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Objekttyp: **Article**

Zeitschrift: **Bulletin de la Société Vaudoise des Sciences Naturelles**

Band (Jahr): **87 (2000-2001)**

Heft 4

PDF erstellt am: **27.07.2024**

Persistenter Link: https://doi.org/10.5169/seals-281406

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SVSN *Bull. Soc. Vaud. Sc. Nat. 87.4: 337-352.* *ISSN 0037-9603*

Bulletin de Géologie de l'Université de Lausanne n° 347

Isotopic and hydrogeochemical investigations on the fluid regime of the Dallol Bosso, Niger

by

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Abstract.–HUNZIKER J.C., GALADIMA S.A. and PASTORELLI S., 2001. Isotopic and hydrogeochemical investigations on the fluid regime of the Dallol Bosso, Niger. *Bull. Soc. vaud. Sc. nat. 87.4*: 337-352.
The combined use of field geology, chemical analyses and stable isotopes of oxygen and hydrogen helps to characterize and to quantify the water resources of the Dallol Bosso, Niger. These resources for an arid area as the Sahel zone are of primary importance. In this context questions like water volume and quality, as well as recharge mechanisms are addressed. Finally recommendations for a sustainable management of the water resources are proposed.

Keywords: hydrogeochemistry, Niger, isotopes, sustainable management.

Résumé.–HUNZIKER J.C., GALADIMA S.A. et PASTORELLI S., 2001. Etudes isotopiques et hydrogéochimiques du régime des eaux du Dallol Bosso (Niger). *Bull. Soc. vaud. Sc. nat. 87.4*: 337-352.
L'utilisation combinée de la géologie de terrain, des analyses chimiques et des isotopes de l'oxygène et de l'hydrogène permet de caractériser et d'évaluer quantitativement les ressources en eau du Dallol Bosso au Niger. Pour une région aride comme le Sahel, ces ressources sont d'importance primordiale. Dans un tel contexte, la question du volume d'eau disponible et de sa qualité, ainsi que la connaissance des mécanismes de recharge doivent être abordées. Enfin, des recommandations pour une gestion durable des ressources en eau sont proposées.

Mots clés: hydrogéochimie, Niger, isotopes, gestion durable.

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INTRODUCTION

A collaboration between the «Direction des Ressources en Eau au Ministère de l'Hydraulique et de l'Environnement de Niamey», the Earth Sciences Department of the University of Lausanne and the International Atomic Energy Agency (IAEA) in Vienna, led in 1990 (GALADIMA 1990) to a hydrogeochemical and isotopic study of the Dallol Bosso area, Niger, in order to answer the following questions:

1.–Why did the water table of the Dallol Bosso remain more or less constant over the last 20 years, although evaporation exceeds precipitation by an order of magnitude (GALADIMA 1990)?

2.–Are the deep seated (several hundred meters) water resources, showing more negative isotopic values, paleo-waters, as proposed by previous workers (FONTES 1980, JOSEPH and ARANYOSSY 1985, 1989), or are other mechanisms responsible for these light waters?

3.–How is the use of these deep seated waters as drinking water for urban supply going to affect the more shallow water tables, the only local water resources for agriculture?

4.–How can the effects of growing salinity caused by irrigation of the agricultural grounds be kept at tolerable limits?

GENERAL SITUATION

The Dallol Bosso represents the southern 65'000 km^2 area of the N-S trending 600'000 km^2 non metamorphic Oulimenden sedimentary basin with in-fill of Mesozoic, Tertiary and Quaternary conglomerates, sands, marls and sandy clays (ARMAND 1987) (fig. 1). This basin rests on a predominantly Panafrican basement, showing several phases of Phanerozoic tectonisation, and outcropping in the Aïr mountains to the northeast and again southwest of Niamey (BALL 1980, BLACK *et al.* 1967, BLACK 1984). The Oulimenden basin extends from the southern boundary of Niger to Benin, across the southwestern corner of Niger, and crosses to Mali in the north.

The names Dallol Bosso and Dallol Maouri (fig. 1) stand for fossil valleys with north-south extension over 450 km, where the western branches (Dallol Bosso) could represent former arms of the 4200 km long Niger river, the third biggest African river, the eastern branch (Dallol Maouri) descending from the Aïr massif (fig. 1). The subaeral waters of the Dallol Bosso show a whitish color (dollolo).

The sedimentary basin reaches down to a depth of over 1500 m (fig. 2) and shows a high porosity and three superposed watertables, some of them under artesian pressure. The uppermost is in the Quaternary alluvial sands of the

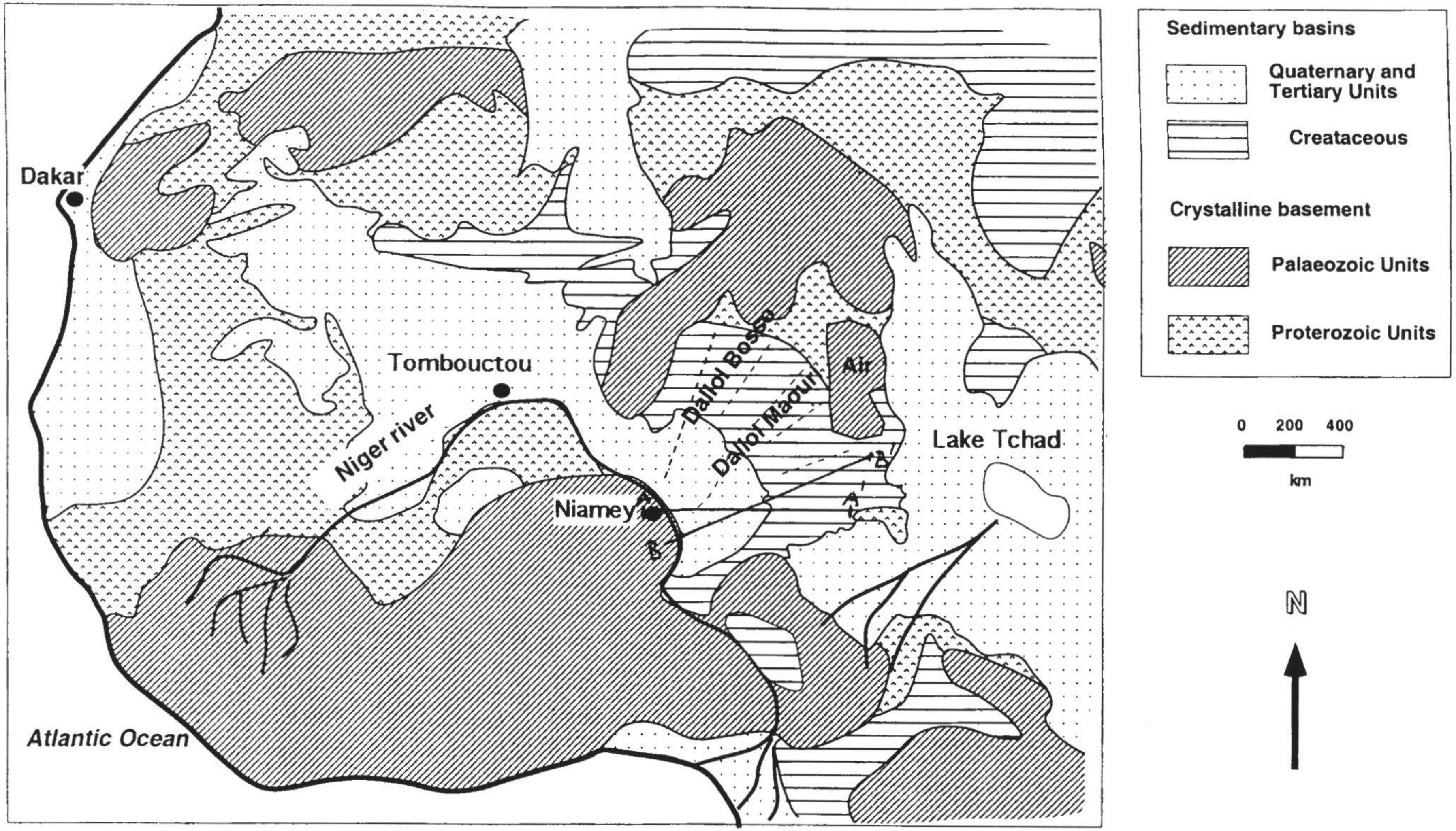

Figure 1.–Geologic sketch of Western Africa with the Proterozoic and Paleozoic Basement and the superimposed Cretaceous to Quaternary sedimentary basins with their infill of conglomerates, sands, marls and sandy clays (ARMAND 1987). A-A' and B-B', location of the profiles: figure 2.

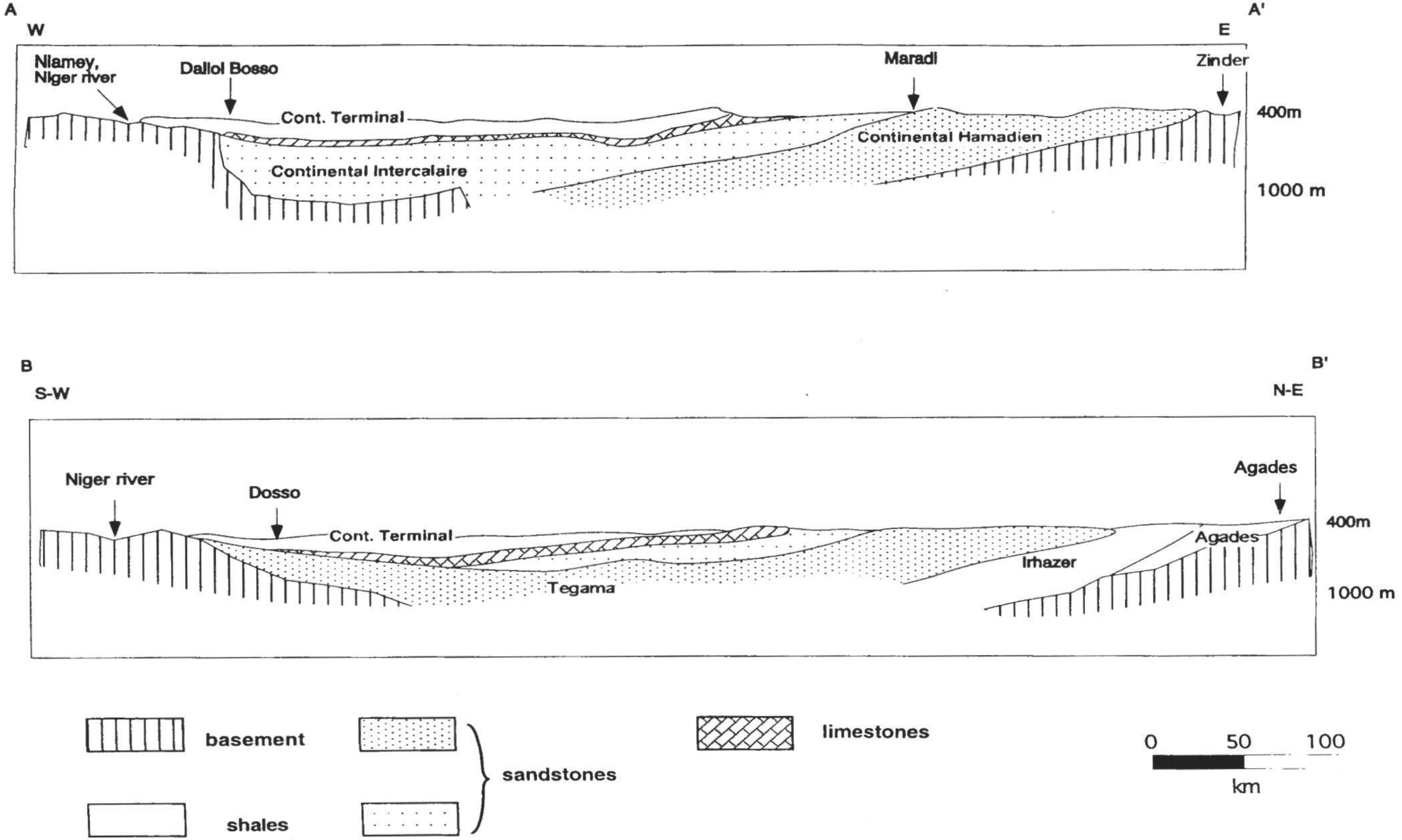

Figure 2.–Geological E-W profile through the Dallol basin (GREIGERT 1966) showing the Cretaceous to Quaternary infill on the old basement.

Dallol, the intermediate reservoir is in the Pliocene sands of the Continental Terminal, and the third water table in the sands of Cretaceous to Paleocene age. These three watertables nevertheless show a certain interconnection (fig. 3).

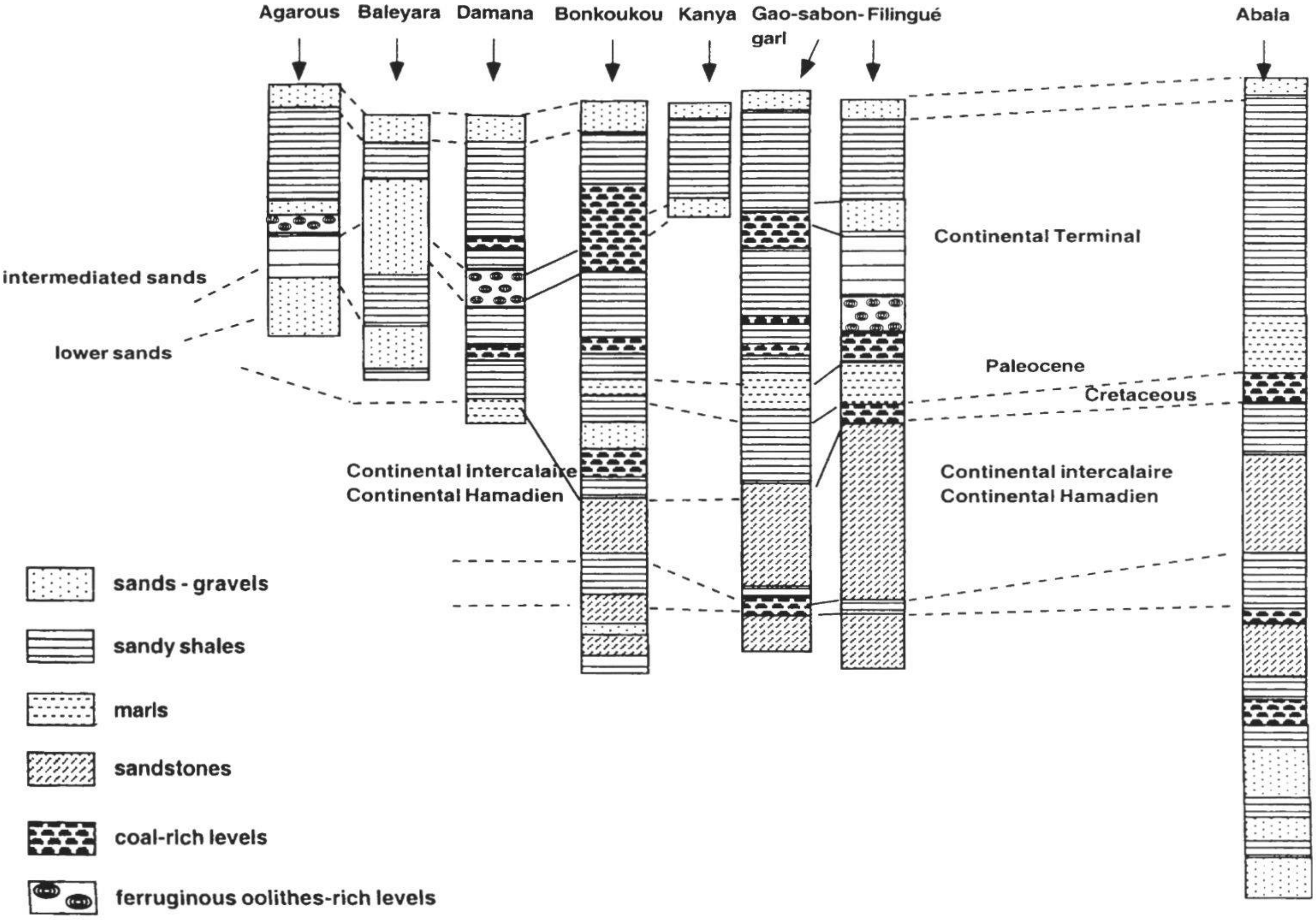

Figure 3.–Sedimentary profiles through the northern part of the Dallol Bosso, according to ARMAND (1987).

For local agricultural purposes and also as drinking water source of the villages, the farming population manually digs wells into these sediments, down to a depth of 50 m, from where water is produced by hand-pumps and also by rope and bucket techniques. For the drinking water supply of the nearby capital deep wells into the third aquifer were drilled accepting the danger of a possible drop of the subsurface watertables, thus possibly rendering these inaccessible to the local population. In addition previous workers (MAZOR *et al.* 1977, JOSEPH and ARANYOSSY 1985, JOSEPH and ARANYOSSY 1989,) had deduced both from the lack of ^{14}C and from strongly negative oxygen and hydrogen isotopic ratios of deep seated waters in the Sahara and the Sahel zone, that these waters represented paleowaters from the last humid period corresponding to the last ice age of northern Europe, precipitated under cooler climatic conditions, and therefore isotopically lighter than local precipitation. The use of these old water would consequently impoverish the reservoir and ultimately would increase the aridity of the Sahel zone.

Annual precipitation (mainly during the months July to September) during the last 45 years shows a sinking tendency from around 700 mm in the fifties, to around 250 mm today, (see running means over 3 and 5 years, fig. 4) (GALADIMA 1990).

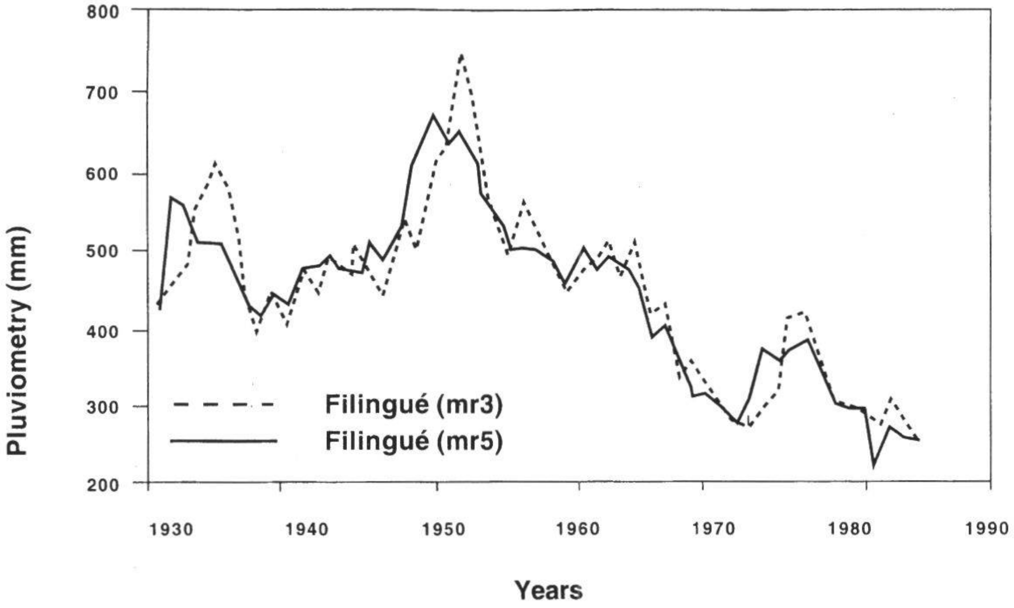

Figure 4.–Annual precipitation during the last 45 years, showing a decreasing tendency from around 700mm in the fifties to around 250 mm today (GALADIMA 1990).
(mr3 = running mean of 3 years, mr5 = running mean of 5 years).

Mean annual temperatures during the last 15 years at Chikal station (Filingué) are around 30°C with a positive trend (28°C in 1980 to 31°C in 1988). During the year the air temperature shows two peaks, one in April/May, after the first river high-stand, caused by the rain season of the fore-year, from 2500 km upstream, reaching Niger in March and April, during the dry season, and a second, less pronounced peak after the humid season of June to August, in Niger, reaching Niamey in September/October.

The annual potential evaporation measured at Niamey airport during the last 20 years, shows a growing tendency between 3000 and 3500 mm/year i.e. over 10 times the local precipitation values (GALADIMA 1990).

Both the discrepancy between rainfall and evaporation and the fact that the Dallol Bosso still shows a considerable number of young Baobab trees, known to root in the watertable, shows that there must be a recharge coming from elsewhere than local precipitation, a plausible source being the annual floods of the Niger river, during the humid period flowing with over 10’000 m^3/s, 5 m above its low level stand. As the mean altitude of the recharge area of the

Niger is around 1000 m in the mountains and highlands of Guinea and Ivory Coast with a mean annual pluviosity above 1500 mm, the recharge must take place with relatively light water, as could be proven by the measurements of summer, high stand Niger water (fig. 7, p. 350) and has also been reported from Mali by GOURCY *et al.* (1995).

Obviously the local mass balance between precipitation, runoff, evapotranspiration and infiltration in the Dallol Bosso is out of equilibrium. These parameters are linked by the following equation:

$$P = Q + E + I$$

where P = precipitation
Q = runoff
E = evapotranspiration
I = infiltration

with practically no runoff at all and evaporation 10 times larger than precipitation, an explanation has to be found. Here the only possible solution represents additional infiltration- but where from?

For this study, in the Dallol Bosso, along a stripe covering 8500 km^2, 126 sampling sites were visited, mostly wells (around 107), surface waters and rainfall were sampled at 97 sites. Conductivity, pH, temperature, oxygen content, and alkalinity were measured at 85 sites and from 60 samples isotopic as well as chemical analyses were performed (see tables 1 and 2). The outcome of this study was presented in an internal report (GALADIMA 1990). Since then, 15 well selected, additional analyses led to a more evaluated comprehension of the mechanisms controlling the water resources of the Dallol Bosso.

Table 1.–Isotopic ratios and physico-chemical parameters of the alluvial aquifer of the Dallol Bosso, Niger.

Locality	Sample Nr.	$\delta^{18}O$ ‰	δD ‰	Piezo m	Cond. µS/cm	Oxyg. diss. %	pH	HCO_3^-
Korankasa	3	-4.23	-22.7	-15.1	63	39	4.8	
Dabaga	4	-3.33	-28.1	-3.84	486	31	5.57	
Kourfarey	6	-4.24	-20.3	-3.72	390	54	6.02	8.6
Sassanbangou	7	-5.55	-34.8	-2.81	113	55	6.1	
Kobiel	10	-3.04	-21.7	-2.94	144	47	6.43	9.2
Debedebe	11	-3.59		-3.87	138	52	6.22	3.7
Guilagi	13	-2.09	-14.3	-3.6	407	64	6.13	8.6
Saboula	16	-2.68	-38	-5.6	113	57	6.13	3.7
Falmey	18	-2.63	-17	-3.18	181	38	5.01	
Kouassi	21	-2.45	-17.7	-7.74	528	53	5.91	11
Bombogi	22	-2.72		-3.52	154	51	6.54	

Table 1 (continued).–Isotopic ratios and physico-chemical parameters of the alluvial aquifer of the Dallol Bosso, Niger.

Locality	Sample Nr.	$\delta\,^{18}O$ ‰	δD ‰	Piezo m	Cond. µS/cm	Oxyg. diss. %	pH	HCO_3^-
Boumba	25	-2.67	-15.3	-6.87	115	38	6.35	8.6
Kotaki	27	-3.06		-2.94	320	35	6	4.9
Fono Birgui	28	-4.34	-15.8	-4.5	150	72	6.16	
Yéda	37	-2.38	-18.7	-1.89	735	35	6.71	19.5
Balandé	46	-3.42	-18.4	-4.99	171	44	5.95	8.5
Touroutourou	47		-15.7	-1.36	446	52	6.46	7.3
Yéni	50		-21.9	-4.14	371	46	6.53	
Koygolo	51	-3.31		-6.9	561	50	6.77	30.5
Kabé	52	-3.41	-22.8	-3.62	719	53	6.78	
Tabla	53	-1.88	-24.9	-6.5	305	48	6.52	11
Damana	59	-2.85	-26.9	-7.8	257	36	6.5	13.4
Kania	60	-2.5		-8.98	160	38	6.67	18.3
Guébé bamba	69	-2.31	-17.5	-20.88	128	50	5.72	9.8
Gaoh SG	77	-3.06	-17.9	-22.85	198	45	6.9	14.6
Schatt	79	-2.46	-15.1	-9.31	136	42	6.85	12.2
Bonkoukou	80	-2.22	-19.6	-5.73	787	40	6.7	11
Kobi	82	-2.74	-18.4	-5.2	740	25	6.88	35.4

GEOLOGY AND HYDROGEOLOGY OF THE DALLOL BOSSO

As already pointed out the Dallol Bosso contains three major water tables, a first one in the Quaternary sands, a second in the Pliocene strata and the third, deep seated in the Cretaceous (Greigert 1966, 1978) (fig. 3).

1.–*Alluvial aquifer*

The Quaternary water-table comprises the alluvions of the plateau or higher terrace, the alluvial sediments of the valley, or lower terrace, and the intermediate slopes. The sediments are lateritic sands of reddish colour and dune sands, generally 0-20 m thick, occasionally up to 45 m. Locally, specially towards the South this highest water table is interconnected with the lower water tables.

2.–*Pliocene aquifer*

The so called «Continental Terminal» is a predominantly sandy sequence with intercalated white kaolinitic clays and oolithic layers, the whole sequence 0–300 m thick in places interconnected with the lowermost and the uppermost watertables.

The two uppermost watertables, according to Armand (1987) have a maximum thickness of 70 m and drop in depth from N towards S around 140 m following the drop in general topography along the 400 km profile.

Table 2.–Isotopic ratios and physico-chemical parameters of the Pliocene CT-aquifer of the Dallol Bosso, Niger.

Locality	Sample Nr.	δ D ‰	δ O^{18} ‰	Piezo m	Cond. µS/cm	Oxyg. diss.%	pH	HCO_3^-
Gounoubi	1	-50.1	-4.81	-30	205	70	5.4	30.5
Bossagi	2	-46.2	-6.9	-26.45	1300	21	7.17	65.9
Fabigi	17	-25.4	-4.19	-30.07	52	38	4.99	2.4
Tondi bangou	20	-38.2		-30.82	3850	63	5.69	8.6
Sakala gonga	29	-27.6	-4.34	-41.66	82	45	4.95	3.7
Boulkorgi	32		-3.92	-12.03	57	27	5.13	7.3
Drouel	33	-23.2	-2.69	-30.03	101	73	5.91	7.3
Tchiankargui	43	-34.1		-24.01	1155	17	6.69	56.1
Bassipeul	45	-42.7	-6.42	-30.84	35	64	7.08	72
Danya	61	-41	-5.71	-13.9	300	36	6.36	42.7
Itchiguine	64	-47.4	-5.01	-18.03	94	24	5.75	
Dogon gaoh	66		-5.25	-23.76	312	42	6.38	14.6
Chikal	67	-23.9	-5.06	-25.18	300	44	6.06	14.6
Taramnya	68	-23.5		-23.02	194	43	6.31	
Guébé bambafor	69	-31.4	-4.64	-18.7	91	34	5.4	9.8
Bakin toulou	74	-34	-5.1	-43.68	388	23	4.52	4.9
Fakey	75	-25.6	-4.08	-34	352	34	6.48	15.9
Tarkassa	76		-3.17	-35.28	316	46	6.13	9.8
Gaohtshogari	77	-17.9	-3.06	-22.85	198	45	6.9	14.6
Tadénagabén	83	-27.9		-15.59	165	37	6.98	13.5
Isotopic ratios and physico-chemical parameters of the deep seated aquifer of the Dallol Bosso, Niger								
BN. Gaouré	39	-52.5	-7.82		1495	36	7.44	85.4
Fandou	56	-52.7	-7.67		1395	12	7.41	
Damana	59	-56.3	-7.69		3230	12	7.38	74.4
Gaoh sabongari	78	-54.1	-7.76		855	25	8.1	95.2
Isotopic ratios of the river Niger								
Boumba		-17.7	2.83					
Niamey								
		-50.2	-7.99					
Tillabery		-3.4	5.45					
		-48.6	-5.6					
		-35.2	-4.12					

3.–*Cretaceous to Paleocene aquifer*

The so called «Continental Intercalaire et Hamadien» comprises Albian to Paleocene well washed ungraded fine to coarse grained quartzitic and partly carbonatic sands alternating with pebbly horizons of fluviatile, lacustrine and partly deltaic origin. The whole intercalating with sandy clays and clays, decreasing from bottom to top, locally the whole sequence shows a thickness of over 1000 m.

The watertable shows its greatest thickness in the North and shrinks towards S, following the underlying basement. The top of this deepest watertable is at a variable depth ranging from 250 m in the N to 30 m in the S of the Dallol Bosso, and reaching down to the basement. This lowermost aquifer generally is under artesian pressure.

Both, the volume of water stored in this sedimentary basin, as well as the presumed annual recharge possibilities from the Niger, would exceed by at least two orders of magnitude any possible consumption by the local population, as the mean discharge of the Niger amounts to around 180 km^3 from a drainage area of over 2 million km^2.

The productivity in all the visited wells is strongly variable between 0.5 and 40 m^3/h. The flow rates vary between 0.1 and 10 l/s (GALADIMA 1990).

HYDROGEOCHEMISTRY

Alkalinity, pH, electric conductivity, dissolved oxygen content, temperature and depth of the watertable below surface were measured on site (see tables 1 and 2).

Over 50 partial chemical analyses were performed later in different laboratories as our own facilities were at the time only operational for stable isotopes. This fact represents the major drawback of the present study. In the light of the far-reaching consequences, that nevertheless can and have to be drawn from these analyses, a similar work should be repeated with the now routine techniques for main and trace elements.

A first series of chemical analyses were measured at the ONAREM laboratory in Niamey previous to our visit and could be used for comparison.

The pH in the alluvial and the CT (Continental Terminal) water tables varied between 5 and 7, while for the deeper seated waters the pH varied between 7 and 8 in correlation with the HCO_3^- content. This interdependence between pH and depth or rather dissolved carbonate content renders the ^{14}C age determination of the so called paleowaters dubious as exchange between ^{14}C of the water and ^{12}C of the carbonates during water/rock interaction would have completely depressed the ^{14}C content of the water making it seem older than in reality.

The range in electric conductivity reaches from 100-1050 µS/cm representing mineralisations between 70 and 1150 mg/l for the alluvial waters (fig. 5). In the alluvial water table, deeper than 10 m below surface, water shows conductivities below 200 µS/cm, while shallower waters show elevated conductivities (fig. 6).

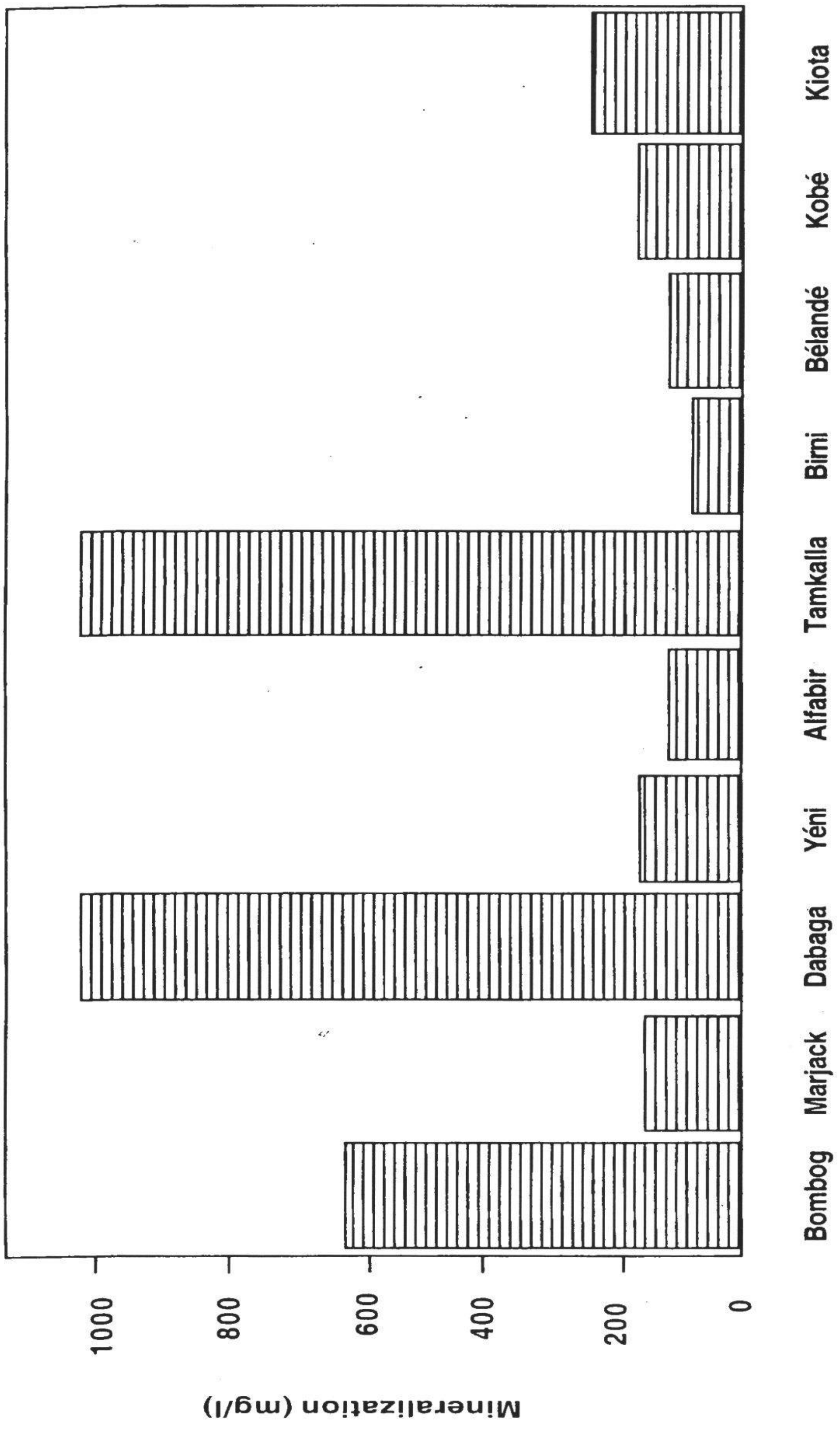

Figure 5.–Mineralization of the alluvial waters showing salinities between 70 and 1150 mg/l (GALADIMA 1990).

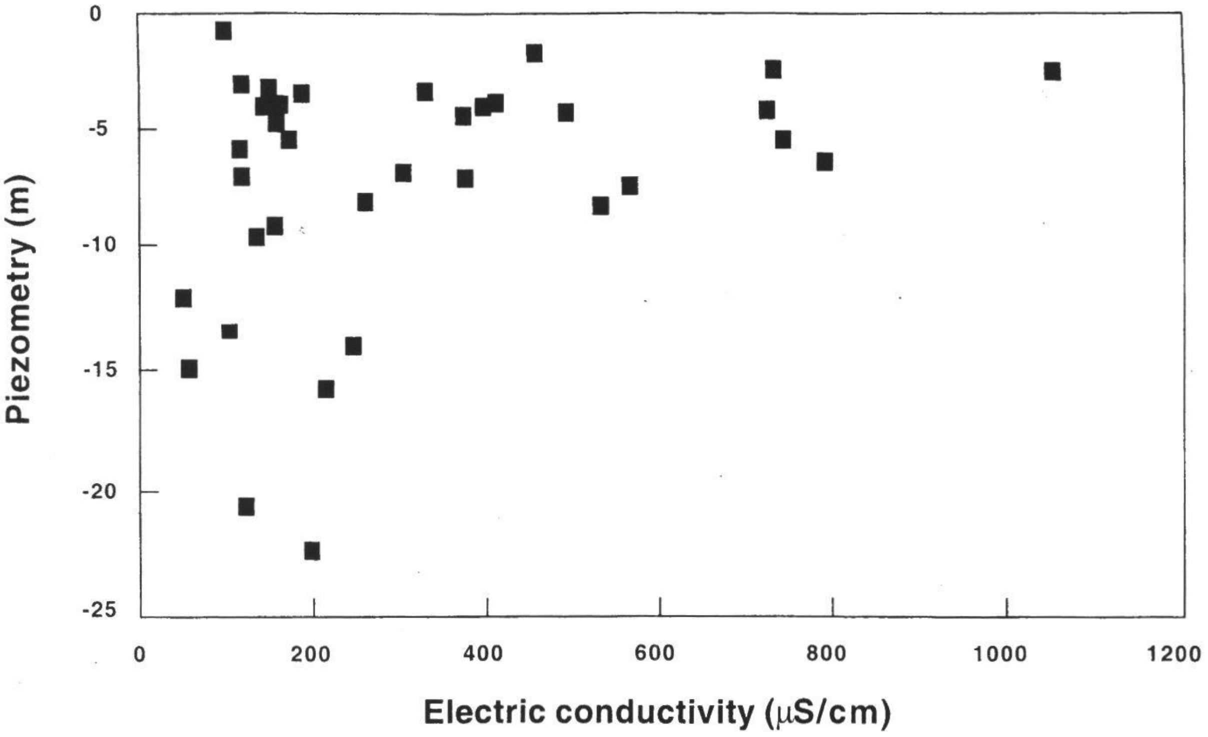

Figure 6.–Through evaporation in the topmost layers of the alluvial water table salinity's tend to increase drastically. This shows clearly that for irrigation purposes, water should only be extracted from wells deeper than 10 m (GALADIMA 1990).

For the Pliocene CT waters, conductivities range between 100-3900 μS/cm, the high values related to the kaolinitic layers. The deeper Paleocene to Cretaceous reservoir waters show conductivities between 700-1300 μS/cm. As the conductivity is related to the total dissolved salt charge of the water with the few total analyses at our disposal, according to the relation: conductivity in μS/cm = K x dissolved salt charge in ppm, we were able to calculate K, to vary between 0.7 and 1.2

The figure 6 shows drastically that for agricultural purposes (irrigation) water should always be taken from depths exceeding 10 m as in the uppermost 10 m due to preferential evaporation/precipitation the salt load of the sediment and the contained water is too high and in long terms leads to saline soils. The same argument holds for the Cretaceous water-table, where marls and clays, the slightly higher temperature and pressure again led to an increased salt load. Chemical analyses showed that the predominant salts in the uppermost level were NaCl and KCl. These salts are locally produced by handicraft extraction.

Dissolved oxygen measured in % of saturation varies between 93% for shallow water and 25% for the deep seated waters.

The measured water temperatures range between 16°C and 28°C generally in equilibrium with the mean annual air temperature.

For the chemistry of the water the following cations were considered: Ca, Na, K, Mg as well as the anions HCO_3^-, CO_3^{2-}, NO_3^-, SO_4^{2-}, Cl^-. The sum of these ions represents the total mineralization varying between 70 and 1150 mg/l in the alluvial water table, see figure 5. The waters of the deepest water table contain again high NaCl loads that generally range around 200 ppm.

In general the waters can be classified as sodium bicarbonate-, calcium bicarbonate-, and sodium sulfate waters.

OXYGEN AND HYDROGEN ISOTOPES

Hydrogen and oxygen isotopes of 60 water samples were measured on a Finigan MAT 251 Mass spectrometer (see tables 1 and 2). For oxygen 5 ml of H_2O were equilibrated for 12 hours at 25°C with a standard CO_2, which in turn was measured on the mass spectrometer. From a 2 µl water sample hydrogen was extracted using 10 mg of Zn according to the reaction

$$H_2O + Zn = ZnO + H_2$$

whereby the reaction products were heated to 450°C for 2 hours in a sealed Pyrex tube (COLEMAN *et al.* 1982). The measured isotopic values are reported in the SMOW-scale.

On figure 7, the analyses of the wells fall more or less on the meteoric water line (CRAIG 1961). The local (Bamako) meteoric water line as proposed by JOSEPH and ARANYOSSY (1985) is not used in this context, as we came to the conclusion that this so called local meteoric water line represents a simple evaporation effect. The subsurface waters partly fall on such an evaporation line in good agreement with their heavy salt load. The deep seated waters show the most negative values and the subsurface values are more positive, while the CT waters from the Pliocene sediments clearly fall into the intermediate gap suggesting a mixture of deep seated with subsurface water. The intermediate and deeper water-tables in general follow the meteoric water line, the shallow waters as already stated show a distinct tendency to follow an evaporation path (fig. 7).

If we assume that the relevant local precipitation (Aïr region) with δ D values around –1 + – 4 ‰ represent one endmember of the mixture (MAZOR *et al.* 1977, JOSEPH and ARANYOSSY 1989) and the deep seated aquifer, with values around -55 ‰ the other endmember, we can calculate the relative proportions in the alluvial aquifer to be 70% meteoric, respectively 30% deep seated water. For the Pliocene aquifer this percentage of light water would range between 40 and 90%. The deep seated water of the Paleocene to Cretaceous aquifer finally would represent the light endmember, in other words infiltrated river water.

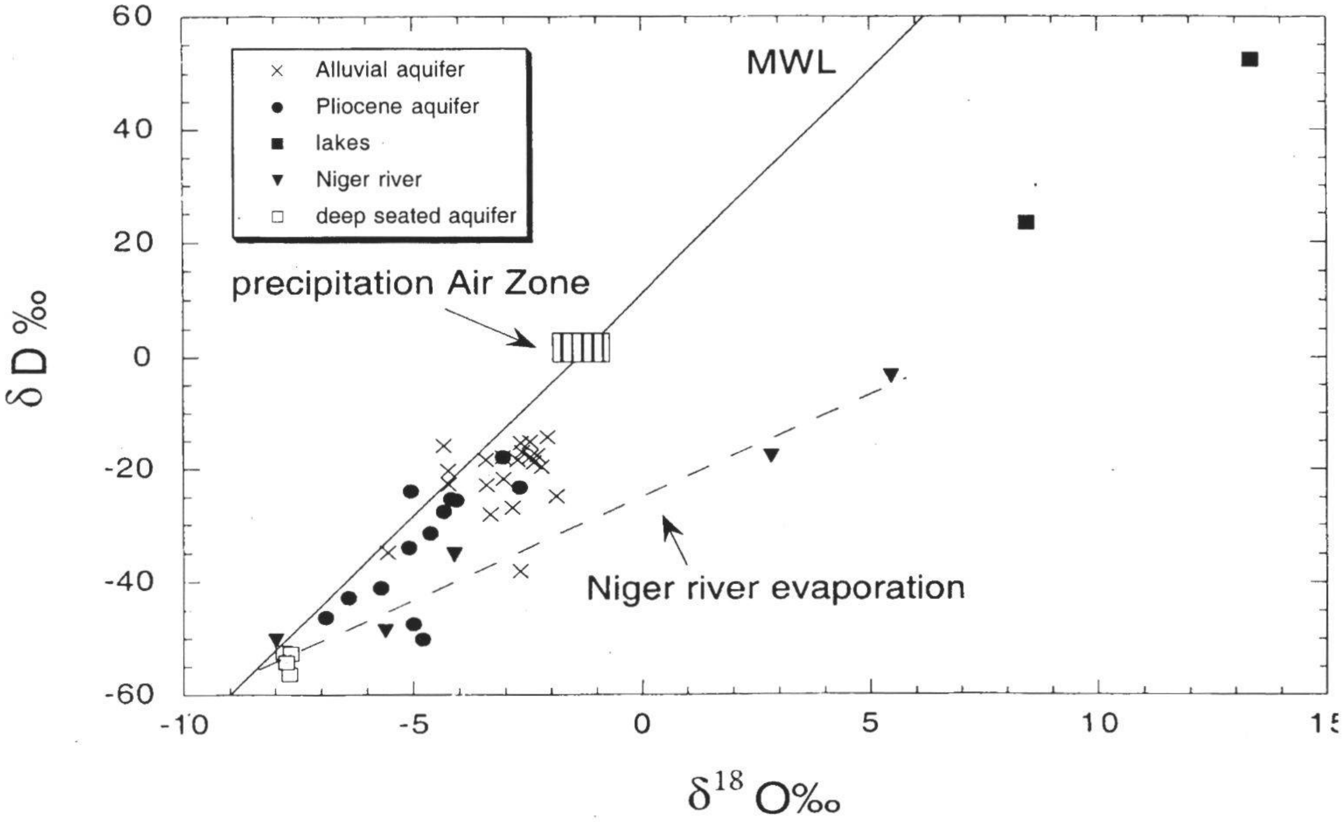

Figure 7.–Oxygen versus hydrogen isotope plot of the analysed waters, showing the relation between depth of the aquifer and lighter isotopes with depth and the evolution of the Niger river water, where the least evaporated samples of the river high-stand fall together with the deepest aquifer samples, suggesting an annual recharge of the aquifers through high-stand Niger water.

Clearly distinct to this pattern of the well waters, the river waters fall on an evaporation line, that crosscuts the meteoric waterline at the location of the deep seated waters. The distance of the analytical points of the river waters from the meteoric waterline depends on the season, (higher evaporation parallel to higher salt load during the dry season). This coincidence shows clearly that the yearly flooding of the Niger having highly negative δ D values around -55 ‰ in agreement with the high elevation recharge area of the river, could well account for the strongly negative isotopic values of the deep seated waters and that the paleowaters theory at least for the Dallol Bosso thus finds a much more plausible explanation. This change in origin of the water sources has far reaching consequences not only for the hydrous resources of Niger but also most likely for the water management of the even drier Mali.

The standing waters or lake waters fall on an evaporation line also, as can be seen on figure 7 for the two lakes and for the dry period Niger samples, where lake Tabaga sample with a total salt charge of over 1100 ppm corresponds to a δ D value of +50 ‰, the most positive value measured in our laboratory.

CONCLUSIONS AND RECOMMENDATIONS

An amelioration of the economic situation for the growing population of Niger demands an increased access of water both for drinking and agricultural use. As a majority of the population of this country lives in and from the Dallol Bosso area, the water resources of this region are of crucial interest and an up to date management of these waters highly critical. In this context the contraproductive irrigation system with surface irrigation allowing the loss of 80% of the water due to evaporation, concomitant with the enhancement of soil salinity, should be changed to a more efficient subsurface irrigation. The present study is only a beginning of the understanding of the delicate and complex ecosystem controlling the hydrological equilibrium of this country that should be followed by similar interdisciplinary studies distributed in time, and on other regions in order to finally lead to the construction of a management model for the totality of the hydric resources of the country including the possibility of a decrease of evapotranspiration by the rapid buildup of a vegetation cover, thus considerably increasing the agricultural potential.

In this context also seismic and other geophysical investigations for the exact evaluation of the morphology of the basins and watertables are of great interest and should be envisaged. So far the preliminary results lead to the following conclusions:

1.–The yearly flooding of the Niger thoroughly replenishes the entire basin most likely down to the deepest watertables.
2.–Although the three watertables are interconnected, an extraction for drinking water purposes of the intermediate reservoir is of little danger for the lowering of the higher levels as the extracted quantities are much smaller than the refill.
3.–For agricultural purposes, as well as for drinking use, the water should be taken from a depth exceeding 15 m, as above generally the salt load is elevated due to evaporation and in long terms will lead to increase the salinity of the soils, thus rendering them of no further use for agriculture. The same argument holds for the Cretaceous to Paleocene reservoir, due to its locally high sulfate and NaCl charges.
4.–As a general rule, chemical analyses of the water should precede its possible use. Here a new campaign with modern analytical facilities now running in routine, and with the new interpretations in mind would greatly help to clarify this critical situation.

5.–Rather fast a feasibility study should evaluate the possibility to drastically reduce evapotranspiration of this arid zone by a change of the irrigation system coupled to a rapid buildup of a strong vegetational cover predominantly with brush and trees perhaps using reinforced infiltration techniques of river water during the Niger's yearly highstand, or even the construction of a dam system for irrigation purposes.

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Manuscrit reçu le 1er février 2001