of Africa. In: Isotope techniques in the study of past and current environmental changes in the hydrosphere and the atmosphere. IAEA, Vienna, pp 231–248

Gat JR (1980) The isotopes of hydrogen and oxygen in precipitation. In: Fritz P, Fontes J-Ch (eds) Handbook of environmental isotope geochemistry, vol 1. Elsevier, Amsterdam, pp 21–44

Goni IB (2002) Realimentation des eaux souterraines dan le secteur Nigerian du bassin du lac Tchad: approche hydrogeochimique [Hydrogeochemical approach to groundwater recharge studies in the Nigerian sector of the Chad basin]. These de Doctorat d'etat, Universite d' Avignon, 123 pp

Goni IB, Fellman E, Edmunds WM (2001) A geochemical study of rainfall in the Sahel region of northern Nigeria. Atmosph Envir 35:4331–4339

Goni IB, Kachallah M, Aji MM (2000) Another look at the peizometric head declines in Middle Zone aquifer of the Chad Formation in the Southwestern Chad basin. Borno J Geol 2(1/2):51–64

Lebel T, Sauvageot H, Hoepffner M, Desbois M, Guillot B, Hubert P (1992) Rainfall estimation in the Sahel: the EPSAT-NIGER experiment. J Hydrol Sci 37:201–215

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

Mbonu M, Travi Y (1994) Labelling of precipitation by stable isotopes ($^{18}O$,$^{2}H$) over the Jos Plateau and the surrounding plains (north-central Nigeria). J Afr Earth Sci 19:91–98

Ndubisi OL (1990) Managing groundwater resources of the Lake Chad basin in Nigeria. In: Proc 1st Biannual Nat. Hydrology Symp. Maiduguri, pp 429–436

Offodile ME (1972) Groundwater level fluctuations in the East Chad basin of Nigeria. J Min Geol 7(1/2):19–34

Olugboye MO (1995) Groundwater monitoring network as an aid to averting some ecological disaster; the case for Chad basin area. Water Resour 6(1/2):57–60

Oteze GE, Fayose SA (1988) Regional development in the hydrogeology of Chad basin. Water Resour 1(1):9–29

Saxena RK, Dressie Z (1984) Estimation of groundwater recharge and moisture movement in sandy formation by tracing natural Oxygen-18 and injected tritium profiles in unsaturated zone. Isotope Hydrology, 1983. IAEA, Vienna, Proc Symp 1983, pp 139–150

Schneider J-L (1989) Geologie et Hydrogeologie de la republique du Tchad [Geology and hydrogeology of the republic of Chad]. These de Doctorat d'etat, Universite d' Avignon, vol I

Taupin J-D, Coudrain-Ribstein A, Gallaire R, Zuppi GM, Filly A (2000) Rainfall characteristics ($\delta^{18}O$, $\delta^{2}H$, $\Delta T$ and $\Delta H_r$) in western Africa, regional scale and influence of irrigated areas. J Geophys Res 105:11911–11924

Taupin JD, Gallaire R, Arnaud Y (1997) Analyses isotopiques et chimiques des précipitations sahéliennes de la région de Niamey au Niger: implications climatologiques (Isotope and chemical analyses of Sahelan precipitation of the Niamey region of Niger republic: climatological implications). In: Peters NE, Coudrain-Ribstein A (eds) Hydrochemistry. IAHS Publ 244:151–162

Taupin JD, Gallaire R, Fontes J-Ch (1995) Isotopic study of rainfall in the Sahelian Zone (Niger) along two sections, east-west (Lake Chad-Niamey) and north-south (Agadez-Niamey). In: IAEA (ed) Application of tracers in arid-zone hydrology. IAHS Publ 232:285–292

 DOI 10.1007/s10040-005-0469-y