Progressive rising and falling water tables lead to the accumulation of solute towards the top of the SUZ over time, where it becomes increasingly inaccessible to mobile fissure water. The implication is that in areas with a large SUZ, it (the SUZ) will act as a repository of solute mass and prolong the duration of groundwater contamination.

Modelling also demonstrates that, in many cases, the SUZ will have a strongly attenuating effect, releasing contaminants back to mobile groundwater over many decades, at significant concentrations. The strong relationship between groundwater chemistry and water table elevation, consistent with the SUZ process, also has important implications for the timing of site investigations.

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Comparison of recharge estimates for the two largest aquifers in Niger, based on hydrodynamic and isotopic data

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Abstract The hydrodynamic and isotopic characteristics of the two largest phreatic aquifers in Niger have been studied. Even though the climate, geomorphology and vegetation seem similar, these aquifers differ. In the Iullemmeden basin, a seasonal fluctuation of the water table during the rainy season is combined with a significant long-term rise due to a change in land use; isotopes (^{18}O, ^{2}H, ^{3}H, ^{14}C) show a median renewal rate of between 0.1% and 0.2%. In the Lake Chad basin, seasonal fluctuation is much rarer and the long-term trend is of stability or even a small decline of the water table due to the drying up of the Lake Chad; isotopes indicate a median renewal rate of between 0.1% and 0.06%. In both cases, the large difference between the extreme values underlines the great variation in time and space of the recharge.

INTRODUCTION

Estimates of annual recharge in arid and semiarid areas are highly variable, depending on the methods used and regions, but also on data scarcity and on the great heterogeneity of natural processes. In Niger, the phreatic aquifers in the two large sedimentary basins (Iullemmeden basin, hereafter abbreviated IB, and the Lake Chad basin, LCB), at the southwestern and southeastern ends of the country (Fig. 1), have been investigated in detail. At first sight, both aquifers seem very similar (flat areas, semiarid climate, recharge occurring at local points), but their hydrodynamic behaviour and isotopic content show a difference in the volume of annual recharge to each and their long-term evolution.

THE IULLEMMEDEN BASIN

In the western Niger, the most recent deposits of the IB are at its western fringe. They are dated Continental Terminal (i.e. Eocene to Pliocene) and Quaternary. The Continental Terminal is sandy to clayey, mainly silty, often lightly cemented into sandstone, and topped by a horizontal lateritic plateau. The geological history results in

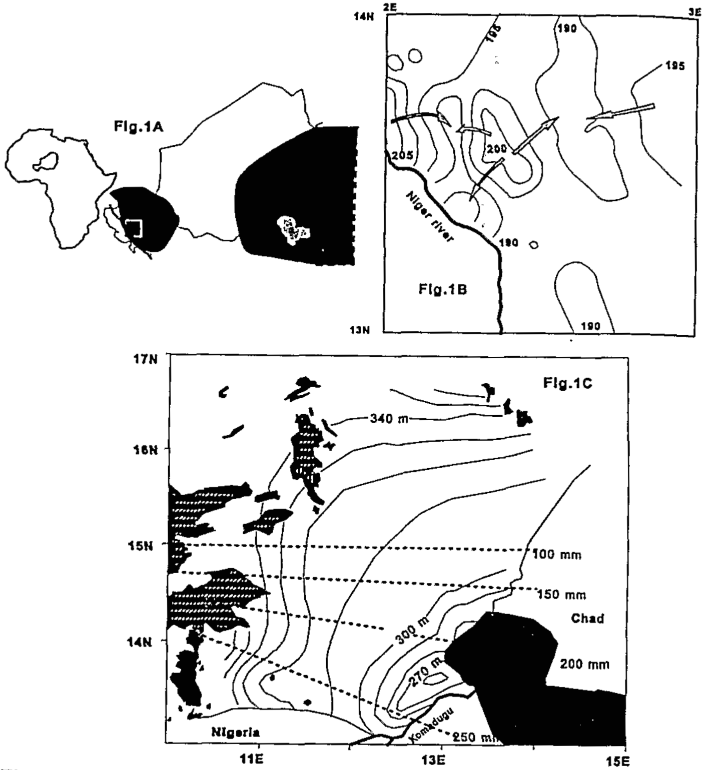

Fig. 1 The study area. (a) Continental Terminal outcrops in the Iullemmeden basin, southwestern Niger (with location of the Niger River and of the Niamey degree square) and Quaternary outcrops in the Lake Chad basin (with location of the Komadugu River and of the Lake Chad). (b) Water table levels in the Niamey degree square in June 1994 (5 m contour) and main groundwater flow directions. (c) Water table levels in the Niger part of the LCB (continuous contour every 10 m) and isolines of 1981/1996 mean rainfall (dashed line every 50 mm year^{-1})

a region entirely split into a lot of small endoreic catchments. Our study is restricted to the Niamey degree square, a small but representative part of the Continental Terminal outcrops between 2° and 3°E and 13° and 14°N. The mean annual rainfall in Niamey is 565 mm with extreme values of 281 mm in 1915 and 1161 mm in 1998. On average, the annual rainfall decreases by 1 mm km^{-1} northwards. In fact, rainfall is highly variable in time and space. The rainy season is short (May to October) with 60% of the rainfall in July and August.

Groundwater hydrodynamics

The water table survey of the 8000 km^2 region north of the Niger River is based on data from more than 250 wells monitored since 1991, and some older data (Desconnets et al., 1997; Leduc et al., 1997). The water table can show a seasonal rise and fall due to infiltration during the rainy season, and a long-term rise due to a change of the natural vegetation to cultivated areas (Leduc & Loireau, 1998). Gradients in the water table are generally low (of the order of 1‰). A large closed depression exists in the east of our study area; it can be explained only by a very small but significant evaporation uptake and a very poor horizontal flux.

Stable water isotopes

Results are reported in δ-notation relative to the reference Vienna Standard Mean Oceanic Water (SMOW).

Since a previous paper (Leduc & Taupin, 1997), new ^{18}O and ^{2}H samples have been analysed giving a total of 243 values of ^{18}O and 102 values of ^{2}H. The isotopic content of the water table varies between –1.30 and –6.41‰ for ^{18}O and between –15.2 and –45.9‰ for ^{2}H, with median values of –4.24 and –28.0‰ respectively. In a few cases, when the water table is close to the ground surface, the ^{18}O–^{2}H diagram shows an enrichment due to evaporation. Elsewhere, isotopic contents of groundwater are close to the local meteoric water line. Between 1992 and 1995, the average isotopic content of rainfall, weighted by the amount of rainfall, was –3.97‰ and –5.13‰ in July and August respectively, which are the highest rainfall months and so the most useful for water table recharge (Taupin et al., 1997). In most cases, there is no significant difference in isotopic content between the groundwater and present rainfall. This strongly suggests that the major part of the groundwater could have infiltrated under climatic conditions similar to the present.

Radio-isotopes

Carbon results are reported relative to the reference Pee Dee Belemnitella, PDB. Tritium results are expressed in Tritium Units, TU.

Forty-five ^{3}H samples have been analysed already, 20 others will be processed soon. The first half of the available results comes from sites distributed throughout the Niamey degree square (Leduc et al., 1996), and the other half comes specifically from the closed depression. The ^{3}H content varies between 20 TU and values below the detection threshold, which is usually 1 or 2 TU. The median is 4.0 TU for the first half, and lower than 2.0 TU for the second half and also for the results as a whole. Older apparent ages in the closed depression were expected because of very slow movement of groundwater in such a region. A simple model of perfect mixing is best suited to representing the hydrodynamic processes operating in this aquifer. It simulates the aquifer content of tritium depending on a renewal rate (Leduc et al., 1996). The calculation gives a renewal rate varying between 4.8% and less than 0.1% (Fig. 2), with a median value of about 0.2% (0.38% for the first half).

In the Continental Terminal water table, the ^{14}C of the dissolved inorganic carbon (DIC) comes only from atmosphere through soil respiration. It can therefore be used without a mixing correction. Sixty-four analyses of $^{14}C/^{13}C$ were used. ^{13}C contents vary between –10.1 and –18.5‰ PDB, typically in the range of values of the savannah

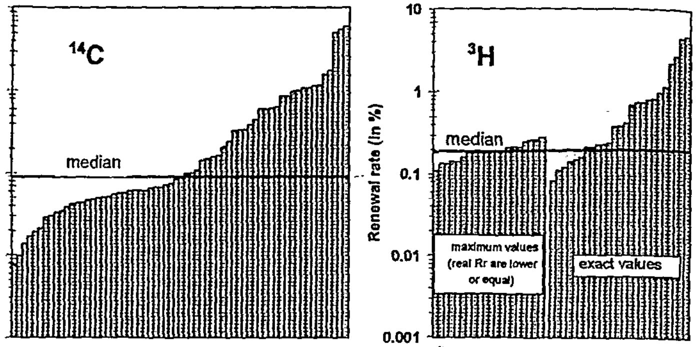

Fig. 2 Distribution of the annual renewal rate in the Niamey region, Iullemmeden basin, estimated from ^{14}C and ^3H analyses (in % of the total groundwater reserve).

vegetation (mixing of plants in C-3 and C-4). The lack of any particular trend in the ^{13}C–^{14}C diagrams confirms the purely atmospheric origin, via the soil system, of the DIC. ^{14}C activities vary between 53 and 126 pmC (81, 89 and 105 pmC for the quartiles) with only six samples lower than 70 pmC. Samples from boreholes penetrating the whole aquifer depth, and from wells reaching only the first upper metres, do not differ significantly. This shows a good vertical homogenization in the aquifer. Using a model identical to that used for tritium, the renewal rate is estimated as between 0.01% and 6% with a median value of 0.09% per year (Fig. 2).

THE LAKE CHAD BASIN

The LCB extends over more than 2 000 000 km^2 with a large part in Niger. The water table lies in thick, flat continental deposits of alluvial and aeolian Quaternary sediments, mainly sandy and silty. The annual rainfall varies from a few millimetres, in the Tenere desert, to 350 mm, in the south. Between 70 and 95% of the annual rain falls in July and August. Rainfall variability in time and space is as high as in the Niamey region. Surface water is very limited: the northern pool of Lake Chad, which has generally dried up over the last decade; the Komadugu Yobe, a non-permanent river; a lot of small endoreic ponds.

Groundwater hydrodynamics

The LCB contains a very large phreatic water table in the Quaternary sediments. In Niger, information about it is scarce and mainly available only for the southern part of the aquifer. The water table evolution is generally smoother than in the Niamey region: few localities show a seasonal variation. The flow is from the northern and western borders to the lake area in the centre of the basin, and hydraulic gradients are generally very small. Close to Komadugu Yobe and the northern pool of the Lake Chad, in the Kadzell region, a large anomalous closed depression reaches 40 m amplitude. For most

of the aquifer we are unable to identify with any certainty the long-term evolution of the water level (Leduc *et al.*, 1998). However, close to Lake Chad, the water table level has dropped (by as much as 8 m in one decade), because of the drying up of the northern pool of the lake. This also affects the Kadzell depression, where a slow decrease (between 2 and 5 cm year^{-1}) is observed.

Stable water isotopes

In 1995/1997, 17 sites were sampled in the Quaternary aquifer in Niger. In 1967/1968, 49 other sites were measured in Niger and in neighbouring Chad at the same latitude (Leduc *et al.*, 2000). Values are scattered between –6.16 and +4.4‰ for ^{18}O and between –49 and +13‰ for ^2H, with median values of –3.9 and –32.0‰ respectively. Comparisons with rainfall data can be made only with the N'Djamena records (IAEA/WMO, 1998), 300 km further to the south. Some parts of the aquifer match with the present isotopic rainfall content, but other parts seem to be evaporated with original waters having an isotopic content more negative than now. This suggests that a part of groundwater has infiltrated under more humid conditions.

Radio-isotopes

The only available ^3H measurements come from the sampling conducted in 1967 and 1968 (Leduc *et al.*, 2000). Their interpretation is based on 15 points in Niger and 21 others in nearby Chad. In 1967, extreme values were 0.4 and 256 TU in Niger and 0.5 and 143 TU in Chad, with medians of 5.2 and 3.8 TU respectively. It shows an annual renewal rate varying between 0.01 and 32%, with a median of 0.1% and a mean of 1.4% (Fig. 3).

As in the IB, all the DIC is believed to come from the atmosphere and there is no relationship between ^{13}C and ^{14}C contents. Only five values were available in the Niger part of the LCB and five others from Chad, in 1967/1968 (Leduc *et al.*, 2000). Nine analyses from Niger were added in 1995/1997. Extremes are 11 and 146 pmC with a median of 82 pmC. The lowest value is alone, all others being higher than 59 pmC; the values exceeding 120 pmC are doubtful because they imply that recharge in the desert to the north is much greater than in the more humid south. Using the same model as for the Iullemmeden basin, we obtain a renewal rate varying between 0 and 16%, with a median of 0.06% and a mean of 1.7% (Fig. 3).

ISOTOPIC INTERPRETATION

The density and reliability of isotopic sampling in the two aquifers are very different: 45 ^3H and 64 ^{14}C samples from the 8000 km^2 of the Niamey degree square, compared with 15 ^3H and 14 ^{14}C samples from the 200 000 km^2 of the Niger part of the LCB. We have a good idea of the reliability of each sample in the Niamey region but this evaluation is more difficult in the LCB. As this paper aims only at a general comparison, we have included all the samples in the data analysis and interpretation.

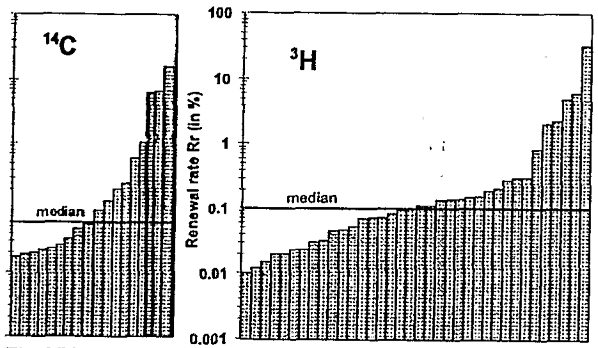

Fig. 3 Distribution of the annual renewal rate in the Niger part of the Lake Chad basin estimated from ^{14}C and ^{3}H analyses (in % of the total groundwater reserve).

The first limitation of our model is the precision of the isotopic content data for the atmosphere. The ^{14}C content is fairly homogeneous in the northern hemisphere and has varied progressively but the ^{3}H content is much more variable. Without any ^{3}H record in Niger during the 1960s and 1970s, the yearly chronicle must be reconstructed by correlation with IAEA stations (Bamako and N'Djamena, 1963–1979; Ottawa, 1953–1999). Moreover, the ^{3}H content of the heaviest rainfalls, which also result in the most infiltration, can differ greatly from the annual mean.

Another limitation of the model is the hypothesis of a steady infiltration rate each year. Such a regularity does not exist locally in the IB, and even less in the LCB where very large areas probably receive infiltration only once or twice in a decade. The mixing of different infiltration years in the aquifer is supposed to smooth this bias.

In the same way, our results are based on the hypothesis of constant infiltration each year. Even if this is not true at point scales, it is acceptable at larger space and time scales. It is true in the LCB where, except close to the Lake Chad, the water table depth seems invariant in the long term. But, the water table survey in the IB has shown a great increase of the recharge during the last decades, which implies a change in the annual input in the isotopic model.

HYDRODYNAMIC INTERPRETATION

The first difference between the two basins is the measurement density. The Niamey region is covered by a very detailed survey of water table levels for many years. Less precise investigations over the rest of the IB have shown that the Niamey region is representative of the processes and of the evolution of the whole basin. Information is much sparser for the LCB. The understanding of the hydrology is therefore much better in the IB than in the LCB.

A second important difference is the interaction between groundwater and the drainage network. In the IB, the Niger River is disconnected from the Continental Terminal aquifers. In contrast, the water table in the LCB is fed by the Komadugu River and is in hydraulic equilibrium with the northern pool of the Lake Chad. The sensitivity to climatic changes, either directly through the rainfall or through the river runoff, is therefore probably weaker in the IB than in the LCB.

A third difference is man's impact on the environment. The Niamey region has undergone population growth of 4% per year, higher than the national rate (3%); population growth is lower in eastern Niger. In the Niger part of the LCB, the average human density is about one inhabitant per km^2. Most of the population is concentrated in the south, close to the Komadugu River; the rest of the area has a density of less than 0.1 inhabitant per km^2. Most of the area is used for extensive pastoralism or is nearly desert. The limited vegetation seems to have poorly evolved. In contrast, in the Niamey area outside of the city, the population density is about 22. This means that man has considerably modified his environment in the IB replacing the natural vegetation by millet fields and fallows, whereas his impact has been much weaker in the LCB. In the IB, this environmental change has greatly modified the runoff ratio: due to greater crusting of the soil surface, more water flows to the valley bottoms, reaches the temporary pools and then infiltrates to the water table.

In both cases, the hydrology is greatly influenced by the very high variability in time and space of the rainfall. Very variable recharge is therefore the rule. It has been observed in detail in the IB: over the last seven years, the mean rise of the water table in the study area has varied from 0.10 to 0.47 m per year. At the point scale, the local seasonal fluctuation can be even more variable; in the Maourey Zéno village, the extreme annual amplitudes are 0.25 and 6.15 m.

In the IB, Desconnets *et al.* (1997) have calculated a runoff ratio in two sandy watersheds varying between 7 and 23% for complete years. Over 85% of the water having reached the temporary pools infiltrates to the water table. Nevertheless, at the larger scale, that does not mean that the same proportion of the total rainfall effectively recharges the water table. Large parts of many watersheds produce surface runoff that disappears mid-slope (by infiltration into the soil of the upper slope, and by evaporation) and never reaches the pools. The present groundwater recharge is certainly lower than 10% of the total rainfall at the large spatial scale (the whole Niamey degree square) and large time scale (the decade).

In the studied part of the IB, the mean interannual water table rise was 20 cm per year over the last decade (Favreau & Leduc, 1998). The total infiltration must be greater than this reserve increase indicates but in a proportion that we can not clearly define from the present hydrodynamic information. This implies an annual infiltration of greater than 10–20 mm for an aquifer porosity of 5 or 10%.

DISCUSSION

All our isotopic samplings represent an integration in time of a series of variable annual recharges. This integration does not allow annual fluctuations to be distinguished but allows one to interpret the past well before the first water table measurements. They help to represent the variability in space of the recharge. On the other hand, the water-table measurements date back only to 40 years but give a much more detailed idea of the short-term variability.

In both basins, there is at least a factor of 100 between the extreme values of the renewal rates calculated from isotopes, even when doubtful analyses are excluded.

This is explained by a high variability in space of the recharge volume itself, by different distances from the infiltration points, and by differences in hydrodynamic parameters which result in very different transit times. As local isotopic values can be considered as integrated in time, a similar range of values could be expected from the hydrodynamic data. Effectively, for a given year, many points do not show any seasonal fluctuation while at others the water table can rise by 5 m or more. The points showing no variation do not necessarily reflect less infiltration in those localities because of the importance of porosity in the transformation of the recharge into water table rise.

The flatter and drier LCB has a lower median renewal rate, calculated from isotopes. But, because of the large difference in annual rainfall between IB and LCB (560 mm *vs* 0–350 mm), a much larger difference should have been expected. The infiltration difference between the two regions is not just the ratio between the mean rainfalls because it is well known that the total annual rainfall amount has no correlation with the recharge volume, and that only the heaviest rains are useful for infiltration.

In both aquifers, there is a difference of 1 to 2 between the median estimates of renewal based on ^{3}H and on ^{14}C, that of ^{14}C being smaller. This could be due to bias during the sampling or to the uncertainty of the atmospheric tritium content. It should be noted that some ^{3}H values are below the detection threshold and their associated renewal rate is therefore a maximum value.

In both basins, the existence of a closed depression in the water table (light in the IB and very marked in the LCB), requires a local water budget deficit (evaporation greater than infiltration, even at a depth of several tens of metres), and weak horizontal groundwater flows due to poor permeabilities. The continental nature of the sedimentation explains the rapid changes in hydrodynamic parameters laterally and vertically. In the Niamey region, the renewal rate calculated in the closed depression is twice as small as in the rest of the aquifer. This agrees with smaller flux required by the durability of such a form. In the LCB, the number of samples is not yet sufficient to show the same pattern.

The transformation of the renewal rate into an infiltrated water depth requires estimation of the total amount of water in the aquifer. Porosity is largely uncertain because of the very few ground values to rely on. Assuming a porosity of 10%, a saturated thickness of 35 m in the LCB and 30 m in the IB, we obtain median values of infiltration of 6 and 3 mm per year according to ^{3}H and ^{14}C respectively in the IB, and of 3 and 2 mm in the LCB. Even if the calculated renewal rate has to be considered as an estimate rather than as a precise value, it gives a good impression of the small amount of infiltration in the Sahel.

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