The use of unsaturated zone solutes and deuterium profiles in the study of groundwater recharge in the semi-arid zone of Nigeria.

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Abstract. Two unsaturated zone profiles (MF and MG) in NE Nigeria have been sampled for inert tracers (Cl, Br, NO_3 and δ^2H to investigate recharge rates and processes. The upper MF and MG profiles have sandy lithology, lower moisture content (<5%), low conservative solute concentrations and δ^2H around -30‰. All these indicate that present day recharge is taking place. The lower section of the MF profile shows a distinct contrast with high moisture content (up to 27%), very high chloride (average 2892 mg/L) and relatively enriched deuterium (-12‰), indicating the effect of evaporative enrichment. This lower section corresponds to low permeability lacustrine deposits probably representing the former bed of Lake Chad where little or no infiltration has been occurring since the mid-Holocene when the lake extended over this area. The sand-covered areas of the Sahel of the NE Nigeria provide an important phreatic aquifer. An estimation of the amount of recharge using the unsaturated zone chloride mass balance gives significant rates of 14 mm/a and 22 mm/a for the upper MF and MG profiles respectively. These rates mainly span the period of the recent Sahel drought and even higher recharge rates may occur during wetter periods. These rates fall within the 14 mm/a to 53 mm/a range estimated for the Manga Grasslands area in the NE Nigeria obtained in an earlier study. From the water resource point of view, the region has potential for perennially-recharged groundwater resources that can sustain the present abstraction level which is mainly via dug wells.

1. Introduction

A rational approach to groundwater resources management and development requires knowledge of the origin of the resources and especially of their replenishment. This information represents basic input data for quantitative modelling, which increasingly is being used as a tool for groundwater management practices. The estimation of the amount of recharge is fundamental for a sustainable management of groundwater resources. This is extremely important especially in semi-arid and arid regions where surface waters are either seasonal or non-existent, and groundwater becomes the perennial source of water supply. The use of solutes in conjunction with isotope methods provides a powerful tool for the investigation both of modern hydrological processes and to reconstruct palaeohydrology. Recent reviews of techniques for estimating groundwater recharge [1, 2 & 3] emphasise the value of chemical and isotopic methods, especially in semi-arid zones.

The present study area is situated in the northeastern part of Nigeria, north of latitude 12°00'N (Fig. 1) and is mainly characterised by low rainfall (<500 mm) and high evaporation rate (>2000 mm). The landscape is characterised by sand dunes of different ages [4] and interdunal depressions. The loose sandy surface cover shows no runoff and supports annual grasses, shrubs and occasional trees. However, the interdunal depressions are moderately vegetated, but at the fringes of playa lakes are densely vegetated with doum palm, date palm, acacia and cultivated crops. Two sites (Malam Fatori and Magumeri) were selected to carry out unsaturated zone profiles (Figure 1). The Malam Fatori site has a series of prominent and

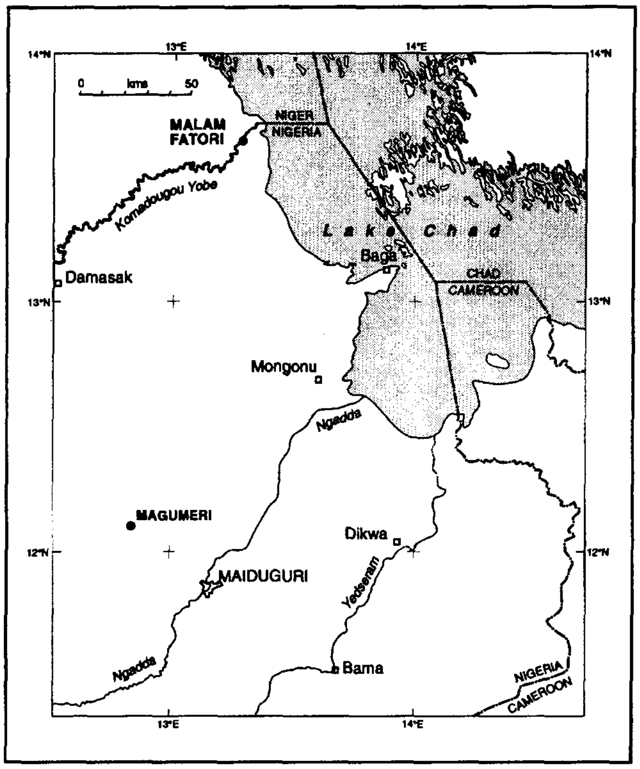

Fig. 1

relatively stable dunes, which form domes that probably represent past barchanoid dunes, and undulating sandy flatlands. Vegetation in this site is composed of annual grasses and shrubs. The Magumeri site shows a more stabilised longitudinal dune with axis trending in NE-SW directions. It is also characterised by annual grasses, shrubs and few tress. The dune sands are composed of quartz and feldspar with minor mica, while the depressions are composed of fluvio-lacustrine clays. The sediments of the dunes and depressions constitute the superficial deposits lying on top of the Quaternary Chad Formation, the youngest stratigraphic formation of the Chad basin. These superficial deposits provide an important phreatic aquifer that supplies perennial groundwater resources to a number of communities via dug wells. However, the local people have observed declines in the water table, and this has raised questions on the overall sustainability of the resource.

The aim of this paper is to present results of recharge estimation using inert chemical and isotopic tracers from these two unsaturated zone profiles in NE Nigeria.

2. Methodology

Hand augering was used to drill two profiles to an average depth of 16 m. One site (MF) was at Malam Fatori (13°39.02'N & 13°20.03'E). The second site (MG) was at Maigumeri (12°05.92'N & 12°49.06'E) MG. Samples were collected at intervals of 0.25 m for the first 10 m and then at 0.50m to the total depth of the profiles. Samples were homogenised over the interval in a thick nylon bag and subsampled into glass Kilner® jars, which were then sent to the BGS laboratory in UK for analysis. Moisture contents were measured gravimetrically. Subsamples of the field-moist sand were processed by elutriation using deionised water (50 ml deionised water added to 50 g of soil sample). Chloride, bromide and nitrate concentrations were determined by automated colorimetry. Deuterium content was measured by direct reduction of the soil sample over zinc shot [5].

Groundwater samples were also collected in 60ml Nalgene® bottles from the shallow phreatic aquifer and the deep confined aquifer. All samples were analysed at BGS for inorganic analysis by ICP-OES and automated colorimetry.

3. Results

Two meteorological stations (Kaska and Garin Alkali) in the area have been used to obtain annual amounts and chloride concentrations in rainfall for the period 1992-97 and these results are described in greater detail [6]. The results from these stations were used to obtain a mean rainfall amount of 389 mm/a and mean weighted chloride of 1.7 mg/L for the study area. These form input data for the estimation of groundwater recharge using the chloride profile technique.

The MF profile shows variable lithology and texture (Fig. 2), with fine sand at the top 3 m, changing to silty clay, and clay with bands of silt to the total depth of the profile. The water table was not reached because of difficulty in drilling through the plastic clay encountered at 13 m up to 16 m, using the manual hand auger. The total depth of the profile is 16 m. From the data of nearby wells the water table is at a depth of 21 m. The moisture content in MF shows distinct variability that reflects the changes in lithology and texture (sand to clay), and ranges from 2% to 27%. The chloride results obtained by elutriation are given together with Br, NO_3 and δ^2H in Table 1. In this profile a clear hiatus can be seen at about 3m depth, shown by the moisture content which marks the transition from sandy lithology to clays, as well as by the discontinuity in Cl and δ^2H. Concentrations of chloride have a mean value of 47 mg/L Cl in the upper 3m but in the lower clay sequence the mean Cl concentration is 2892 mg/L (Table 2). The δ^2H values in the upper profile ranges from –27‰ to –39‰ with an average of –30‰. These are also lighter than in the clays in which δ^2H ranges from +1‰ to –23‰ with an average of -12‰, reflecting the effects of evaporative enrichment as shown by Cl.

The MG profile consists of pure sand, with noticeable changes in colour and texture at different depths (Fig. 3). The generally sandy MG profile shows moisture content over a narrow range, and mostly less than 5%. This profile has low solute concentrations, with chloride ranging from 5 mg/L to 170 mg/L while nitrate ranges from 1 mg/L to 150 mg/L (Table 3). Deuterium is expressed as δ-values, the deviations in parts per mille from the International Standard V-SMOW; this ranges from –14‰ to –39‰ with an average of -26‰.

The equation $R_d = C_pP/C_s$ is used to calculate direct recharge R_d [6] where C_p is the mean chloride in rainfall, P is the long term mean average annual rainfall amount and C_s mean chloride concentration in the unsaturated zone. Values used are C_p (1.7 mg/L) and mean annual rainfall (P) of 389 mm. The mean unsaturated zone Cl concentration C_s for the MF profile from the upper 3m is 47 mg/L and from the lower section (3-16 m) is 2892 mg/L. From these input data estimated the direct vertical recharge for the top 3m at the MF site is 14 mm/a and 0.2 mm/a for the lower section respectively. This confirms that active recharge is only taking place to 3 m and that below this little or no water is passing through the lower section at the present day.

In the case of the MG profile C_s is 29.5 mg/L and, using the same average rainfall amount and chloride in rainfall, the estimated rate of recharge is 22.5 mm/a, while the residence time of water over the depth sampled is 21.4 years. Table 3 summarises the recharge estimates for the profiles in the present work as well as from other profiles in the area obtained under a BGS and Oxford University initiative (the Sahel project) funded by NERC UK [8].

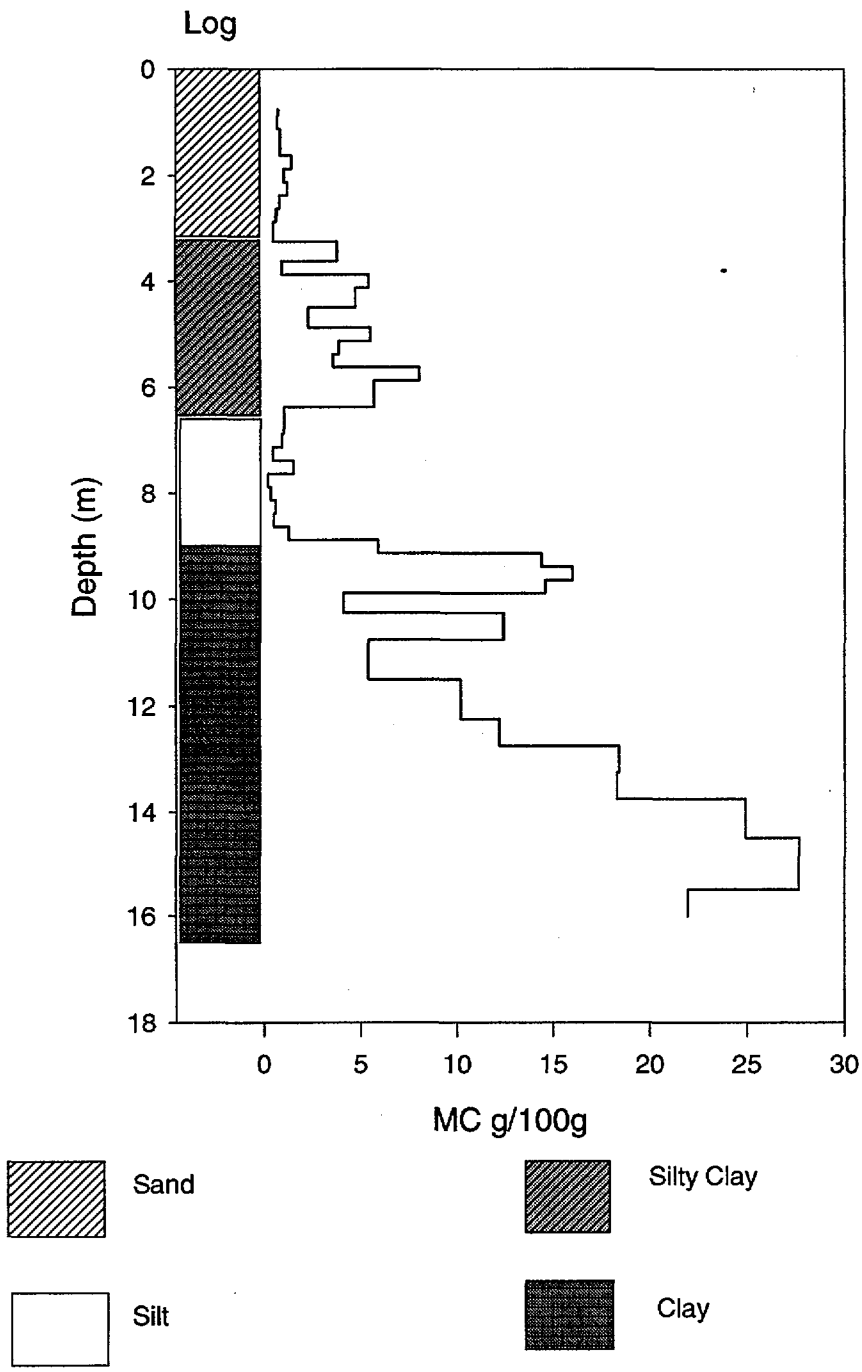

Fig. 2. Depth distribution of lithology and moisture content for MF profile.

Water analyses from river and groundwater show that the concentrations of major ions are generally low. Chloride and nitrate concentrations areless than 5 mg/L and 0.5 mg/L respectively (Table 4).

Table 1. Rainfall amount and chloride concentration

Year	Station	Rainfall (mm)	Weighted Cl (mg/L)
1992	Kaska	320.5	2.83
1993	Kaska	327.3	1.28
1992	Alkali	549.4	1.55
1995	Alkali	614.5	3.36
1996	Alkali	297.5	0.57
1997	Alkali	226.7	0.72
Average		389.3	1.72

4. Discussion

The topography of the study area is generally very flat with difference in elevation of <5 m over tens of kilometers [9], however, the dune ridges and interdunal depressions are local exceptions. The numerous depressions or playas in NE Nigeria at almost the same elevation of ~300 m and characteristic clay deposits imply a surface related to former lake extension (Lake Mega Chad). The clay deposits probably representing the floor of this former mega Chad underlie the dune ridges in some places. At present the average level of Lake Chad is at ~282 m, which is higher than the water table at 275 m [10] and the lake at the present day (if present) probably acts as a recharge source. Thus the groundwater flow direction is to the southwest, away from the Lake [9].

The 3 upper metres of the MF profile contains low concentration of chloride and other conservative solutes - bromide and nitrate (Fig. 4). This indicates present day atmospheric origin for these solutes, which are progressively washed into the profile during the subsequent rainy seasons and accounts for the lack of accumulation of salts in the surface. The concentrations of chloride in the upper 3m indicate a recharge rate of 14 mm/a (similar to MG profile with 22 mm/a); the difference is attributable to relatively finer sediments of the upper 3 m of the MF profile.

The concentration of chloride for the lower part of the MF profile (Fig. 4) is quite distinct and brackish with one peak at a depth of 9 m with chloride concentration of up to 7000 mg/L. The lower impermeable lacustrine deposits (mainly clays) below 3 m probably represent the former bed of Lake Chad where little or no infiltration has been occurring since the lake extended over this area during the mid Holocene. Schneider [11], has mentioned the existence of large palaeolake Chad at the 320 m level at about 6000 yr B.P. During this period it must have invaded large areas including the area of the MF site and deposited beds that are of low permeability. The lower profile therefore consists of waters of low mobility, a partial relic of the former lake sediment pore waters.

Bromide (and Br/Cl) has been used as an additional tool to investigate the origins of Cl and its use as an environmental tracer has been discussed elsewhere [12, 13]. The interstitial water samples from MF profile have been plotted in Fig. 4 and then in the Br/Cl plot (Fig. 5) where the two sets of data above and below 3m are separated. The hiatus in the source of Cl is clearly shown in the depth plot. Both these sets of data lie above the marine line (Br/Cl = 0.00353) indicating Br enrichment. The upper 3m has a mean ratio of 0.031 significantly higher than the lower, more saline profile (Br/Cl of 0.0117). Local Br concentrations in rainfall from the two stations [6] also show enrichment over Cl when compared to the marine ratio, where all data points fall above the marine line with a mean Br/Cl ratio of 0.007. The enrichment of Br relative to Cl has been observed in soils as well as the in unsaturated zone [14] and is likely to be related to the breakdown of organic matter, which is selectively enriched in Br. The data imply that the source of strong Br/Cl enrichment is initially from rainfall, but that subsequent enrichment takes place in soil horizons and/or lake deposits.

Table 2. Solutes and deuterium concentrations in MF profile

MF Profile elutriation				
Depth (m)	corr Cl (mg/L)	corr Br (mg/L)	corr NO_3-N (mg/L)	δ^2H
0.75	57	1.95	16	-22
1.00				
1.25	35	1.65	14	-30
1.50	35	1.58	14	-37
1.75	12	0.68	8	-29
2.00	29	0.41	12	-27
2.25	24	0.40	10	-32
2.50	37	0.30	15	-39
2.75	64	2.22	19	-27
3.00	173	5.20	116	-28
Average	**47**		**22**	**-30**
3.50				-21
3.75	795	9.04	789	-4
4.00				-7
4.25	1670	21.07	1400	1
4.75	1228	14.38	941	-8
5.00	1273	15.01	1064	-12
5.25	3320	22.72	1573	-12
5.50	2454	27.89	1543	-6
5.75	2560	37.89	861	-2
6.00				-9
6.75	4114	51.13	423	-9
7.00	1518	18.20	176	-6
7.25	5185	65.38	726	-5
7.50	2437	29.71	373	-22
7.75	6944	80.91	1122	-20
8.00	6624	78.25	1118	-23
8.25	5328	65.42	927	-12
8.50	5365	64.49	920	-9
8.75	2796	34.19	528	-12
9.00	2834	35.95	567	-1
9.25	4738	61.36	943	-15
9.50	5861	77.51	1221	-20
9.75	6192	77.54	1254	-16
10.00				-16
10.50	3742	45.25	1170	-17
11.00	2442	28.97	993	-13
12.00				-21
12.50	2832	35.26	1432	-20
13.00				
13.50	1627	23.60	745	-15
14.00				-18
15.00				-16
16.00				-13
Average	**2892**		**786**	**-12**

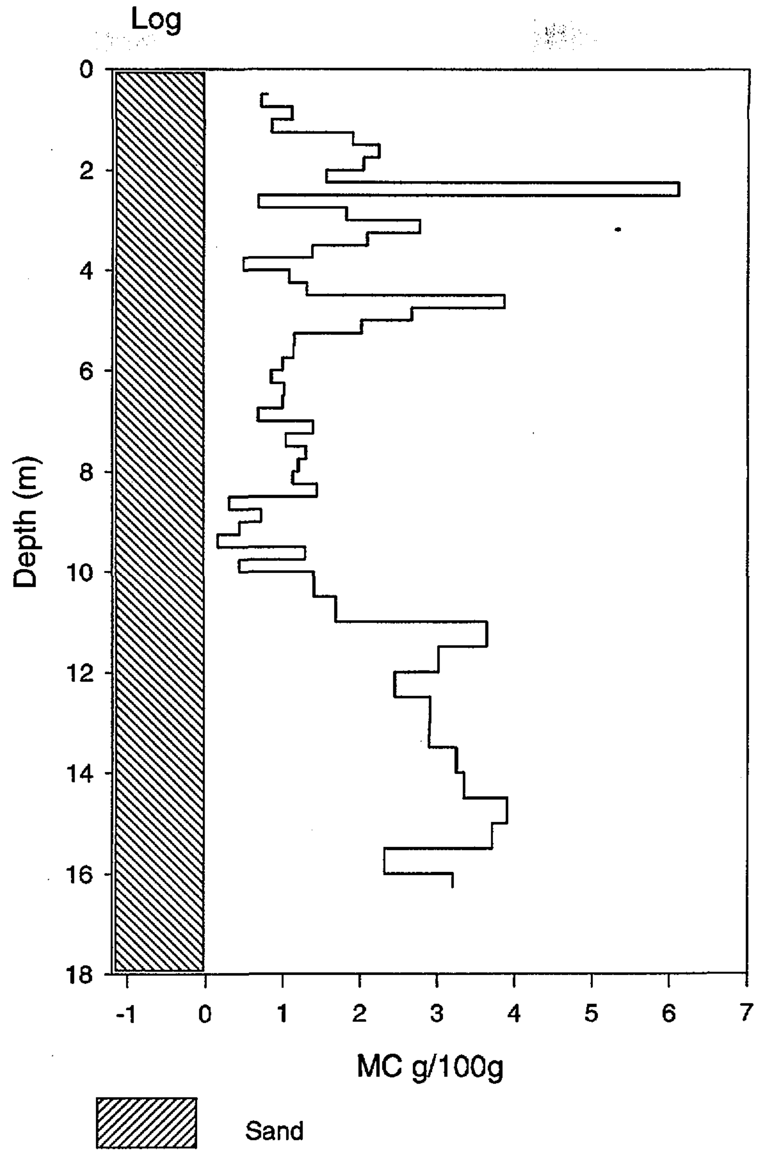

Fig. 3. Depth distribution of lithology and moisture content for MG profile.

The MG profile has relatively low concentrations of Cl and NO_3-N. The mean chloride concentration is 29.5 mg l^{-1}, and its relative uniformity down the profile (Fig. 6) demonstrates that homogenous displacement of an atmospheric input value is the main control. Oscillations about the mean may, however, relate to *recent* antecedent climatic variations. Recharge estimated from the chloride technique gives a long term average of 22 mm/a spanning the period of ca 21 years. Rates of recharge could have been higher in the past, especially since the last 21 years represent the period of Sahel drought.

There is a reasonably good agreement in the estimated rate of recharge between the upper 3 m of the MF profile, the MG and the earlier profiles in the Manga Grasslands [8,14]. Both sites in the present study (upper MF and MG profiles) give therefore recharge estimates of 14 to 22 mm a^{-1}, although at the MF profile an impermeable clay layer encountered below 3 m depth has limited the vertical percolation of moisture. Estimates of recharge for the Manga

Table 3. Solutes and deuterium concentrations in MG profile

MG Profile elutriation			
Depth (m)	CorrCl (mg/L)	corrNO_3-N (mg/L)	δ^2H
0.50	31	47	-14
0.75	42	35	-36
1.00	15	45	-37
1.25	16	41	-31
1.50	64	55	-24
1.75	11	18	-30
2.00	9	9	-28
2.25	17	13	-21
2.50	4	4	-14
2.75	27	49	-27
3.00	9	8	-39
3.25	6	4	-30
3.50	9	7	-20
3.75	16	11	-23
4.00	50	110	-25
4.25	28	39	-28
4.50	19	23	-23
4.75	9	12	-26
5.00	17	18	-27
5.25	26	53	-18
5.50	54	152	-19
5.75	54	164	-26
6.00	49	95	-26
6.25	52	93	-28
6.50	44	78	-32
6.75	35	40	-21
7.00	35	9	-26
7.25	22	4	-30
7.50	37	12	-28
7.75	27	14	-28
8.00	30	31	-21
8.25	26	60	-11
8.50	17	26	-29
8.75	78	100	-26
9.00	39	51	-23
9.25	95	84	-23
9.50	172	160	-22
9.75	23	10	-23
10.00	64	14	-25
10.50	15	4	-29
11.00	9	7	-33
11.50	17	4	-33
12.00	8	2	-27
12.50	10	3	-25
13.00	6	5	-19
13.50	10	4	-34
14.00	8	4	-31
14.50	9	4	-29
15.00	10	7	-31
15.50	9	5	-18
16.00	30	16	-21
16.26	17	28	-34
Average	**29**	**36**	

Table 4. Unsaturated zone profiles and recharge estimates from N.E. Nigeria. The MF and MG sites are from the present study with other data from Edmunds et al. (1999)

Profile	Depth (m)	No. Samples (n)	Mean Cl Cs (mg/l)	Mean annual recharge Rd (mm/a)	Residence time (years)
GM 1	15.50	51	14.1	44.0	17.6
KA 1	14.75	50	18.3	33.9	13.8
MD 1	22.50	65	11.5	53.9	14.3
MN 1	16.50	53	41.6	14.9	34.0
N-TM	18.75	58	11.7	53.0	16.2
MG	16.26	53	29.46	22.5	21.4
MF (upper)	03.00	10	47	14	09
MF (Lower)	16.00	42	2892	0.2	16677

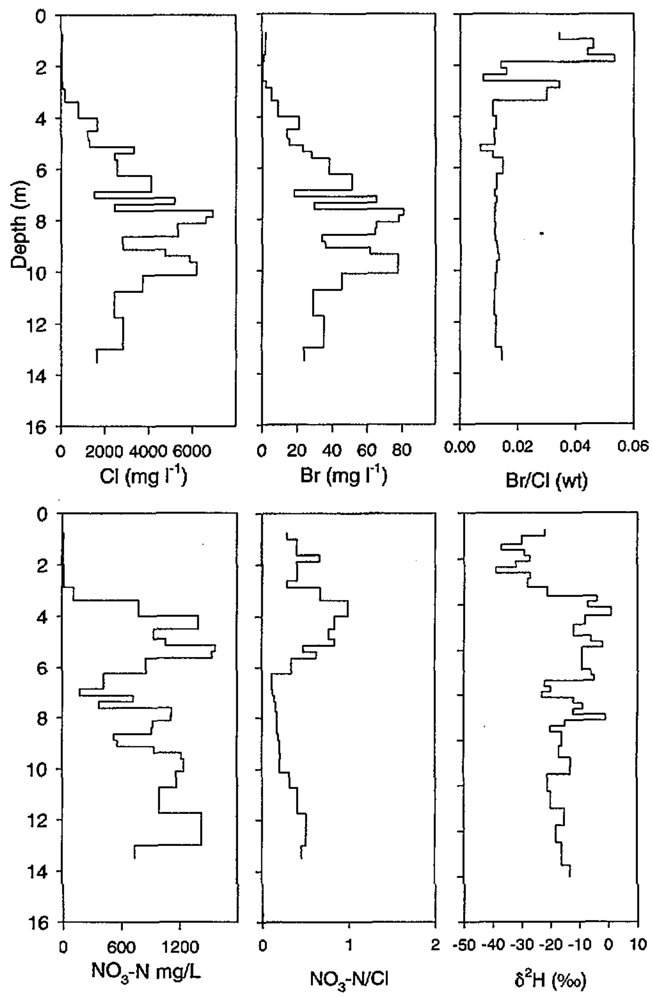

Fig 4. Cl, Br/Cl, NO_3, NO_3-N/Cl and δ^2H values in interstitial waters from the unsaturated zone for the MF profile.

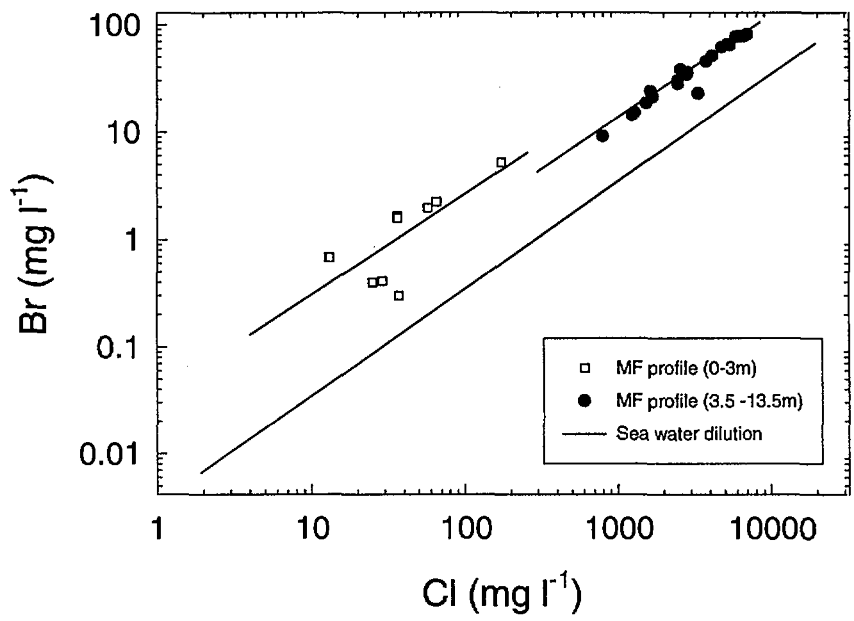

Fig. 5

Grasslands sites give a range of 14 mm a^{-1} to 53 mm a^{-1} (Table 4). Edmunds et al. [14] have used regional groundwater chloride to obtained an average long term recharge estimate of 60 mm a^{-1} for NE Nigeria. High recharge rates therefore occur over much of the sand-covered area of the Sahel of NE Nigeria. These high estimates must imply either that at the regional scale other sources of recharge, probably ponding and surface runoff, may also contribute significantly in addition to direct recharge via the unsaturated zone, or that estimates from the MG and upper MF profiles only indicate low recharge rates during the period of the prolonged drought from the early 1970's.

Water samples from local wells have been used to provide a check to the estimation of recharge using the unsaturated zone chloride profile technique. Chloride concentrations in the water table from Barikuraram well, situated about 100 m from the MF profile, give a relatively high concentration of 189 mg/L (Table 4) when compared to the 47 mg/L average chloride concentration for the upper MF profile. This indicates that solutes from the evaporated lake sediments are also likely to have been incorporated.

The major ions of two of the wells (Lambawa and Abadam) closer to river Yobe show concentrations that are similar but slightly enriched relative to the river. Chloride for instance show slight increase in concentration from 1.6 mg/L in the river water to 2.2 and 3.6 mg/L in the wells (Table 4), which is attributable to evapotranspiration. Similarities in the major ion concentrations indicate some hydraulic links between the river and groundwater systems. This further adds weight to the possibility of recharge taking place laterally from the river Yobe, which is at higher elevation in relation to the groundwater level to the wells close to the river channel.

Depth concentrations of NO_3-N and chloride in the MG profile (Fig. 6) show similar peaks and troughs (although different amplitudes), supporting the conservative behaviour of nitrate. In the upper 3m of the MF profile total nitrate concentrations are enriched (average 22 mg l^{-1} NO_3-N) with some concentrations approaching NO_3-N/Cl ratios of 0.5. Below 3 m very high nitrate concentrations are found with an average of 786 mg/L NO_3-N. There is a clear separation at about 6m between a zone with very high NO_3-N ratio and a lower zone less enriched in nitrate; this division corresponds to the geological log and must be related to conditions of deposition. Once nitrate has entered the largely inorganic and aerobic unsaturated zone, it will behave as a conservative anion and its geochemical behaviour will be similar to chloride. Denitrification is likely to be insignificant under oxidising conditions of most semi-arid environments, especially where water contents are low and organic C contents are also low. As well as the high nitrate concentrations the very low Fe concentrations

Table 5. River and groundwater chemical data

Locality	Point Type	Temp	Ph_Lab	Sec	$\delta^{18}O$	δ^2H	Na	K	Ca	Mg	Hco3_ Lab	So4	Cl	No3_N
River Yobe	river	28.6	7.62	108.3			8.4	4.6	7.48	2.39	59.6	2.3	1.6	-0.5
Barikuraram	well	30.3	8.27	4170	-2.4	-30	864	26.1	60.3	75.9	1765	374	189	64
Lambawa	well	33	7.64	259	-1.1	-14	15.5	6.5	21.8	6.31	134	9.8	3.6	0.52
Abadam	well	33.8	7.79	31.8	-0.6	-7	33.7	8.5	24.2	5.94	212	0.3	2.2	-0.5
Alagarno	well	30.1	8.05	1738	3.4	16	274	37.6	90.8	45.3	785	238	42.1	1.14
Abadam	BH	31.8	7.84	907	-7	-43	145	15.7	27.5	12.2	192	202	60	0.98
MF Doro	BH FF	41.3	7.98	1021	-6	-47	150	16.1	33.8	14.1	204	244	63.5	-0.5
Duhuri	BH FF	36.3	7.93	10510	-5.7	-46	148	16	31.6	13.5	195	226	65.1	1.14
Arege	BH FF	38.8	8.11	998	-6.8	-51	158	16.2	34.4	14.5	209	240	62.1	-0.5
Bundur	BH FF	41.5	7.93	595	-6	-48	101	7.8	7.68	3.35	191	71.3	23.8	1.92
Kekeno	BH FF	39.3	8.08	470	-6.8	-50	84.1	7.1	6.08	2.76	209	38	17	-0.5

Well = Dug well BH = Borehole BH FF = Borehole Free Flowing

(generally below detection limits) are also indicative of oxidising conditions. Total NO_3-N concentrations derived from atmospheric inputs in the Sahel are low [6, 16]. Subsequent variations in the concentrations of nitrate will be modified by physical processes (evapotranspiration) or biochemical transformations in the soil and rooting zone [17].

The nitrate concentrations in MG profile show quite wide variations but with some similarity to the Cl profile. Concentration maxima (at 6 and 9m) are however found at two intervals which are also seen in the NO_3-N/Cl profile where strong enrichment (up to 3.5 times Cl) reflects nitrate being the dominant anion in the profile. This must reflect changes in input conditions (land use/vegetation) over the past 20–30 years, but an explanation is not readily available.

The result of stable isotope analysis for 1997 rainfall at Garin Alkali meteorological station shows a linear regression line through the data points and is similar to the meteoric water line, but the relationship is: $\delta^2H = 6.33\delta^{18}O + 9.9$ with a correlation coefficient of $r = 0.92$. The range for $\delta^{18}O$ is from –6.8‰ to +4.2‰, and for δ^2H is from -36‰ to +36‰. These values are slightly enriched and indicate modification due to evaporation in the monsoon rains producing departure from the GWML. Detailed discussion on the isotope chemistry of rainwater of the region is given in [6].

Depth distribution of δ^2H for the profiles is shown in Figures 4 and 6. The deuterium profiles broadly reflect the trends shown by chloride, especially in distinguishing the active, present day recharge section from the evaporated section in the MF profile. The mean value of δ^2H in profile MG is –26‰ which is slightly more enriched than but similar to the upper

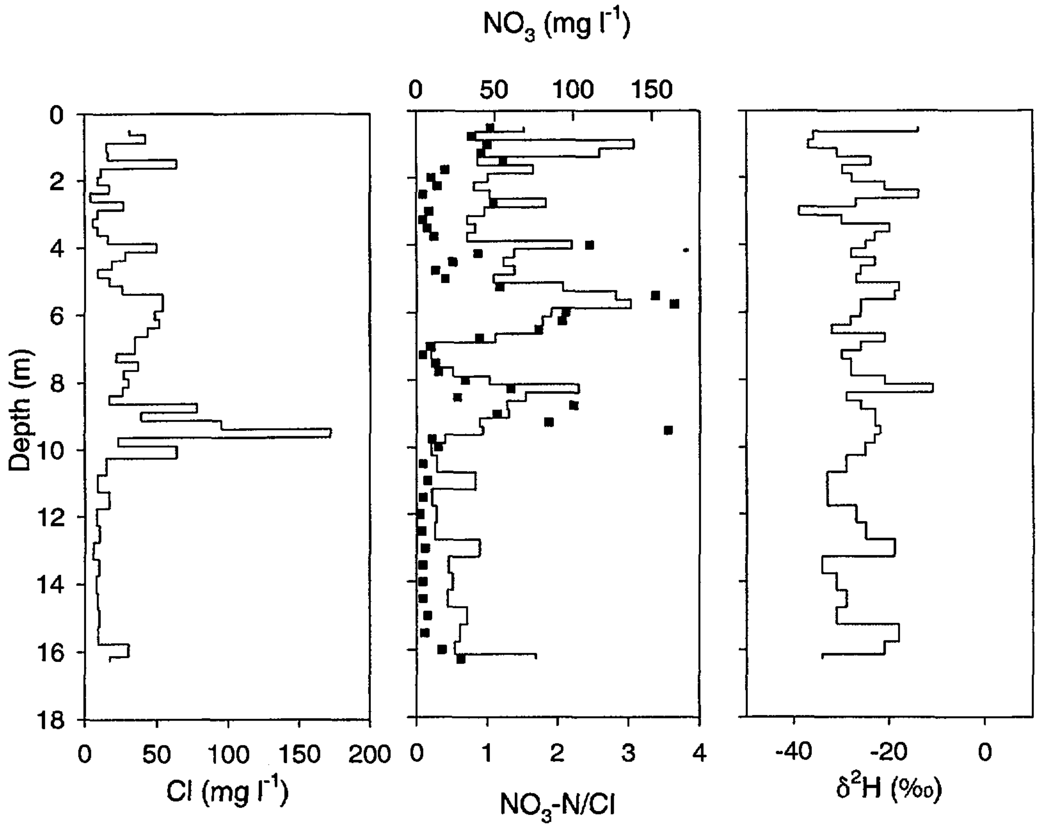

Fig. 6. Solute concentrations and deuterium in the MG profile. On the NO_3-N/Cl diagram NO_3-N concentration is plotted as solid symbol.

section of MF (-30‰). This compares with the mean δ^2H of –10.4‰ in local rains. It is possible that the discrepancy relates to the non-representativeness of the rainfall inputs for this area, since it would be expected that the unsaturated zone samples would be enriched due to evaporation as compared with rainfall.

In the MF profile (Fig. 4) depth distribution of deuterium clearly separates the upper 3 m with an average δ^2H of -30‰ from the lower section with an average δ^2H of -12‰. The fact that the lower section of MF profile has relatively enriched deuterium and also high concentration of solutes shows that relative evaporative enrichment is the likely control, in line with the Cl results. Small oscillations of deuterium values in the lower MF profile may indicates cycles of flooding of Lake Chad during former climatic conditions.

The result of stable isotope analysis for 1997 rainfall at Garin Alkali meteorological station, MF unsaturated zone moisture (the lower section) and groundwater from shallow dug wells were used to plot a delta diagram (Fig. 7). The unsaturated zone moisture and groundwater from some of the wells plot in the same area and have δ^2H value ranging from -14‰ to +2‰ and $\delta^{18}O$ from –1.3‰ to +1‰. These wells are few metres away from river Yobe, and get recharged with heavier water from an evaporated river Yobe, thus plotting in the same area as the evaporated lower section of MF. Solute concentrations also show that there is

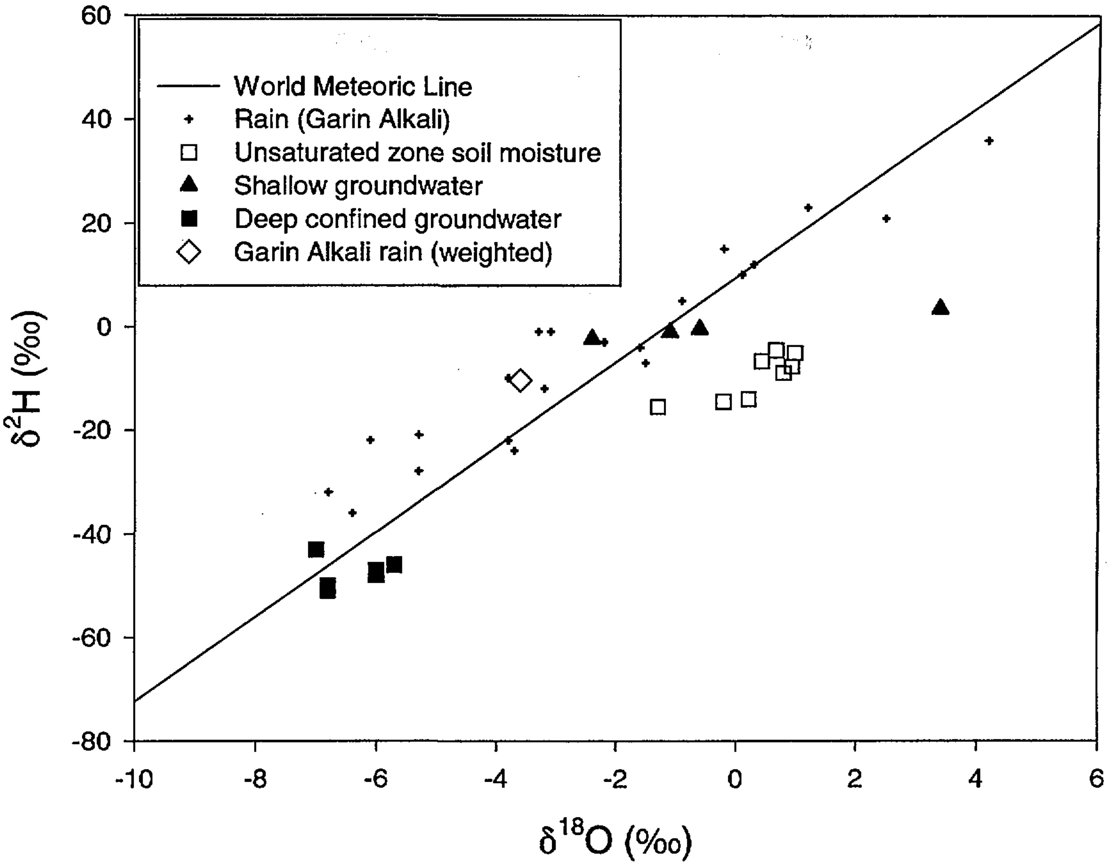

Fig. 7. Plot of 18O versus d2H for rainfall, unsaturated zone moisture, shallow groundwater and deep confined groundwater.

hydraulic link between the river Yobe and the wells close to it. Groundwater from Barikuraram the closest well to the MF profile shows a depleted stable isotope with δ^2H = -30‰ and $\delta^{18}O$ = -2.4‰. Barikuraram well is ~2 Km from river Yobe, and might be receiving its recharge mainly from heavy rains that are depleted in stable isotopes. This also shows that recharge from river Yobe is restricted to wells within only a short distance (tens of metres) of the river channel.

5. Summary and conclusion

Manual augering was used to obtain interstitial waters from two profiles in the unsaturated zone of NE Nigeria to depths of 16 m. This technique is robust and effective in sandy and silty soils. Drilling through clay-rich sediments was also achieved, although thick plastic clays were not able to be sampled. Results of hydrochemical data (solutes and stable isotope) from rainwater, unsaturated zone soil moisture and groundwater from the phreatic aquifer were used to estimate the amount of recharge via the sandy unsaturated zone to the semi-arid region of NE Nigeria. The chloride profile technique gives an estimated direct vertical recharge rate of 14 mm/a and 22.5 mm/a, and residence times of 9 years and 21 years for the upper 3m MF and MG profiles respectively. Below 3 m depth in the MF profile there is a low permeability silt/clay sequence which probably represents the bed of the former lake Chad. The concentration of solutes coincident with enriched deuterium values in the interstitial waters of this section point to an evaporative enrichment and a recharge regime unrelated to the present day. Br and NO_3-N have been used to interpret the source of the solutes, and together with deuterium give the trend of the recharge processes and an insight into the past climate and environments.

In the sand-covered areas of the Sahel of NE Nigeria therefore significant direct vertical recharge takes place via the unsaturated zone, which on a regional scale is complimented by surface runoff. The amount of recharge can sustain the present local abstraction via dug wells, however caution has to be exercise in using submersible pumps to exploit this resource.

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