Applied Water Science (2021) 11:141
https://doi.org/10.1007/s13201-021-01473-7

ORIGINAL ARTICLE

Isotopic composition of precipitation and groundwater onshore of the Rio del Rey Basin, southwest Cameroon: local meteoric lines and recharge

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Received: 18 May 2019 / Accepted: 16 July 2021 / Published online: 24 July 2021

Abstract

The link between rainfall and groundwater recharge in the Rio del Rey Basin, which is of socio-economic importance to Cameroon, is poorly understood. Accordingly, the stable isotopes in monthly rainfall from January to December 2012 (in Lobe and Mundemba) and 52 surface water and groundwater samples were investigated. High values of $\delta^{18}O$ and δD were recorded in the dry period (February to March), and the least values of $\delta^{18}O$ and δD were observed in the wet period (September). This indicates that different condensation processes primarily influenced stable isotopes in rainfall as a function of the difference in moisture sources. The relationship between δD and $\delta^{18}O$ defined the Lobe meteoric water line as $\delta D = 7.97\ \delta^{18}O + 12.48$ and Mundemba water line as $\delta D = 7.75\ \delta^{18}O + 10.79$. The similarity of their slopes to the global meteoric line suggests that the isotopic composition of investigated rains was not significantly affected by evaporation during precipitation. The ranges in deuterium-excess of precipitation from 5.8 to 16.56‰ suggest the source of vapour is from the Atlantic Ocean. The groundwater isotope values (ranging from −3.81 to −2.52‰ for $\delta^{18}O$) plotted close to and along the GMWL, showing that its isotopic composition is of meteoric origin under rapid recharge conditions. The isotopic similarity between groundwater and June–August rains suggests a significant recharge during this period.

Keywords Rainfall · Groundwater · Stable isotopes · Meteoric water line · Recharge · Ndian-Cameroon

Introduction

The availability of freshwater is necessary for any meaningful socio-economic development. Due to the lack of pipe-borne water in the study area (Ndian), 80% of the population depends on groundwater sources such as hand-dug wells and springs and faced with water shortages during the dry season. Therefore, these communities' resort to poor quality water from streams, rivers and the creeks for household use during such periods (Wotany et al. 2013). The quality of the available water in this area is affected by deterioration from effluents from processing factories owned by CDC and PAMOL that are piped or channelled directly into streams and rivers of the area (Tening et al. 2014). Chemicals from the effluents find themselves in water bodies and hence undesirable burdens to the mangrove ecosystem of the study area. Consequently, the assessment and management of water resource in the area are of importance. In recent years, the isotope techniques have been used in water resource management investigations by studying of isotopic composition of surface and groundwater (Craig 1961; Dansgaard 1964; Fontes 1980; Gonfiantini et al. 1998; Gat 2010; Wu et al. 2012). Based on the socio-economic importance of the Rio del Rey Basin, and the lack of isotopic data, studies of the seasonal variation in stable isotope values are of importance to determine the source and recharge of groundwater in the study area. The oxygen-18 and deuterium isotopes are used as tracers for hydrologic studies because their local

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abundance varies significantly with environmental factors such as the altitude of precipitation, source of moisture, amount of rainfall, and extent of evaporation (Ingraham 1998). They are used as tracers in understanding the movement of air masses and continental moisture, evaporation of water bodies and origin of surface and groundwater (Gibson et al. 2005; Kendall and Coplen 2001; Liu et al. 2004; Wirmvem et al. 2014). The objectives of this study included: (1) define the spatio-temporal variations of isotopic composition in rainfall of the study area; (2) produce local meteoric water lines; (3) deduce the origin and recharge period of groundwater for development and sustainability management of groundwater resource.

The study area is located at the western end of the Gulf of Guinea at latitude 4°30′–5°00′N and longitude 8°30′–9°00′. The hydrological cycle is mainly a function of the precipitation regime of an equatorial climate (Etia 1980), with an alternating long rainy season that begins from April to October and a short dry season that spans from November to March.

The drainage pattern (Fig. 1) is dendritic and dominated by rivers that flow into the Atlantic Ocean. These rivers may partly recharge groundwater through unconsolidated sediments and weathered volcanic and basement rocks in the area. The topography can conveniently be divided into different topographical regions (Fig. 2): the Mosongeseli-Isangele area with an elevation between 2 and 40 m (m) above sea level (a.s.l). It generally consists of long ridges with flat or gently undulating crests. Between the ridges are flat, swampy areas where the water table is at or close to the surface. The Mundemba-Ekwe area elevation increases from 80 m a.s.l. in the south-west to 555 m a.s.l. in the south-east along the edge of the rugged Rumpi Hills.

This area is characterized by mangroves of 0–5 m high (Gabche and Smith 2002). Mangroves occupy approximately 30% (3500 km^2) of Cameroon coastal zone (Gabche and Smith 2002) and proceed inland by evergreen forest, which is subjected to intense destruction for plantation agriculture (oil palm, cocoa, and coffee). Four different associations exist: a lowland evergreen, the swamp forest, the piedmont and submontane forests found at altitudes between 500 and 800 m (Letouzey 1985; Thomas 1995, 1997). The canopy type here is 10–15 m high which protects the watershed of the Rumpi Hills. Within the Rio del Rey, apart from the

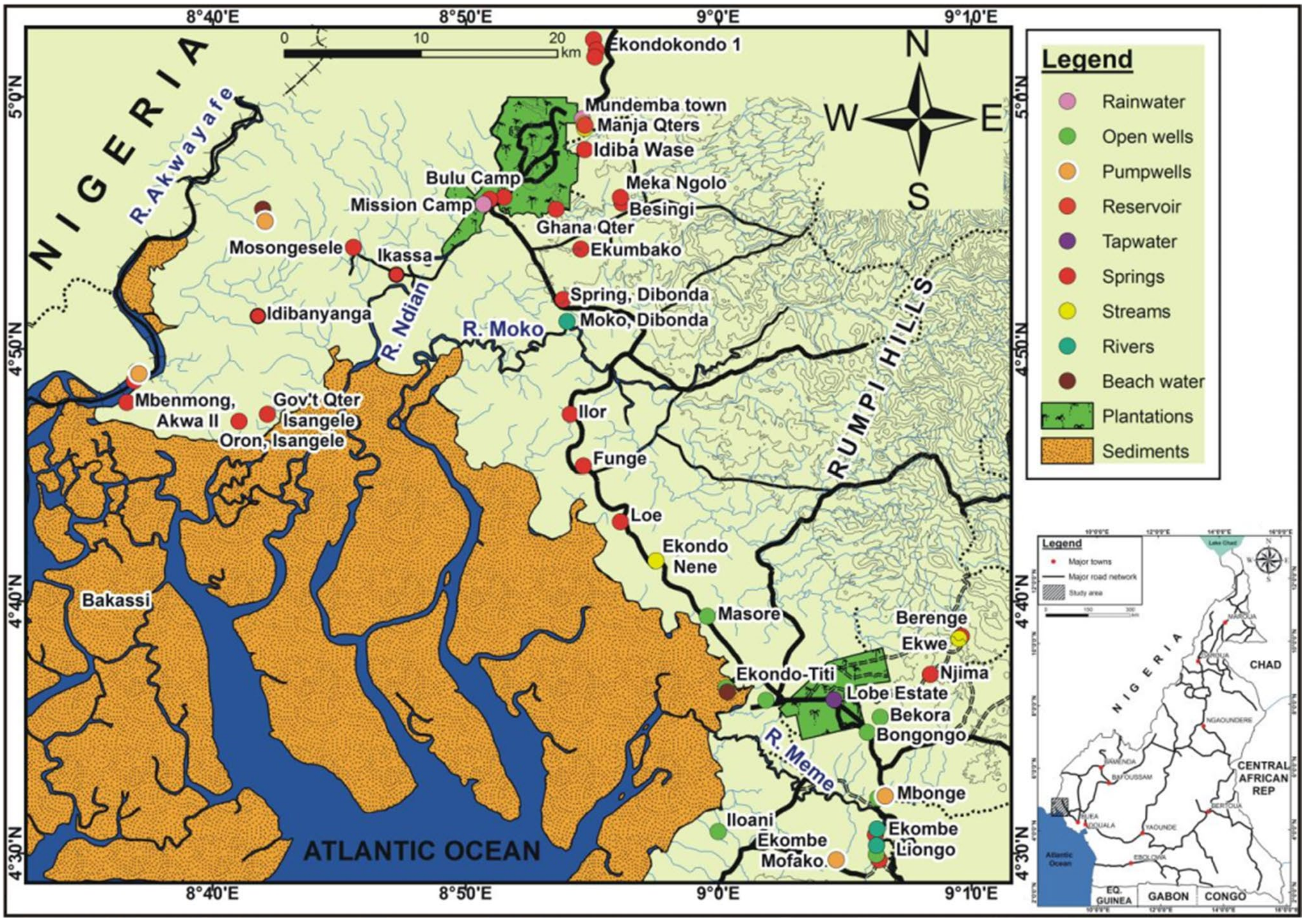


Fig. 1 Map location of sampling sites and drainage pattern of the study area. Inset: Cameroon map showing study area (shaded rectangle)

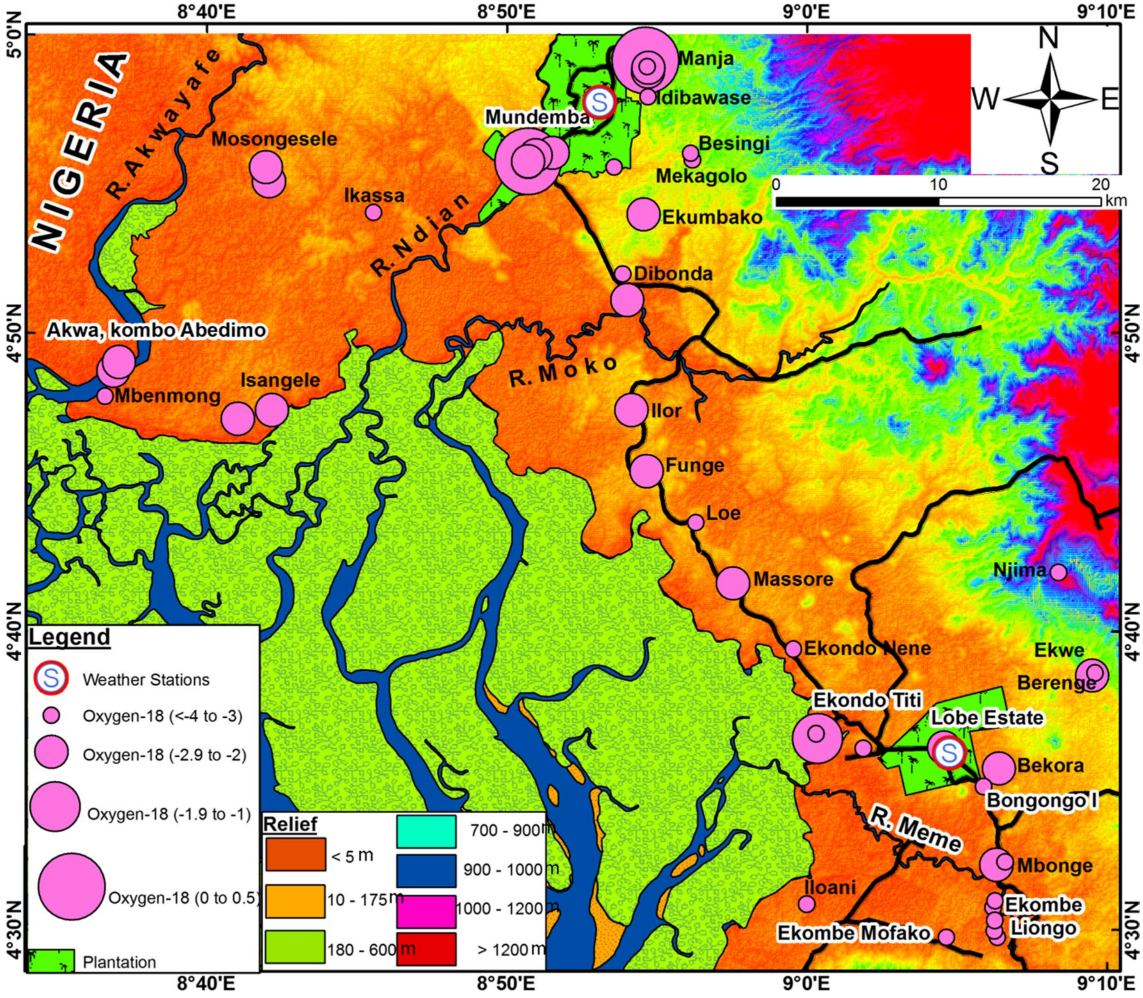


Fig. 2 Map of study area showing relief and spatial distribution of oxygen-18 of ground and surface water sources

traditional cash crops such as cocoa, agro-industrial activities of the area concern essentially oil palm, rubber and banana, which are in the hands of large scale agro-industrial establishments (Tening et al. 2013; Wotany et al. 2014).

The study area is characterized by varied geological settings: metamorphic, volcanic and sedimentary rocks. The variety of rocks includes gneisses, micaschists, and quartzites overlain uncomfortably by limestones, sediments which are essentially clastics consisting of sand, sandstones, conglomerates, limestones, shales, clays, alluvium and basaltic lava flows from the Rumpi Hills (Dumort 1968; Obenesaw et al. 1997; Njoh and Petters 2008; Wotany et al. 2013). Regnoult (1986) also describes the area as made up of limestones, shales, clays of Cretaceous age, and Mio-Pliocene sediments with recent alluvium. Alluvial sand, fractured basement and basaltic materials make up the unconfirmed aquifers. The aquifers of the study area are similar to those of the Oligocene Benin and the Eocene Ogwashi/Asaba aquifers within the Niger Delta Basin, Nigeria. The area has a multi-aquifer system characterized by alternating layers of gravels, sands, silts and clays similar to the aquifers of the Douala basin as described (Mafany et al. 2006; Takem et al. 2010; UNESCO – ISARM 2011; Wotany et al. 2014: Fig. 3).

Materials and methods

Precipitation samples were collected as described by Goni (2006) for a period of one year (January to December 2012) from two rain gauge stations owned by the Pamol research centres (Mundemba: UTM 54,480; 484,386:32masl and Lobe: 508,790; 508,299:61masl) (Fig. 1). Rain samples collected daily for twelve months were poured into 5 L sealed plastic containers. The integrated rain samples were poured into100 mL polythene bottles tightly capped and stored in a cold environment preceding laboratory analysis. Temperature and relative humidity measurements were also recorded. Fifty-two

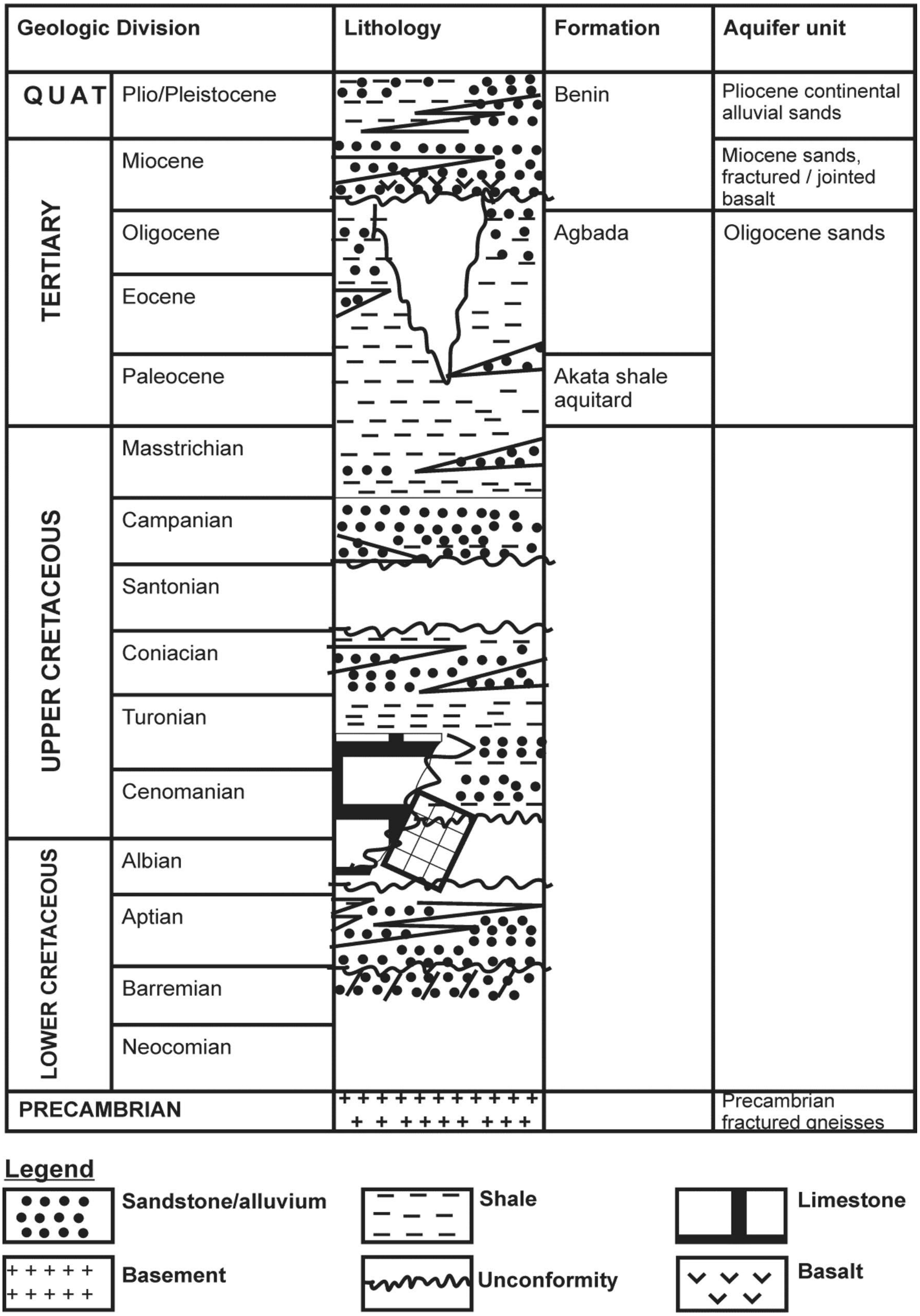


Fig. 3 Hydrostratigraphic column of the Rio del Rey Basin showing the various aquifer units modified from UNESCO – ISARM (2011)

water samples obtained from ground and surface water were also put in plastic bottles (100 mL) for oxygen and hydrogen isotope analysis. The deuterium (D) and oxygen-18(^{18}O) composition were analyzed using a cavity ring-down spectrometer analyzer (model L2120-i from PICARRO) as described in Wirmvem et al. (2014). Total analytical precisions were ± 0.05‰ (δ^{18}O) and ± 0.12‰ (δD). The precipitation weighted average values (w.a.v) of δ^{18}O and δD for each month and the annual values were computed from Eq. 1(IAEA 1992):

$$\delta = \sum_{1}^{n} P_i \delta / \sum_{1}^{n} P_i \tag{1}$$

where P_i is rainfall amount, and δ_i is isotopic composition per month. The deuterium-excess (*d*-excess) parameter was obtained as defined by Dansgaard (1964) as:

$$d = \delta D - 8\delta^{18}O \tag{2}$$

Results and discussions

The isotopic data for the monthly precipitation are presented in Table 1. The monthly precipitation values for δ^{18}O and δD of the two stations show a temporal variation from −5.26 to + 0.35‰ and from −34.4 to + 13.88‰, respectively (Table 1).

Monthly weighted average values (w.a.v) of δ^{18}O and δD in precipitation ranged from –0.98 to 0.00‰ and from −3.59 to 0.59‰, in that order. The annual precipitation weighted mean of δ^{18}O and (δD) varied from −3.36 to −3.34‰ and from −15.07 to −14.0‰, respectively (Table 1). The seasonal variations of δ^{18}O and δD showed

Table 1 Isotopic data of monthly rainfall and weather records from Rio del Rey Basin, 2012

Month	δ^{18} O (‰)	δD (‰)	d-excess (‰)	Rainfall (mm)	w.a.v δ^{18}O	w.a.v δD	w.a.v d-excess	Rainy days	RH (%)	Temp (°C)
LOBE (*UTM* 508,790; 508,299 m; *alt* 60 m; *distance from the Atlantic Ocean:* 32 km)										
January	− 1.57	− 2.61	9.97	43	− 0.02	− 0.04	0.13	3	90.2	27
February	− 0.99	2.16	10.08	147	− 0.05	0.10	0.46	12	90	27
March	− 1.54	2.61	14.94	14	− 0.01	0.01	0.07	3	90	27
April	− 2.26	− 1.53	16.56	139	− 0.10	− 0.07	0.72	11	90.1	27
May	− 4.53	− 20.70	15.55	217	− 0.31	− 1.41	1.06	17	90.1	28
June	− 3.90	− 16.74	14.43	327	− 0.40	− 1.71	1.48	16	90.7	27
July	− 2.94	− 9.79	13.73	424	− 0.39	− 1.30	1.82	27	90.2	27
August	− 1.60	− 0.18	12.64	342	− 0.17	− 0.02	1.36	29	90.3	27
September	− 5.26	− 34.44	7.61	770	− 1.27	− 8.32	1.84	22	90	27
October	− 4.81	− 25.38	13.13	541	− 0.82	− 4.31	2.23	24	90	27
November	− 2.14	− 7.01	10.12	109	− 0.07	− 0.24	0.35	9	90.1	27
December	− 2.31	− 6.37	12.13	116	− 0.08	− 0.23	0.44	6	90.1	28
Mean	− 2.82	− 10.00	12.57	3188	− 2.82	− 10.00	12.57	179	90	27
Annual w.a.v					− 3.7	− 14.0	12.7			
MUNDEMBA (*UTM* 544,804; 484,386 m; *alt* 30 m; *distance from the Atlantic Ocean*: 61 km)										
January	− 1.10	− 0.18	8.60	65	− 0.01	0.00	0.11	5	N/A	31
February	0.02	13.01	12.86	217	0.00	0.56	0.55	17	N/A	27
March	*0.35*	*13.88*	11.08	214	0.01	0.59	0.47	11	N/A	29
April	− 1.80	0.81	15.21	290	− 0.10	0.05	0.87	16	N/A	28
May	− 4.30	− 21.68	12.72	223	− 0.19	− 0.95	0.56	17	N/A	28
June	− 3.32	− 11.65	14.88	650	− 0.43	− 1.49	1.91	21	N/A	27
July	− 4.28	− 19.33	14.91	941	− 0.79	− 3.59	2.77	30	N/A	25
August	− 3.48	− 14.49	13.35	486	− 0.33	− 1.39	1.28	21	N/A	25
September	− 4.66	− 31.45	5.83	1065	− 0.98	− 6.61	1.23	26	N/A	26
October	− 4.53	− 24.49	11.75	570	− 0.51	− 2.75	1.32	21	N/A	27
November	− 2.38	− 10.86	8.19	289	− 0.14	− 0.62	0.47	19	N/A	27
December	− 0.34	4.74	7.44	57	0.00	0.05	0.08	6	N/A	27
Mean	− 2.48	− 8.47	11.40	5067	− 2.48	− 8.47	11.40	210	N/A	27.33
WAV					− 3.36	− 15.07	12.16		N/A	

NB; relative humidity (*RH*), not available (*N/A*), bolditalics min values, italics max values, weighted average value (*w.a.v*) some distinct fluctuations in the rainy and dry seasons. In the rainy season, the least of δ^{18}O and δD were recorded in September and relatively high values in March during the dry season (Fig. 4a, b). The precipitation amount effect generally shows a decrease in the isotope values in wet period with increasing precipitation (Dansgaard 1964) and usually with high values during the dry period with decreasing rainfall (Wirmvem et al. 2014). The isotopic amount effect pattern observed (Fig. 4a, b) suggests that the rainy and dry season rains are connected with the air masses rain formation processes. This suggests the inter tropical convergence zone (ITCZ) influence associated with the easterly winds during the rainy period and the dry season with less frequent rains carried by northerly or westerly winds. An abrupt decrease in δ^{18}O in November possible marks the retreat of the ITCZ (Fig. 4a, b).

The least δ^{18}O values in September, corresponding with the highest rainfall, correspond with the behaviour of low latitudes rains (Dansgaard 1964; Rozanski et al. 1993). Similar patterns of least values of δ^{18}O obtained during the rainy season have been recorded in Cameroon (Njitchoua et al.1999; Wirmvem et al. 2014).

The annual variation in the weighted δ^{18}O was observed with similar v-shape patterns in the Ndop plain in the North West Cameroon (Wirmvem et al. 2014) which suggest a moisture source from the Atlantic. (Taupin et al. 2000).

Rain samples from high altitudes are more depleted in isotope content (Lobe (61 m above sea level); −0.56‰ to −0.99‰) than precipitation sampled at low altitude station (Mundemba (32 m); −0.56‰ to 0.35‰) Table 1. The annual weighted average value (w.a.v) for δ^{18}O in precipitation in Mundemba (−3.36‰), Lobe (−3.34‰) compared with Kribi (−1.5‰) (Njitchoua et al. 1999) in

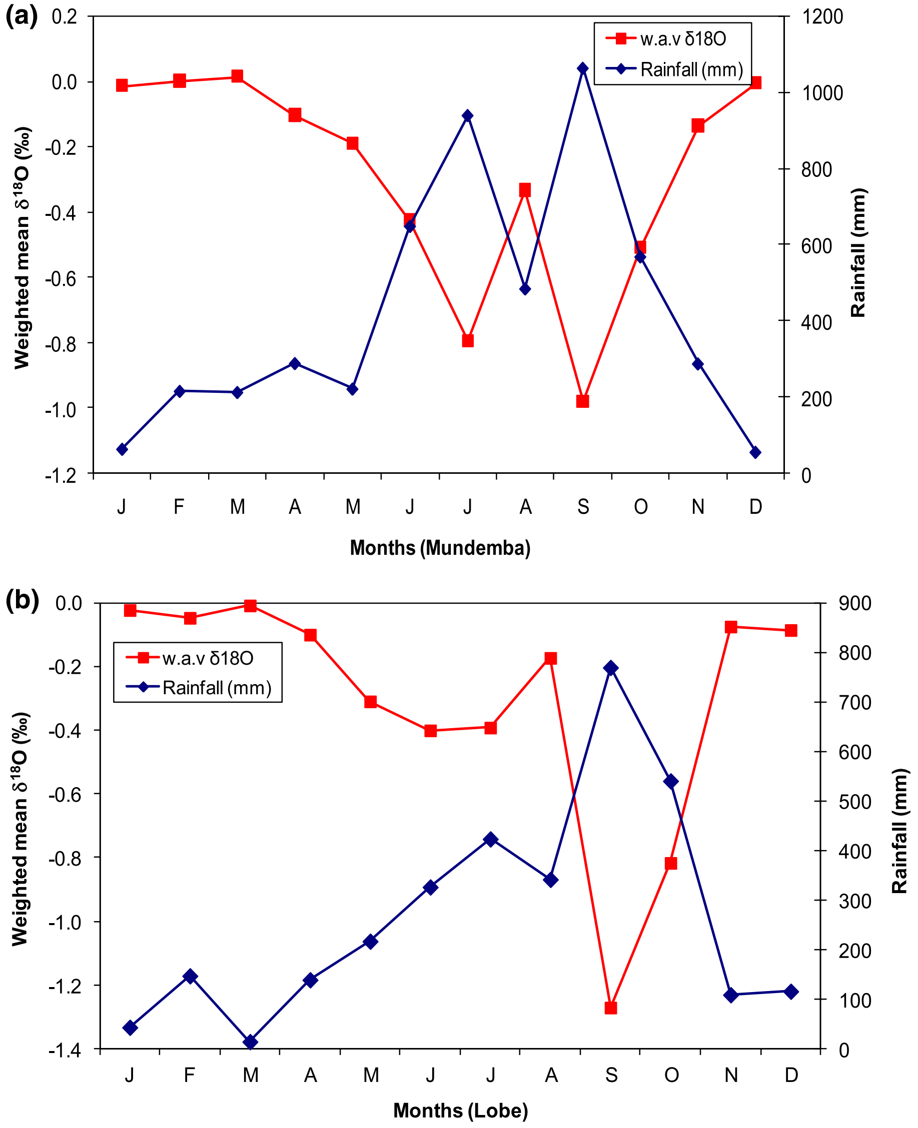


Fig. 4 **a, b** Inverse relationship between monthly rainfall amounts and weighted mean of δ^{18}O for **a** Mundemba and **b** Lobe

Fig. 5 shows a decrease with increasing latitudinal distance from Kribi (−1.5‰/km) to Lobe (−3.34‰:32 km), and Mundemba (−3.36‰:61 km) inland. Two main trends are defined (Fig. 5): δ^{18}O values which decrease from −1.5 to −3.34‰, from 0 to 32 m, defining an inland isotope of −0.48‰ 10 km^{-1}. This is different from δ^{18}O values from Lobe (−3.34‰) to Mundemba (−3.36‰) of 32 to 61 km inland isotopic gradient of −0.06‰ 10 km^{-1}. This suggests that as Atlantic air mass moves at higher altitudes and latitudes from the Atlantic Ocean, the vapour is produced as rain. This is different from δ^{18}O values (32–61 km inland) influenced recycled continental moisture as also observed by Salati et al. (1979), Njitchoua et al. (1999) and Taupin et al. (2000. The relatively small isotopic gradient of −0.06‰ 10 km^{-1} indicates a lack of continental effect e from the coast as observed in the Ndop plain (Cameroon) by Wirmvem et al. (2014).

Deuterium excess in precipitation has been a useful tool to trace vapour source and recycling moisture (Gat et al. 1994). Monthly d-excess of precipitation ranged broadly from 5.8‰ in September to 16.56‰ in April (Table 1).

The d-excess value in precipitation is influenced by the moisture source (Rozanskiet al. 1993).The d-excess value of Atlantic moisture (10‰) falls between the d-excess ranges of the rain samples (5.8–16.56‰) indicating the significance of the Atlantic ocean as a vapour source of the study area. Higher d-excess values (> 10‰) have been observed where moisture recycling through re-evaporation plays a significant role in the water cycle (Gat et al. 1994; Zhou et al. 2007). Seventeen (17) d-excess values were greater than + 10‰ (Fig. 6a, b), which suggests that besides the Atlantic moisture, an additional source of moisture recycling through evaporation of the numerous surface water bodies and/or evapotranspiration on the dense vegetation in the area plays a role in the water cycle.

The local meteoric line (LML) has been commonly used as an indicator of water vapour source (Jouzel et al. 1997). By using the precipitation isotope values and the least squares fit method (Fig. 7), the following LML were generated:

Lobe meteoric water line (LMWL) $\delta D = 7.97\,\delta^{18}O + 12.48$ ($r^2 = 0.95$, $n = 12$)
Mundemba meteoric water line (MMWL): $\delta D = 7.75\,\delta^{18}O + 10.79$ ($r^2 = 0.95$, $n = 12$)

The slopes (7.9 and 7.7) for the local meteoric lines (Fig. 7) are similar and close to 8 of the GMWL ($\delta D = 8\delta^{18}O + 10$) by Craig (1961), which suggest an insignificant modification of the raindrops by evaporation as obtained in other parts of Cameroon (Fontes and Olivry 1977; Njitchoua et al. 1999; Gonfiantini et al. 2001; Fantong 2010; Wirmvem et al. 2014). Quite identical relationships of δ^{18}O—δD have been reported for precipitation in parts of Nigeria (Loehnert 1988; Mbonu and Travi 1994). The varied d-intercepts reflect seasonal climatic changes (Gonfiantini et al. 2001; Wirmvem et al. 2014).

The uniform and high mean relative humidity (90%) for Lobe (Table 1) suggests its proximity to the coast with a distance of 32 km and to its equatorial location which makes it to be subjected to intense convective uplift of air/water vapour since the sun's rays reach the surface vertically at an angle of 90°. Considering the total amount of rainfall in the study area (Table 1) from January to May and November to December which is 2,143 mm (26%) of the total rainfall (8259 mm), and the June to October heavy rains which is 6116 mm (74%) of the total rainfall, and based on the d-excess and δ-values, one can suggest that 74% of rainfall comes from the Atlantic Ocean, and 26% of vapour originates from recycled inland moisture. The former relates to the fact that the inter tropical convergence zone (ITCZ) has moved further inland which brings with it rain bearing moisture that flows across the region. Therefore, the observed seasonal variation in the isotopic composition of precipitation in the study area is probably as a result of (1) moisture from the Atlantic Ocean, (2) rainfall amounts effects (3) recycled moisture given the 32–61 km distance south-west from the Atlantic Ocean (Gulf of Guinea), (4) movement of air masses.

The stable isotope composition of ground and surface water is presented in Table 2. The groundwater isotope values ranged from −3.81 to −2.52‰ for δ^{18}O and −16.63 to −8.25‰ for δD (Table 3). The groundwater isotope values plot close to and along the GMWL (Fig. 8) showing that its isotopic composition is identical to that of rainwater, which indicates the meteoric origin and rapid recharge of groundwater with negligible evaporative effect. The cluster of these isotopes in groundwater between the June to August rain indicates groundwater is mainly recharged during these months of the year (Fig. 8). The shallow unconfined aquifers

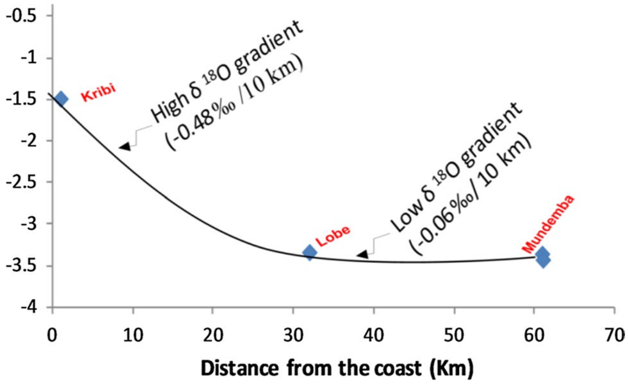


Fig. 5 Distribution of weighted mean δ^{18}O in rainfall per distance and altitude from the Atlantic Ocean

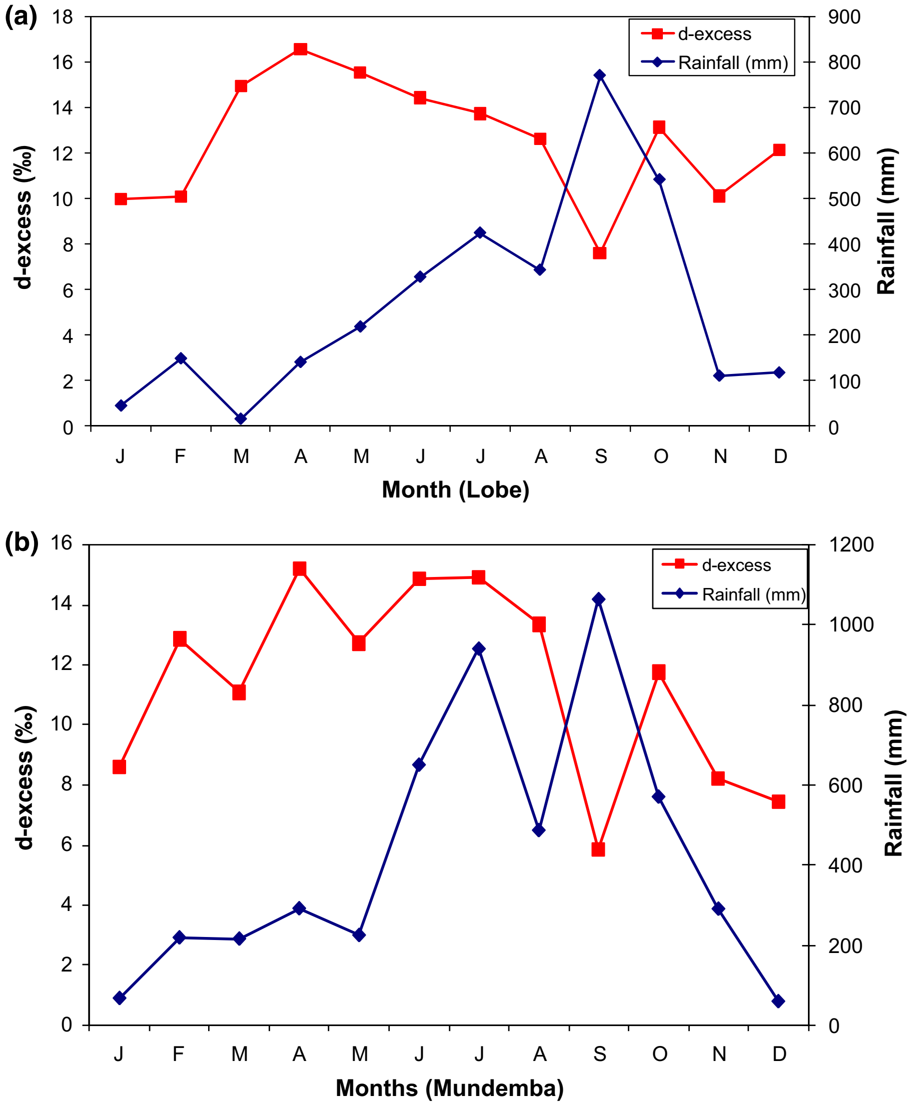


Fig. 6 **a, b** Inverse relationship between monthly rainfall amounts and d-excess for **a** Lobe and **b** Mundemba

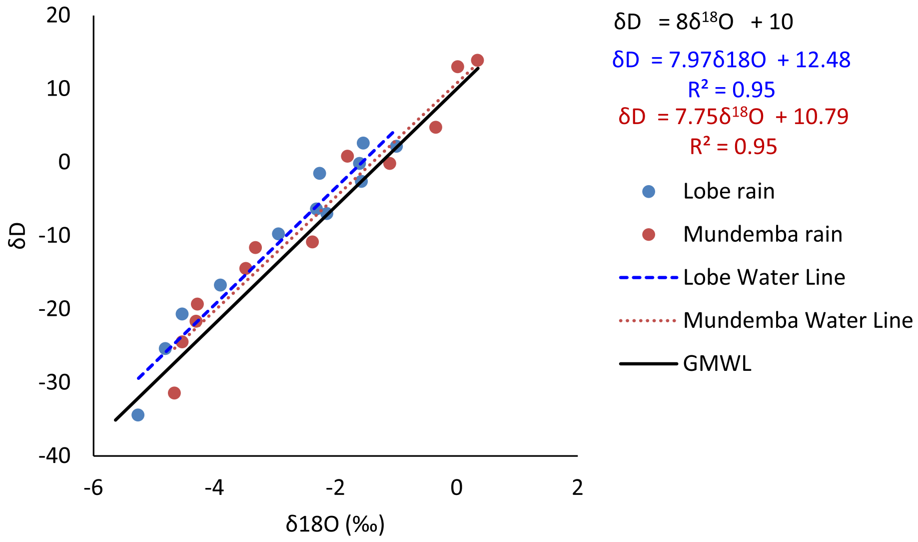


Fig. 7 δ^{18}O-δD correlation of monthly rainfall events in Lobe and Mundemba

Table 2 Oxygen and hydrogen isotope data of ground and surface water

Locality	Water source	Long (m)	Lat (m)	Altitude	δD (‰)	$\delta^{18}O$ (‰)	d-excess (‰)
Bulu Camp, Mundemba	Spring	484,310	545,361	35	−9.78	−2.77	12.35
Mission Camp, Mundemba	Spring	483,280	545,216	30	−9.77	−2.79	12.58
Ikassa Camp, Mundemba	Spring	482,836	544,838	33	−6.16	−2.28	12.07
Last Camp, Mundemba	Spring	482,814	544,840	13	−9.61	−2.72	12.18
Ekondokondo	Spring	490,869	556,878	160	−8.34	−2.66	12.97
Ekondokondo	Spring	491,075	556,114	142	−10.15	−2.98	13.69
Ekondokondo	Spring	490,958	555,612	125	−9.13	−2.82	13.4
Mekagolo	Spring	492,947	544,933	156	−11.94	−3.4	15.28
Ekumbako	Spring	489,943	541,560	123	−9.92	−2.97	13.81
Dibonda	Spring	488,633	537,873	94	−10.81	−3.19	14.72
Funge	Spring	490,123	525,715	20	−9.53	−2.94	13.95
EkombeLiongo	Spring	511,552	497,985	33	−13.81	−3	10.2
EkombeLiongo	Spring	511,743	496,931	44	−15.45	−3.59	13.24
EkombeLiongo	Spring	511,476	498,765	29	−12.8	−3.21	12.91
IdibaNyanga	Spring	456,750	530,354	110	−12.71	−3.03	11.56
Njima	Spring	515,488	519,485	40	−12.66	−3.16	12.64
Oron, Isangele	Spring	467,033	529,483	89	−10.59	−2.93	12.88
Pamol Camp, Mundemba	Spring	473,308	541,683	4	−12.76	−3.26	13.29
Ilor	Spring	489,169	529,483	110	−10.76	−2.99	13.18
Ghana Quarter, Mundemba	Spring	488,124	544,472	105	−11.38	−3.06	13.11
Loe	Spring	482,829	521,639	58	−12.76	−3.25	13.41
Mbengmong, Akwa II	Spring	457,273	531,923	10	−10.02	−2.76	12.09
Gov't quater, Isangele	Spring	464,942	528,959	89	−10.66	−2.83	11.97
Ekwe	Spring	517,754	513,273	555	−11.51	−3.36	15.34
Idibawase	Spring	490,215	548,830	100	−13.08	−3.45	14.49
Besingi	Spring	492,829	545,344	155	−11.66	−3.21	14.03
Massore	Open well	499,171	514,728	32	−16.99	−3.8	13.4
EkondoTiti	Open well	500,564	509,508	9	−12.38	−3.25	13.59
EkondoTiti	Open well	503,472	508,591	52	−13.46	−3.35	13.38
Big Bongongo I	Open well	510,885	506,248	60	−12.35	−3.17	13
EkombeLiongo	Open well	511,534	497,310	33	−14.63	−3.27	11.51
Mbonge	Open well	511,653	501,421	21	−10.74	−2.64	10.39
Iloani	Open well	499,976	498,981	10	−13.66	−3.36	13.2
Bekora	Open well	511,828	507,347	55	−10.23	−2.85	12.55
Mbonge	Pump well	512,191	501,583	26	−13.5	−3.31	12.94
Akwa, KomboAbedimo	Pump well	457,622	532,446	8	−8.35	−2.64	12.77
Mosongesele	Pump well	466,859	543,601	50	−10.43	−2.81	12.02
EkombeMofako	Pump well	508,604	496,923	55	−17.44	−4.05	15.3
Mosongesele	Beach	466,685	544,472	10	−4.68	−2.15	12.53
Beach, EkondoTiti	Beach	500,637	509,210	21	0.09	−1.19	9.65
Moko, Dibonda	River	488,936	536,277	6	−3.43	−2.1	13.33
Mbonge	River	511,578	499,171	26	−16.24	−3.78	13.96
EkombeLiongo	River	511,552	497,985	33	−15.82	−3.69	13.69
River Akwafe	River	457,448	532,620	2	−0.1	−1.24	9.48
Water catchment, Mundemba	Stream	490,170	550,703	166	−11.08	−3.04	13.24
Berenge	Steam	517,579	513,099	59	−8.49	−2.63	12.57
Ekondo Nene	Stream	495,435	518,788	25	−8.61	−2.93	14.84
Manja quarters, Mundemba	Stream	490,215	550,398	109	−10.61	−2.95	12.96
Lobe Estate	Tap water	508,437	508,645	67	−10.95	−2.98	12.89
Mundemba town	Reservoir	490,242	550,613	169	−10.43	−2.91	12.83

Table 2 (continued)

Locality	Water source	Long (m)	Lat (m)	Altitude	δD (‰)	δ^{18}O (‰)	d-excess (‰)
Last Camp, Mundemba	Rain	482,814	544,840	13	12.59	0.1	11.83
Mundemba town	Rain	490,041	551,095		2.29	0.35	13.88

Table 3 Isotope data summary of ground and surface water ($n=52$)

Source	δ^{18}O (‰)			δD (‰)			d-excess (‰)			Alt (m)
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	
Spring ($n=26$)	−3.59	−2.28	−2.94	−15.45	−6.16	−10.81	10.2	15.34	12.77	95
Open well ($n=8$)	−3.8	−2.64	−3.22	−16.99	−10.23	−13.61	10.39	13.59	11.99	34
Pump well ($n=4$)	−4.05	−2.64	−3.35	−17.44	−8.35	−12.9	12.02	15.3	13.66	35
Groundwater ($n=38$)	**−3.81**	**−2.52**	**−3.17**	**−16.63**	**−8.25**	**−12.44**	**10.87**	**14.74**	**12.81**	**54.67**
Beach ($n=2$)	−2.15	−1.19	−1.67	−4.68	0.09	−2.3	9.65	12.53	11.09	11
River ($n=4$)	−3.78	−1.24	−2.51	−16.24	−0.1	−8.17	9.48	13.96	11.72	5
Stream ($n=4$)	−3.04	−2.63	−2.84	−11.08	−8.49	−9.79	12.57	14.84	13.71	7
Surface water ($n=10$)	**−2.99**	**−1.69**	**−2.34**	**−10.67**	**−2.83**	**−6.75**	**10.57**	**13.78**	**12.17**	**7.67**
Tap water ($n=1$)	−2.98	−2.98	−2.98	−10.95	−10.95	−10.95	12.89	12.89	12.89	67
Reservior ($n=1$)	−2.91	−2.91	−2.91	−10.43	−10.43	−10.43	12.83	12.83	12.83	169
Pipe-borne water ($n=2$)	**−2.95**	**−2.95**	**−2.95**	**−10.69**	**−10.69**	**−10.69**	**12.86**	**12.86**	**12.86**	**118**
Rain($n=2$)	0.1	0.35	0.23	2.29	12.59	7.44	11.83	13.88	12.86	13
All ($n=52$)	**−2.41**	**−1.70**	**−2.06**	**−8.92**	**−2.30**	**−5.61**	**11.53**	**13.82**	**12.68**	**48.33**

Min minimum, *Max* maximum, *Alt* altitude above sea level. Bold values represent the average parameter of ground and surface water samples

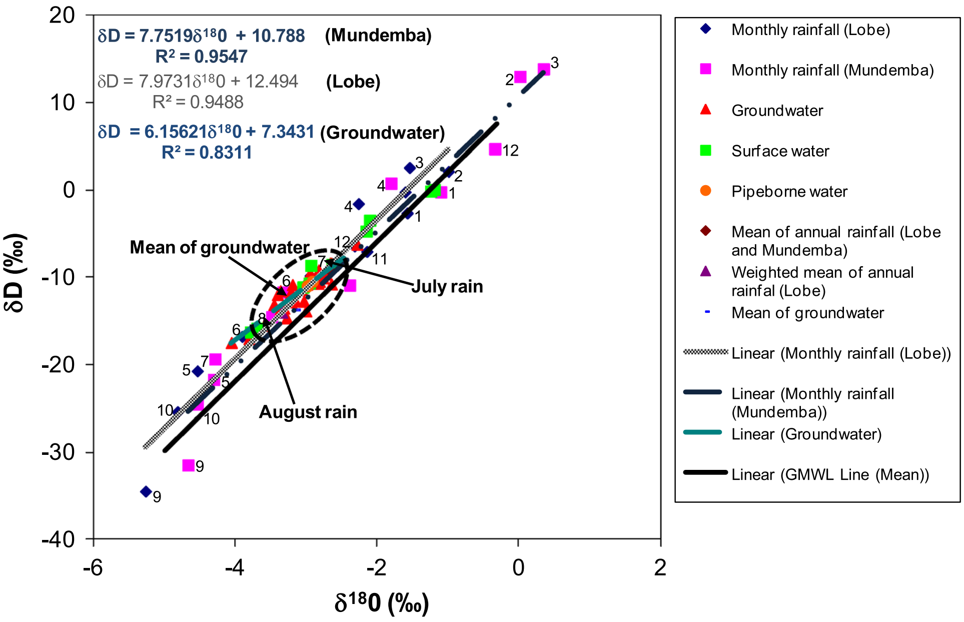


Fig. 8 Plot of δ^{18}O versus δD relationship of rainfall, ground and surface water in the study area

become saturated with June–August precipitation. Isotopic compositions between precipitation and groundwater can reveal the period of groundwater recharge (Mbonu and Travi 1994; Deshpande et al. 2003; Ma et al. 2013) as in the study area. The absence of enriched δ^{18}O and δD signatures in the heavy September to October precipitation (Table 1) suggests insignificant recharge during these months. Since the δ-values of the groundwater, streams, and rivers are not significantly affected by evaporation, the dominant recharge period is likely from June to August precipitation and reduced recharge from, November to December. During the low January–April precipitation, evapotranspiration is probably greater than precipitation resulting in negligible groundwater recharge. As observed by Mbonu and Travi (1994), the heaviest rains of July–September with the most negative stable isotopes resulted to negligible recharge of groundwater. This selective recharge may explain the relatively low d-intercept of groundwater despite their cluster along the Mundemba meteoric water line (MMWL) and Lobe meteoric water line (LMWL) (Fig. 8). The observed June–August precipitation recharge is different from the reported heavy August precipitation recharge of groundwater farther away in the semi-arid north Cameroon (Fantong 2010).

Under base flow conditions, streams and rivers are integrators of isotopic composition of the recent past precipitation (Gonfiantini et al 1998; Matsubaya 2001; Gat 2010) provided the basin largely consists of surrounding mountains (Gonfiantini et al. 1998). A plot of the stream and river samples on and next to the MMWL and LMWL (Fig. 8) suggests recharge from the surrounding Rumpi Hills. The similar isotopic composition of surface water to the groundwater (Table 2) suggests a hydraulic connectively with the unconfined aquifers and a possible recharge as it flows within the basin.

The beach sample from Mosongesele and a sample from river Moko located at 10 and 6 m.a.s.l. (Fig. 9), respectively, showed some δ^{18}O enrichments suggesting that the groundwater which is mostly from spring sources are partly recharged by these surface water bodies. The general cluster of samples on the δ^{18}O-TDS plot (Fig. 9) suggests a homogenous nature of the shallow aquifer of < 10 m depth.

Natural variations in stable isotope ratios have been used to identify recharge areas (Payne and Yurtsever 1974). Plotting δ^{18}O versus altitude (Fig. 10) indicated recharge at different altitudes. The plot of samples (Fig. 10) showed 3 clusters (groups).

Group A: Comprises of 70% of the samples (open wells, pump wells, springs, rivers and beach) which occur at low altitude < 54 m above sea level (Fig. 10).

Group B: 28% of samples mostly springs < 160 m.a.s.l.

Group C: 2% of the spring at Ekwe (555 m. a.s.l.).

The different groups indicate recharge at different altitudes (From A–C). Group A is the most enriched in δ^{18}O. The δ^{18}O value of precipitation in temperate regions characteristically exhibits about a 0.2‰ decrease for every 100 m elevation gain. This variation reflects the temperature dependence of isotopic fractionation during the condensation of water vapour (Dansgaard 1964). Therefore, they are likely to have short flow paths and short residence times in the aquifer. Using the d-excess value to determine the source of moisture indicates that 96% of the ground and surface water samples had d-excess values > 10% with an average of 12.68‰ (Tables 2, 3). This indicates that besides the Atlantic moisture, recharge is derived partly from recycled water and direct infiltration of precipitation (negligible evaporation) (Dansgaard 1964). A similar inference from high d-excess in groundwater has been made elsewhere (Kebede and Tavi 2012).

Based on the results, a theoretical model of the groundwater regime in Ndian is proposed (Fig. 11). From the model, vapour from the Atlantic Ocean and recycled moisture will condense to precipitation which rapidly recharges the groundwater through preferential base flow. The high-altitude localized recharge contributes 30% of the groundwater, while the abundant local precipitation at low altitude provides significant recharge (70%) to the aquifers (Fig. 11). The groundwater sources

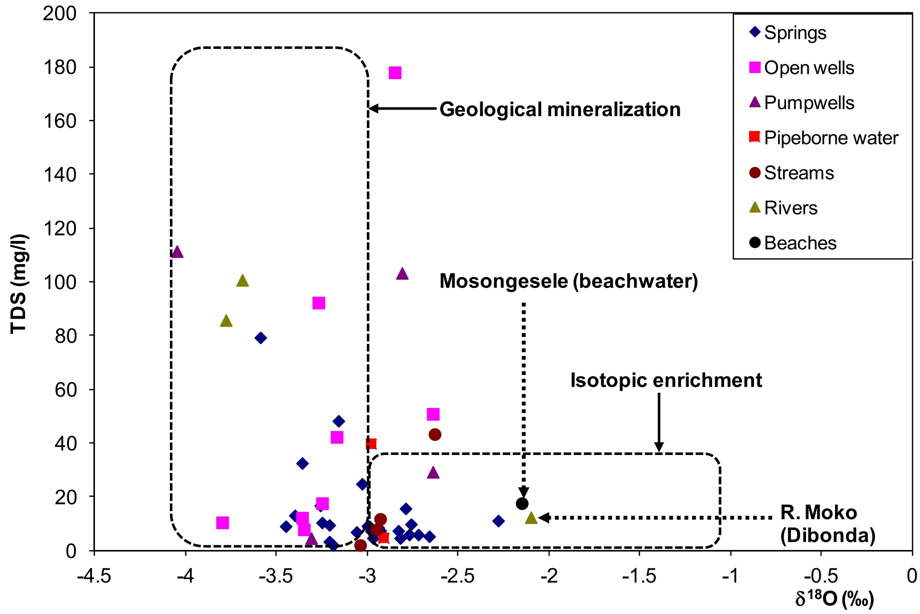
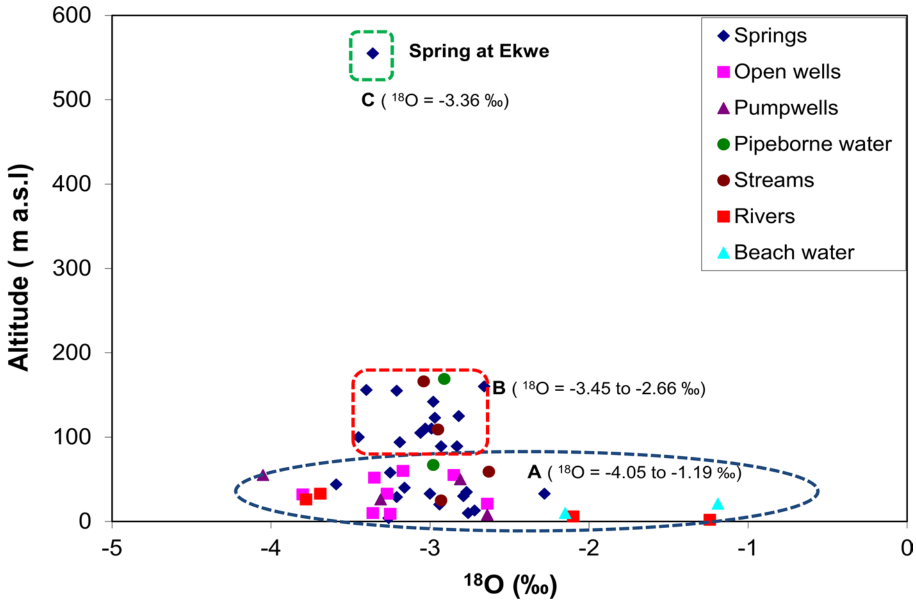


Fig. 9 Plot of δ^{18}O and total dissolve solid (TDS) in ground and surface water sources

Fig. 10 Plot of $\delta^{18}O$ in ground and surface water as a function of altitude



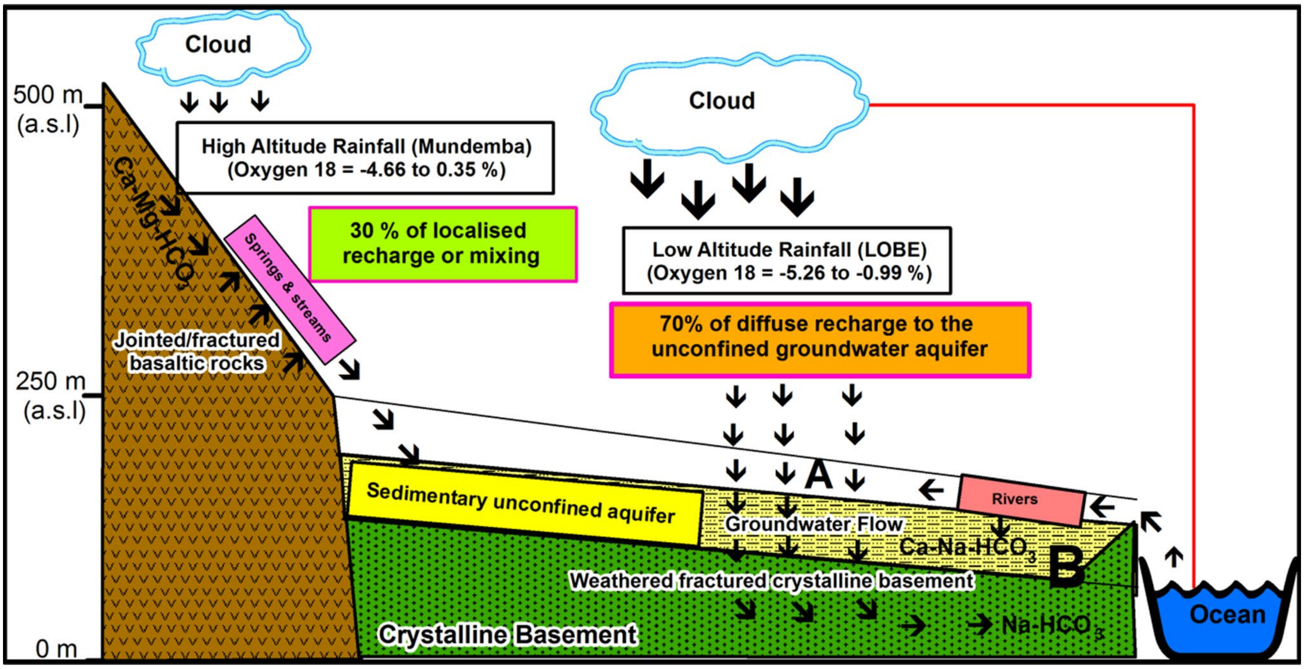


Fig. 11 Conceptual model of the water regime in Rio del Rey Basin. A (vadose zone) and B (saturated zone)

at the high altitude recharge are depleted in $\delta^{18}O$, while the groundwater sources at low altitude are enriched in $\delta^{18}O$ (Fig. 11). The hydrochemical facies (Ca-mg-HCO_3) (Fig. 11) signifies shallow fresh groundwater in volcanic and sedimentary aquifers due to incongruent silicate dissolution and Na–HCO_3 facies, deeper fresh groundwater influenced by ion exchange in sediments and metamorphic rocks (Wotany et al. 2013).

Conclusions

The isotope data for the rainfall samples indicated high values of $\delta^{18}O$ and δD isotopes recorded during the dry season (November and March) and the least value in September. The relationship between δD and $\delta^{18}O$ defined the Lobe meteoric water line as $\delta D = 7.97\ \delta^{18}O + 12.48$

and Mundemba water line as: $\delta D = 7.75\ \delta^{18}O + 10.79$. The similarity of their slopes to the global meteoric water line suggests the isotopic composition of rains has not been affected much by evaporation.

The ranges in deuterium-excess of precipitation from 5.8 to 16.56‰ suggest the source of vapour is from Atlantic Ocean.

The groundwater isotope values plot close to and along the GMWL showing that its isotopic composition is of meteoric origin under rapid recharge conditions. The isotopic similarity between groundwater and June–August rains suggests a major recharge during this period. Taking into account the total amount of rainfall in the study area from January to May and November to December which is 2143 mm (26%) of the total rainfall (8259 mm), and the June to October heavy rains which is 6116 mm (74%) of the total rainfall, and based on the d-excess and δ-values, one can suggest that 74% of rainfall comes from the Atlantic Ocean, and 26% of vapour originates from recycled inland moisture.

The observed seasonal variation in isotopic composition of precipitation in the study area is probably as a result of: (1) Moisture from the Atlantic Ocean, (2) rainfall amounts effects (3) recycled moisture given the 32–61 km distance south west from the Atlantic Ocean (Gulf of Guinea), (4) movement of air masses. The groundwater sources at the high altitude recharge are depleted in $\delta^{18}O$, while the groundwater sources at low altitude are enriched in $\delta^{18}O$. The high altitude localized recharge contributes 30% of the groundwater, while the abundant local precipitation at low altitude provides major recharge (70%) to the shallow unconfined aquifers.

Acknowledgements We thank the staff of the Lobe and Ndian Estate Research Centre for the monthly field collection of rain samples, weather data and members of the Takeshi Ohba Laboratory, Tokai University, Japan for the stable isotope analysis. The paper was greatly improved by review comments from two anonymous reviewers.

Funding This work was carried out under a PhD research programme of the University of Buea – Cameroon, without a grant.

Declarations

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

Ethical approval This article does not contain any studies involving human participants performed by any of the authors.

Informed consent Informed consent was obtained from all individual participants included in the study.

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