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Applied Geochemistry 17 (2002) 1343–1349

www.elsevier.com/locate/apgeochem

**Applied  
Geochemistry**

# Major ion chemistry of groundwaters in the Continental Terminal water table of southwestern Niger (Africa)

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Received 28 January 2001; accepted 7 December 2001

Editorial handling by A. Welch

## Abstract

Numerous chemical analyses undertaken during the last 4 a in the Niamey area of the Continental Terminal groundwaters (SW Niger, Africa) reveal large seasonal variations and high NO<sub>3</sub> content (up to 2.87 meq/l). The positive correlation between conductivity and depth to the water table indicates that the chemical change is associated with the recharge. In the shallow wells, this highly mineralised recharge reflects the rain composition, variably concentrated by evaporation processes. © 2002 Elsevier Science Ltd. All rights reserved.

## 1. Introduction

In SW Niger (Africa), groundwater constitutes the main water resource and most hydrological studies have been focused on recharge processes. Leduc et al. (1997) and Desconnets et al. (1997) described the major role of temporary pools and rivers in recharging the shallow aquifer. During the last 40 a, a marked rise of the water table level has been occurring. Between 1992 and 1999, this rise was about 0.20 m/a and is attributed to increased runoff and decreased evapotranspiration (Leduc et al., 2001) in response to the extension of the cultivated area and land-clearing. Because this shallow aquifer is the only permanent source of drinking water, it is important to know if these physical changes are accompanied by variations of chemical composition.

This paper presents major ion chemistry of groundwaters in a rural region near Niamey (Niger) where seasonal fluctuations of water chemistry occur. The

research effort is to understand the chemical processes causing these variations.

## 2. Study area

In the study area, located in the Niamey region, Niger (Fig. 1), the Precambrian basement composed of extensively weathered and kaolinised gneisses, schists and granites, outcrops in the Niger Valley and lies at shallow depths to the NW. The Precambrian basement is overlain by the Continental Terminal, a late Tertiary sequence of sandstones, silty sandstones and siltstones interbedded with lateritic layers. The Continental terminal forms a multilayer system that contains two confined deep aquifers and one shallow aquifer (Le Gal La Salle et al., 1995). The shallow aquifer, which constitutes the subject of the present study has no hydraulic connection to the two deeper aquifers (Leduc et al., 1997) or to the Niger river.

The rainy season extends from June to September with 60% of the annual rainfall in July and August. The rainfall is highly variable in time and space. In Niamey, the long-term average precipitation is 565 mm/a with extreme

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values of 281 mm in 1951 and 1161 mm in 1998. Potential evaporation is about 2500 mm/a (Favreau, 2000).

Hydraulic gradients are generally low (less than 1%) without any preferential direction of flow (Leduc et al., 1997). The aquifer is recharged by infiltration through the sandy beds of numerous temporary pools (Desconnets et al., 1997) fed by rainfall. Away from the pools, the infiltration is limited at 3–5 m depth. The thickness of the saturated zone ranges between 5 and 75 m.

### 3. Sampling and analysis

The location of the sampled wells is shown in Fig. 1. Samples were taken manually with a bailer at 1 m below the water level. It was impossible to pump all the wells before sampling. However the measurements before and after pumping in some of the studied wells do not show major changes of conductivity (Table 1). Moreover, the coherence of the data set presented in this study suggests that the water is in a first approximation representative of the aquifer.

Conductivity, pH and alkalinity, expressed as  $\text{HCO}_3^-$ , were measured in the field using, respectively, a WTW LF 340 conductimeter, a glass electrode and acid titration.

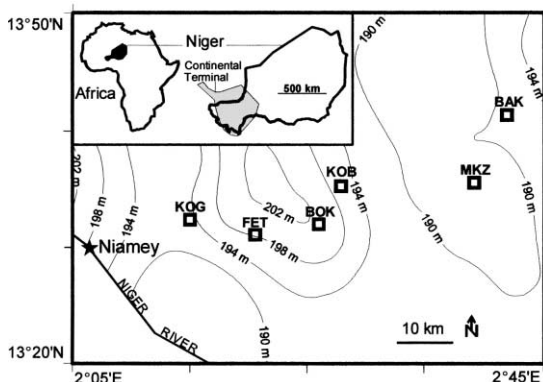


Fig. 1. Sketch map of the square degree of Niamey with location of studied wells. BAK = Bani Kossey, BOK = Boktili, FET = Fetobokki Peul, KOB = Koberi, KOG = Kogorou, MKZ = Maourey Kouara Zeno. The curves indicate the water level altitude.

Table 1

Conductivity of groundwaters ( $\mu\text{S}/\text{cm}$ ) at the beginning (1) and at the end (2) of pumping; volume in  $\text{m}^3$

Well	Date	1	2	Duration	Initial volume	Pumped volume
Kogorou	31/05/1999	146	164	48 h 00	14	900
Maourey KZ	19/05/1999	292	272	48 h 00	3	300

After filtration in the field with 0.4  $\mu\text{m}$  cellulose membranes and acidification (1 vol.%  $\text{HNO}_3$ ) for cations,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$ ,  $\text{K}^+$  and  $\text{SO}_4^{2-}$  were determined by ICP–AES (Vista, VARIAN).  $\text{NO}_3^-$  and  $\text{Cl}^-$  were measured by colorimetry, using a Technicon autoanalyser. The precision of major element analysis was about 5%.

### 4. Chemical composition

Conductivity, pH, depth to the water table and major element concentrations measured between 1996 and 2000 are reported in Table 2 and in a Piper diagram (Fig. 2). Most waters are slightly acidic ( $5 < \text{pH} < 7$ ) with a composition dominated by  $\text{Ca}^{2+}$ ,  $\text{Na}^+$ ,  $\text{Cl}^-$  and  $\text{NO}_3^-$  (Fig. 2). Despite the abundance of  $\text{Ca}^{2+}$ , MINEQL+ (Schecher and McAvoy, 1992) calculations show that the waters are undersaturated with respect to calcite.

Large physical and chemical variations are reflected in the range of conductivity (38–857  $\mu\text{S}/\text{cm}$ ) and total cation charge ( $0.38 < \Sigma^+ < 7.58$  meq/l). Individual element concentrations also vary and several inter-element correlations are apparent. The  $\text{NO}_3^-$  concentrations range between 0.04 and 2.87 meq/l. The highest concentrations were recorded at the beginning of the rainy season with values sometimes higher than the World Health Organization recommendations (0.81 meq/l). When  $\text{NO}_3^-$  concentrations are plotted against  $\text{Cl}^-$  concentrations (Fig. 3), the data define a notable correlation for each well, except for the samples with the highest  $\text{Cl}^-$ . On average, the  $\text{NO}_3^-/\text{Cl}^-$  ratios are close to the rain ratio of the study area (Galy-Lacaux and Modi, 1998).

$\text{Na}^+ + \text{K}^+$  increase with  $\text{Cl}^-$  for each well (Fig. 4). Overall,  $\text{Na}^+ + \text{K}^+/\text{Cl}^-$  ratios vary over a large range (2–40). These ratios decrease with increasing of  $\text{Cl}^-$  concentration and tend to the halite value in the water which has the highest  $\text{Cl}^-$  content (Fig. 5).

Like alkalis, alkali earths behave differently according to wells. In the Boktili, Koberi and Maourey wells,  $\text{Ca}^{2+} + \text{Mg}^{2+}$  are correlated with  $\text{HCO}_3^-$  (Fig. 6) and the data fit to a straight line with a slope of 1. In the other wells, a large scattering of  $\text{Ca}^{2+} + \text{Mg}^{2+}$  is apparent for a given  $\text{HCO}_3^-$  value and the location of the data above the straight line reflects an excess of alkali earths relative to  $\text{HCO}_3^-$ .  $\text{SO}_4^{2-}$  concentrations are overall quite low ( $< 0.48$  meq/l) and display an erratic distribution without correlation with the other chemical components.

### 5. Relation between conductivity and depth to the water table

Conductivity and water levels have been monitored simultaneously for 8 a in each well. The conductivity data are by far more numerous than chemical analyses and provide insight into chemical changes related to

Table 2  
Chemical analysis of groundwaters

Well	Date	Water depth (m)	pH	Conductivity ( $\mu\text{S}/\text{cm}$ )	$\text{Cl}^-$ (meq/l)	$\text{NO}_3^-$ (meq/l)	$\text{SO}_4^{2-}$ (meq/l)	$\text{HCO}_3^-$ (meq/l)	$\text{Ca}^{2+}$ (meq/l)	$\text{Mg}^{2+}$ (meq/l)	$\text{K}^+$ (meq/l)	$\text{Na}^+$ (meq/l)
Bani Kossey	24/7/1996	-24.64	5.96	319	0.320	1.720	0.090	0.670	0.840	0.290	0.140	1.460
Bani Kossey	25/9/1996	-23.04	-	467	0.550	2.360	0.080	0.820	1.340	0.380	0.180	2.030
Bani Kossey	29/1/1997	-24.04	6.21	366	0.397	1.963	0.084	0.640	1.044	0.455	0.241	1.338
Bani Kossey	3/6/1997	-24.43	5.96	301	0.234	1.625	0.102	0.460	0.645	0.296	0.178	1.433
Bani Kossey	18/8/1997	-24.01	5.82	335	0.278	1.775	0.076	0.480	0.762	0.329	0.125	1.473
Bani Kossey	16/10/1997	-24.65	6.14	296	0.273	1.724	0.087	0.950	1.144	0.312	0.131	1.463
Bani Kossey	30/6/1999	-24.00	5.91	196	0.150	1.290	0.080	0.480	0.550	0.230	0.130	1.000
Bani Kossey	17/8/1999	-23.28	-	343	0.280	1.780	0.080	0.760	1.080	0.430	0.210	1.280
Bani Kossey	4/10/1999	-23.24	6.54	355	0.300	1.850	0.090	0.720	1.230	0.450	0.240	1.340
Bani Kossey	16/11/1999	-23.54	6.28	283	0.240	1.620	0.110	0.660	0.850	0.380	0.170	1.220
Bani Kossey	4/4/2000	-24.56	6.91	180	0.160	1.150	0.210	0.560	0.560	0.280	0.170	0.990
Bani Kossey	4/7/2000	-24.29	6.75	203	0.170	1.050	0.170	0.520	0.530	0.230	0.170	0.970
Bani Kossey	22/7/2000	-24.01	6.66	182	0.160	1.100	0.160	0.520	0.560	0.230	0.150	0.970
Boktili	26/8/1996	-26.30	5.33	113	0.050	0.350	0.040	0.630	0.430	0.040	0.030	0.480
Boktili	9/9/1996	-26.50	6.11	174	0.030	0.360	0.070	1.090	0.960	0.030	0.020	0.470
Boktili	14/10/1996	-26.63	-	131	0.040	0.310	0.050	0.880	0.640	0.030	0.030	0.450
Boktili	31/1/1997	-26.84	5.46	74	0.033	0.245	0.017	0.260	0.141	0.016	0.015	0.380
Boktili	21/8/1997	-26.74	6.13	106	0.040	0.311	0.036	0.510	0.382	0.043	0.019	0.445
Boktili	15/10/1997	-26.47	5.65	118	0.042	0.364	0.036	0.474	0.364	0.037	0.024	0.489
Boktili	30/9/1999	-26.10	6.13	65	0.040	0.360	0.030	1.400	1.140	0.050	0.020	0.470
Boktili	5/11/1999	-26.09	5.94	114	0.060	0.380	0.050	0.540	0.400	0.030	0.030	0.450
Boktili	3/4/2000	-26.14	6.71	59	0.010	0.330	0.070	0.200	0.080	0.010	0.010	0.390
Boktili	3/7/2000	-26.15	6.55	243	0.480	1.180	0.133	0.500	0.920	0.320	0.390	0.740
Boktili	25/7/2000	-26.13	6.77	85	0.030	0.240	0.090	0.700	0.410	0.040	0.050	0.410
Fetobokki Peul	24/7/1996	-10.94	5.54	247	0.370	1.300	0.040	0.400	0.720	0.260	0.190	0.840
Fetobokki Peul	6/6/1997	-11.65	5.76	204	0.364	1.020	0.035	0.300	0.559	0.236	0.161	0.793
Fetobokki Peul	18/7/1997	-10.83	5.87	168	0.470	1.158	0.108	0.460	0.695	0.268	0.494	0.919
Fetobokki Peul	20/8/1997	-9.34	6.91	650	1.384	2.379	0.398	1.310	1.622	0.716	1.394	1.878
Fetobokki Peul	8/9/1997	-9.60	6.63	467	0.733	2.456	0.127	0.690	1.436	0.563	0.595	1.452
Fetobokki Peul	29/9/1997	-10.04	6.00	380	0.526	2.170	0.061	0.550	1.295	0.513	0.289	1.222
Fetobokki Peul	15/10/1997	-9.65	6.04	389	0.526	2.245	0.052	0.410	1.264	0.529	0.282	1.126
Koberi	24/7/1996	-60.72	6.10	95	0.040	0.060	0.030	0.860	0.540	0.050	0.030	0.190
Koberi	10/9/1996	-60.68	6.76	161	0.030	0.180	0.060	1.100	0.980	0.050	0.070	0.200
Koberi	4/11/1996	-60.91	6.75	77	0.090	0.110	0.020	0.650	0.390	0.050	0.070	0.260
Koberi	6/6/1997	-60.72	6.18	82	0.042	0.102	0.026	0.540	0.317	0.041	0.035	0.209
Koberi	18/7/1997	-60.77	6.39	99	0.032	0.045	0.031	0.700	0.489	0.034	0.037	0.188
Koberi	23/7/1999	-59.92	-	271	0.090	0.150	0.030	1.820	1.380	0.150	0.190	0.210
Koberi	19/10/1999	-60.02	6.73	143	0.050	0.180	0.040	0.900	0.760	0.050	0.070	0.150
Koberi	15/11/1999	-60.05	6.53	68	0.040	0.060	0.030	0.700	0.520	0.040	0.050	0.170
Koberi	3/4/2000	-60.58	6.91	38	0.050	0.140	0.040	0.160	0.170	0.030	0.070	0.160
Koberi	22/7/2000	-60.05	6.94	88	0.060	0.040	0.070	0.860	0.660	0.050	0.070	0.210
Kogorou	24/7/1996	-16.91	5.96	144	0.180	0.580	0.040	0.580	0.640	0.190	0.040	0.320
Kogorou	5/11/1996	-15.93	-	212	0.550	0.620	0.080	0.710	0.930	0.240	0.150	0.620
Kogorou	30/1/1997	-16.89	6.00	136	0.221	0.609	0.046	0.300	0.619	0.198	0.044	0.312
Kogorou	6/6/1997	-17.27	5.82	151	0.230	0.544	0.027	0.380	0.629	0.207	0.036	0.332
Kogorou	15/10/1997	-15.88	6.04	183	0.266	0.439	0.072	0.550	0.882	0.223	0.133	0.352
Kogorou	31/5/1999	-16.00	7.12	146	0.200	0.700	0.085	0.280	0.700	0.220	0.100	0.320
Kogorou	2/6/1999	-16.03	6.62	164	0.270	0.880	0.070	0.100	0.620	0.318	0.060	0.410
Kogorou	22/7/1999	-15.84	-	236	0.280	0.700	0.030	0.660	0.930	0.310	0.080	0.410
Kogorou	15/9/1999	-14.48	6.31	396	0.640	1.670	0.080	1.160	2.320	0.600	0.110	0.650
Kogorou	18/10/1999	-13.93	6.73	578	0.810	2.010	0.100	1.780	2.810	0.800	0.180	0.830
Kogorou	3/4/2000	-15.84	6.88	200	0.250	1.080	0.070	0.360	1.090	0.370	0.060	0.410
Kogorou	26/6/2000	-16.25	6.95	279	0.350	1.290	0.080	0.620	1.460	0.490	0.080	0.510
Kogorou	27/7/2000	-14.99	6.77	314	0.600	1.960	0.100	0.660	2.050	0.670	0.090	0.620
Kogorou	27/7/2000	-14.99	6.28	273	0.400	1.960	0.070	0.260	1.560	0.718	0.060	0.540

Table 2 (continued)

Well	Date	Water depth (m)	pH	Conductivity ( $\mu\text{S}/\text{cm}$ )	$\text{Cl}^-$ (meq/l)	$\text{NO}_3^-$ (meq/l)	$\text{SO}_4^{2-}$ (meq/l)	$\text{HCO}_3^-$ (meq/l)	$\text{Ca}^{2+}$ (meq/l)	$\text{Mg}^{2+}$ (meq/l)	$\text{K}^+$ (meq/l)	$\text{Na}^+$ (meq/l)
Maourey KZ	1/8/1997	-19.37	5.96	78	0.170	0.060	0.150	0.380	0.230	0.030	0.030	0.500
Maourey KZ	15/9/1998	-13.99	6.05	857	2.870	2.870	0.480	1.050	2.360	0.660	0.810	3.750
Maourey KZ	7/10/1998	-14.98	6.05	450	1.540	2.610	0.080	0.840	1.350	0.300	0.120	3.100
Maourey KZ	27/11/1998	-16.73	6.10	489	1.270	2.610	0.120	0.640	1.120	0.280	0.170	3.150
Maourey KZ	19/5/1999	-17.92	6.61	292	0.680	1.470	0.111	0.380	0.460	0.130	0.090	1.950
Maourey KZ	21/5/1999	-17.92	6.88	272	0.650	1.440	0.100	0.140	0.240	0.110	0.050	1.880
Maourey KZ	4/6/1999	-18.04	6.67	264	0.610	1.330	0.100	0.220	0.320	0.110	0.070	1.840
Maourey KZ	22/7/1999	-18.10	-	320	0.480	1.310	0.070	0.440	0.430	0.110	0.070	1.660
Maourey KZ	31/8/1999	-18.04	6.45	275	0.560	1.250	0.080	0.620	0.520	0.110	0.070	1.620
Maourey KZ	16/11/1999	-18.10	6.17	256	0.460	1.170	0.080	0.500	0.430	0.110	0.080	1.550
Maourey KZ	24/2/2000	-18.70	6.68	235	0.500	1.000	0.100	0.220	0.250	0.090	0.070	1.530
Maourey KZ	18/7/2000	-18.34	6.61	171	0.350	0.690	0.116	0.300	0.300	0.060	0.050	1.170
Maourey KZ	22/7/2000	-18.28	6.63	158	0.340	0.690	0.110	0.380	0.340	0.070	0.050	1.160

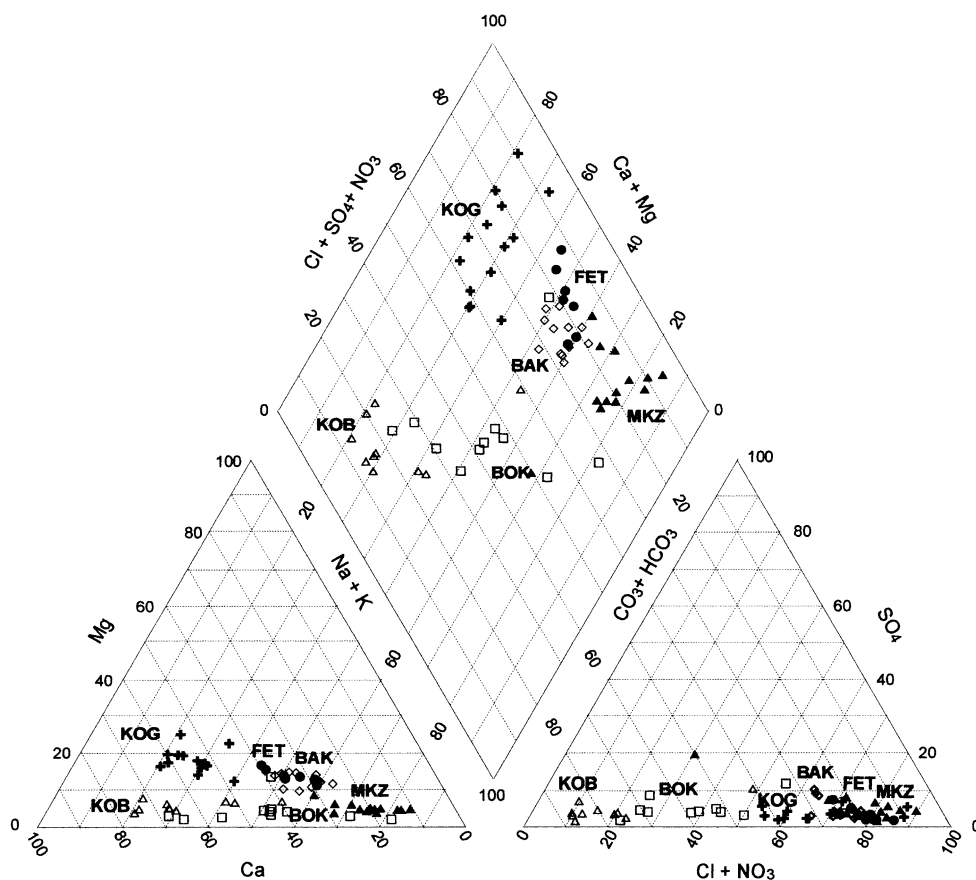


Fig. 2. Piper diagram showing the chemical composition of the analysed groundwaters in the study area during the 1996–2000 period.

recharge. The conductivity displays a clear relation with depth to the water table (Fig. 7). The deepest water levels (–60 to –20 m) are accompanied by relatively low conductivities with a limited range of variation (200–467  $\mu\text{S}/\text{cm}$ ). In the shallower wells (–20 to –10 m), high and variable conductivity values (100–980  $\mu\text{S}/\text{cm}$ ) are recorded.

In the shallower wells, the increase of both conductivity and water level are concomitant and occur during the rainy season (Fig. 8), suggesting the recharge has higher dissolved mineral content. As indicated by the data and in agreement with previously published studies (Leduc et al., 1997), the influence of recharge decreases with

depth but also with increasing distance from the infiltration zones.

### 6. Interpretation

The relationship between alkalis or alkali earths with  $\text{Cl}^-$  or  $\text{HCO}_3^-$  can be used to decipher their origins. Considering alkali distribution, the plot  $\text{Na}^+ + \text{K}^+$  vs  $\text{Cl}^-$  (Fig. 5) suggests a mixing process involving two

end-members. The first one is enriched in  $\text{Cl}^-$  and according to wells has a  $\text{Na}^+ + \text{K}^+/\text{Cl}^-$  ratio close to the rain (1.67) or halite (1) ratio. This end-member is also enriched in  $\text{NO}_3^-$ , which is correlated with  $\text{Cl}^-$ . As NaCl forms as pools dry, subsequent wetting during the rainy season can dissolve it (Smith and Drever, 1976) and  $\text{NO}_3^-$  salts may act the same way as they are highly soluble. In these wells, the excess of  $\text{Ca}^{2+} + \text{Mg}^{2+}$  relative to  $\text{HCO}_3^-$  is also correlated with  $\text{NO}_3^-$  (Fig. 9), again suggesting a relation with  $\text{NO}_3^-$ . This component dominates in the shallow wells during the rainy season and thus probably reflects a surface contribution.

The second end-member is depleted in  $\text{Cl}^-$  and displays high  $\text{Na}^+ + \text{K}^+/\text{Cl}^-$  ratios. In addition, the sum  $\text{Ca}^{2+} + \text{Mg}^{2+}$  is balanced by  $\text{HCO}_3^-$  indicating congruent

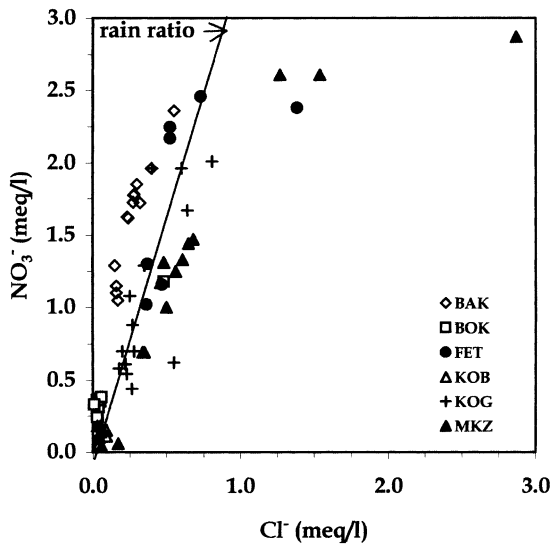


Fig. 3.  $\text{NO}_3^-$  (in meq/l) vs  $\text{Cl}^-$  (in meq/l) in groundwaters and total N ( $\text{NH}_4^+ + \text{NO}_3^-$ )/ $\text{Cl}^-$  ratio in rain. Rain data are from Galy-Lacaux and Modi (1998).

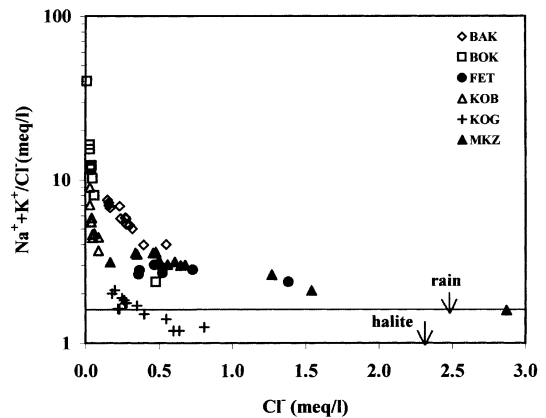


Fig. 5.  $\text{Na}^+ + \text{K}^+/\text{Cl}^-$  (in meq/l) vs  $\text{Cl}^-$  (in meq/l) plot in groundwaters during the 1996–2000 period.

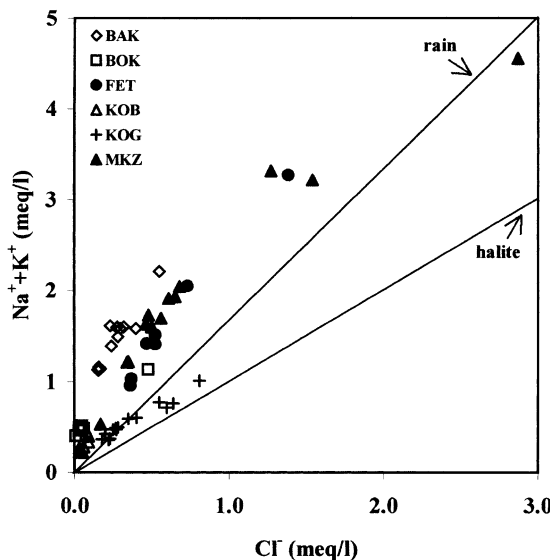


Fig. 4. Relationship between  $\text{Na}^+ + \text{K}^+$  (in meq/l) vs  $\text{Cl}^-$  (in meq/l) in groundwaters sampled during the 1996–2000 period.

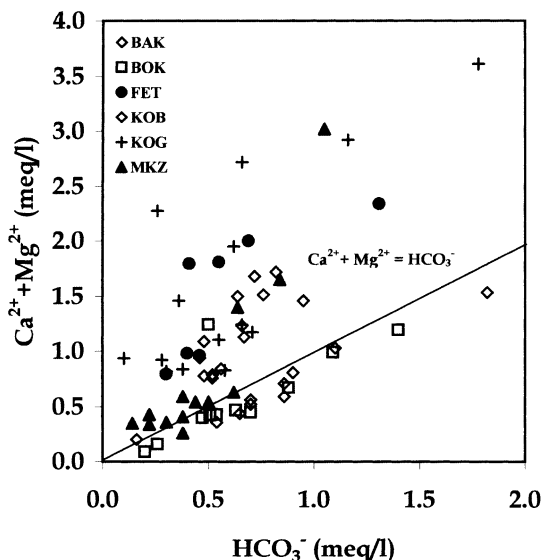


Fig. 6.  $\text{Ca}^{2+} + \text{Mg}^{2+}$  (in meq/l) vs  $\text{HCO}_3^-$  (in meq/l) plot for groundwaters sampled during the 1996–2000 period.

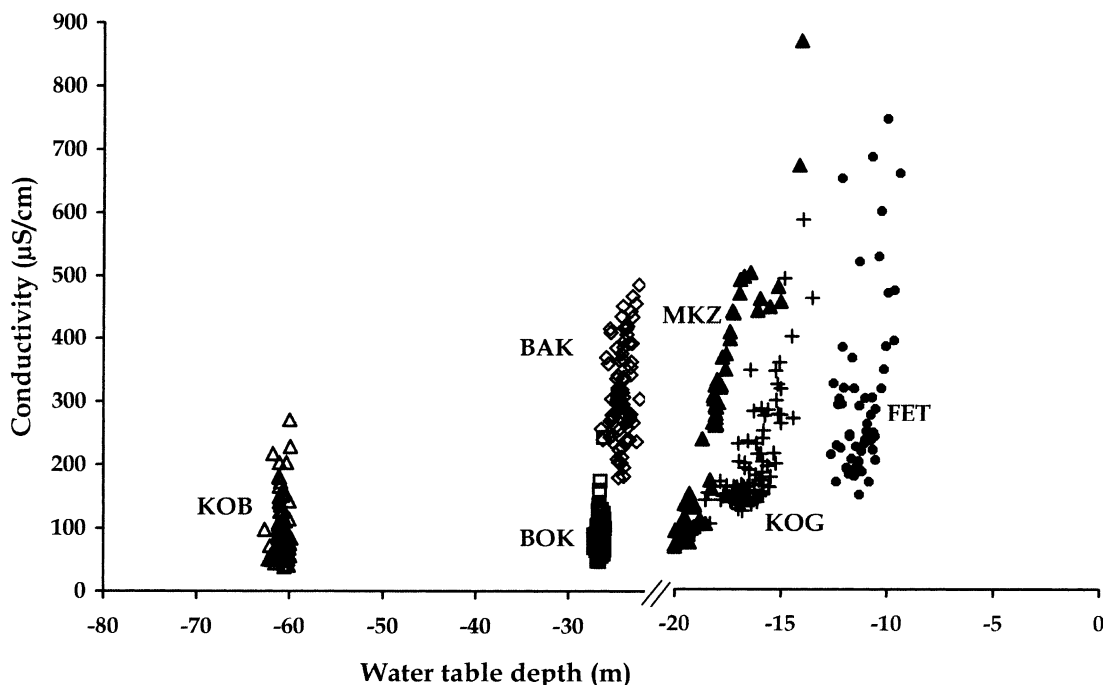


Fig. 7. Relationship between conductivity and depth to the water-table in the studied wells. Abbreviations as in Fig. 1.

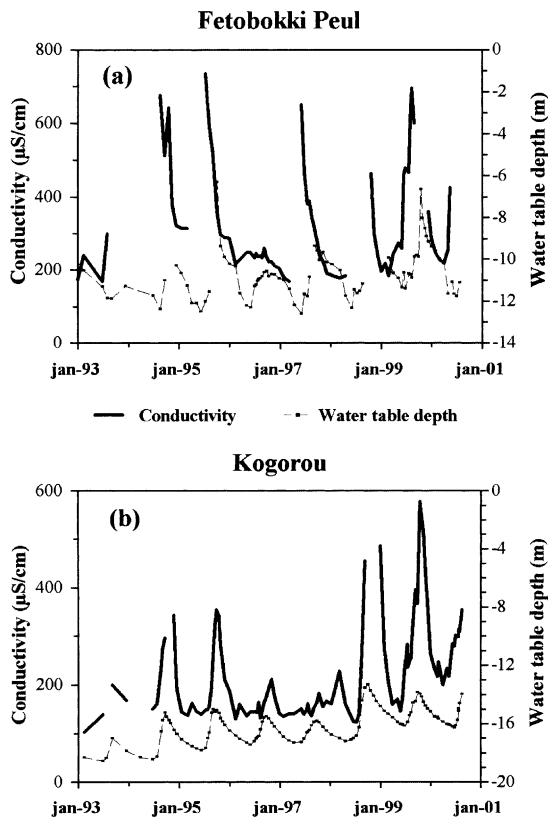


Fig. 8. Variations of conductivity and water-table depth measured during the years 1992–2000 in two selected wells.

dissolution of calcite. These waters, which are diluted, reflect the lithological context of the study area, characterised by an old and highly weathered crust, soluble minerals containing alkalis and alkali earths remaining relatively rare. It corresponds to the water in the aquifer unaffected by current recharge conditions. According to Favreau (2000), the minimum age of this water calculated using <sup>14</sup>C ranges between 1 and 2.5 ka.

During the recharge, the atmospheric fallout is probably the most important source for alkalis and alkali earths. These elements show an increase of concentration, specially marked in shallow wells. In the Sahelian zone, numerous studies (Drees et al., 1993; Orange et al., 1993; Bleich et al., 1994; Galy-Lacaux and Modi, 1998) have reported the presence of Saharan dust containing Ca, Mg, Na and K-rich compounds. This dust is deposited mainly during the Harmattan wind episodes frequent at the beginning of the rainy season (Ntchayi Mbourou et al., 1997) and may contribute to the Ca loading of the surface waters. In addition, the rain evaporates before reaching the aquifer and ultimately may produce an evaporated salt deposit. Dissolution of such salts influences the chemistry of the Kogorou well, as indicated by the  $Na^+ + K^+ / Cl^-$  ratios close to 1.

Surprisingly, since the concentration of  $NO_3^-$  in the aquifer is relatively high (up to 2.87 meq/l) in the absence of chemical fertilisers different origins must be considered. Girard and Hillaire-Marcel (1997) have attributed the elevated  $NO_3^-$  concentrations in the Niamey aquifer to latrines and deforestation. Although this

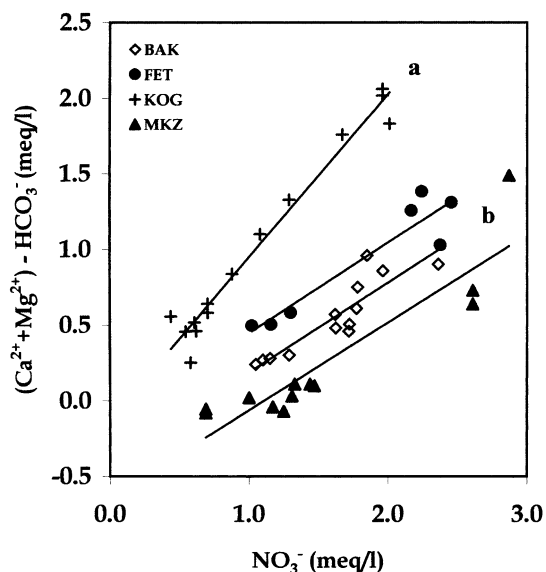


Fig. 9.  $\text{Ca}^{2+} + \text{Mg}^{2+} - \text{HCO}_3^-$  (in meq/l) vs  $\text{NO}_3^-$  (in meq/l) plot for Bani Kossei, Fetobokki Peul, Kogorou and Maourey KZ wells: (a) slope = 1; (b) slope = 0.5.

hypothesis may also apply to the present data, the similarity between  $\text{NO}_3^-/\text{Cl}^-$  ratios in wells and rains (Fig. 2) suggests that the atmospheric fallout contributes to the ultimate source of  $\text{NO}_3^-$  in wells. In the studied area, the atmospheric deposition is noticeably enriched in N (Galy-Lacaux and Modi, 1998), and its concentrations in wet deposition (total N = 25.2  $\mu\text{eq/l}$ ) are comparable to that of industrialised regions despite the absence of factories and the sparse vehicle traffic. Galy-Lacaux and Modi (1998) attribute these elevated concentrations to  $\text{NH}_3$  released by domestic animal excreta, to household fire using wood and to natural emissions from semi-arid savanna soils. These  $\text{N}_n$  containing gases are scavenged by the desert dust which is abundant in the atmosphere and deposited with wet deposition (Galy-Lacaux and Modi, 1998).

## 7. Conclusion

This study has demonstrated that the chemical composition of groundwaters differs according to depth of the water table. The shallower wells (> 20 m) display generally higher conductivities and higher ion ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^{2+}$ ,  $\text{Cl}^-$  and  $\text{NO}_3^-$ ) concentrations indicative of the increasing influence of highly mineralised recharge. For example, the conductivity of the Kogorou Well (KOG) seems to be increasing along with the water-table rise. This has implications for the long term use of this aquifer.

Although direct inputs due to anthropogenic activity cannot be excluded, the mineralisation of the groundwaters

and their high  $\text{NO}_3^-$  content are mainly derived from the atmosphere.

## Acknowledgements

We wish to gratefully thank C. Dupuy, R. Lee, R. Rogers and A. Welch for their helpful comments and suggestions to improve the manuscript. This study was partly supported by the PNRH (French program of Hydrological Research).

## References

- Bleich, K.E., Herrmann, K., Papenfuss, K., Stahr, K., 1994. Dust influx into the soils of the Sahelian zone in Niger: its composition and identification. In: Buerket, B., Allison, B., von Oppen, M. (Eds.), Proc. Internat Symp.: Wind erosion in West Africa: The Problem and its Control. University of Hohenheim, Germany, 5–7 December 1994, Margraf Verlag, Weikersheim, Germany, pp. 311–317.
- Desconnets, J.C., Taupin, J.D., Lebel, T., Leduc, C., 1997. Hydrology of the HAPEX-Sahel Central Super-Site: surface water drainage and aquifer recharge through the pool system. *J. Hydrol.* 155–178, 188–189.
- Drees, L., Manu, A., Wilding, L., 1993. Characteristic of aeolian dust in Niger, west Africa. *Geoderma* 59, 213–233.
- Favreau, G., 2000. Caractérisation et modélisation d'une nappe phréatique en hausse au Sahel: dynamique et géochimie de la dépression piézométrique naturelle du Kori de Dantiandou (sud-ouest du Niger). PhD, Univ. Paris XI, Orsay.
- Galy-Lacaux, C., Modi, A., 1998. Precipitation chemistry in the Sahelian Savanna of Niger, Africa. *J. Atmos. Chem.* 30, 319–343.
- Girard, P., Hillaire-Marcel, C., 1997. Determining the source of nitrate pollution in the Niger discontinuous aquifers using the natural  $^{15}\text{N}/^{14}\text{N}$  ratios. *J. Hydrol.* 199, 239–251.
- Leduc, C., Bromley, J., Schoeter, P., 1997. Water table fluctuation and recharge in semi-arid climate: some results of the HAPEX-Sahel hydrodynamic survey (Niger). *J. Hydrol.* 188, 123–138.
- Leduc, C., Favreau, G., Schroeter, P., 2001. Long term rise in a Sahelian water-table: the Continental Terminal in South-West Niger. *J. Hydrol.* 243, 43–54.
- Le Gal La Salle, C., Fontes, J.C., Andrews, J.N., Schroeter, P., Atahiro, K., Fifield, K., 1995. Old groundwater circulation in the Iullemeden basin (Niger): preliminary results of an isotopic study. In: Application of Tracers in Arid Zone Hydrology. IAHS Publ 232, 129–139.
- Ntchayi Mbourou, G., Bertrand, J., Nicholson, S., 1997. The diurnal and seasonal cycles of wind-born dust over Africa north of the equator. *J. Appl. Meteor.* 36, 868–882.
- Orange, D., Gac, J.Y., Diallo, M., 1993. Geochemical assessment of atmospheric deposition including Harmattan dust in continental west Africa. In: Tracers in Hydrology. IAHS Publ. 215, 303–311.
- Schecher, W.D., McAvoy, D.C., 1992. MINEQL+, a software environment for chemical equilibrium modelling. *Comput. Environ. Urban Syst.* 16, 65–76.
- Smith, C.L., Drever, J.I., 1976. Controls on the chemistry of springs at Teel Marsh, Mineral County, Nevada. *Geochim. Cosmochim. Acta* 40, 1081–1093.