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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INTRODUCTION

Estimates of annual recharge in arid and semi-arid 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, semi-arid 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 IULLEMMEDEGEN BAcIN

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 Miocene) 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
Christian Leduc et al. Comparison of recharge estimates for the two largest aquifers in Niger (Leduc 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 18O and 2H samples have been analysed giving a total of 243 values of 18O and 102 values of 2H. The isotopic content of the water table varies between -1.30 and -6.41‰ for 18O and between -15.2 and -45.9‰ for 2H, 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 18O-2H 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 Belemnite, PDB. Tritium results are expressed in Tritium Units, TU.

Forty-five 3H 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 3H 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 14C of the dissolved inorganic carbon (DIC) comes only from atmosphere through soil respiration. It can therefore be used without a mixing correction. Thirty-four analyses of 14C/12C were used. 14C contents vary between -10.1 and -18.5‰ PDB, typically in the range of values of the savannah.

Groundwater hydrodynamics

The water table survey of the 8000 km² region north of the Niger River is based on data from more than 250 wells monitored since 1991, and some older data (Desconnettes et al., 1997; Leduc et al., 1997). 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 555 mm with extreme values of 281 mm in 1915 and 1161 mm in 1998. On average, the annual rainfall decreases by 1 mm km² 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.

Fig. 1 The study area. (a) Continental Terminal outcrops in the bullpenmeden 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 Niger 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).
Kadzell region, a large anomalous closed depression reaches 40 m amplitude. For most
Niamey region. Surface water is very limited: the northem pool of Lake Chad, which
river; a lot of small endoreic ponds.

Niger, information about it is scarce and mainly available only for the southem part of
borders to the lake area in the centre of the basin, and hydraulic gradients are generally
very small. Close to Komadugu Yobe and the northem 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 +4.48\% for \(^{18}\)O and
between -49 and +13% for \(^{2}H\), with median values of -3.9 and -32.0\% respectively.
Comparisons with rainfall data can be made only with the N'Djamena records
(LAEWMO, 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 \(^{3}H\) 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 \(^{14}\)C and \(^{18}\)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 Inléammeden 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 \(^{3}H\) and 64 \(^{14}\)C samples from the 8000 km\(^2\) of the Niamey degree square, compared
with 15 \(^{3}H\) 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
evulation 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.
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

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.

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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 km². 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 km². 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, 1993). The total infiltration must be greater than this reserve increase indicates but in a proportion that we cannot 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 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 the IB and LCB (350 mm vs 100-350 mm), a much smaller 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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