RECHARGE OF THE PHREATIC AQUIFER IN THE NORTHWESTERN LAKE CHAD BASIN (NIGER)

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ABSTRACT The phreatic aquifer of the Lake Chad basin in Niger spreads over more than 300,000 km^2 and constitutes a huge groundwater resource. In spite of the arid climate, it is primarily recharged by slight rainfall infiltration and from the Komadougou Yobe, the only river in the region. Smaller contributions can come from surrounding aquifers, Lake Chad and the Pliocene artesian aquifer below. According to numerical modelling of the aquifer south of the parallel 17° N, the average of effective infiltration over the whole area is less than 1 mm per year, with annual rainfall varying between 10 and 350 mm. Hydrochemical and isotopic measurements confirm the existence of poor recent infiltration.

INTRODUCTION

The Chad basin extends over a huge area (2 millions of km^2), from which about a quarter is situated in Niger. The main part is centred on Lake Chad and the rest is composed by secondary endoreic basins. In Niger, the Lake Chad basin is divided into three departments (Agadez, Diffa and Zinder). Because of the Saharan climate in the northern part of the basin, the information available north of the parallel 17° N is very scarce. This paper is therefore devoted to the phreatic aquifer in the department of Diffa.

As the region is very broad, sparsely populated and distant from the capital of Niger, it does not contain much hydraulic equipment. Hydrological and hydrogeological data are rare and often poorly reliable. Early hydrogeological studies date from the 1960s and 1970s. More recent information has been collected and synthesized only in 1990 (PNUD, 1991).

Above the granite basement, outcropping in the western border, the thickness of Mesozoic and Cainozoic sediments is rapidly increasing towards the rift axis, where it reaches 10,000 m. Quaternary sand and silt, containing the phreatic aquifer, can exceed 100 m in depth (Fig. 1). They consist of alluvial, eolian and lacustrine deposits (Durand et al., 1984).

The drainage pattern is limited :
- the Komadougou Yobe, an impermanent river without any tributary in Niger and whose flow decreases downstream,
- the northern basin of Lake Chad, dried up since 1988,
- small temporary pools in topographic hollows in the southwest near Nigeria:

The phreatic aquifer, extending continuously towards Chad and Nigeria, has gentle hydraulic gradient (0.01 to 0.25 %) ; generally, groundwater flows converge on Lake Chad. A hydrogeological peculiarity is the Kadzell piezometric depression where the water table is 40 m lower in the centre than along the borders.

Mineralization in the phreatic aquifer is often low (100 to 400 $\mu S.cm^{-1}$) but can reach up to 5000 $\mu S.cm^{-1}$ in areas of high evaporation (Lake Chad basin, topographic hollows with shallow water) where there is a large variability in time and space. From north to south, the hydrochemical facies is sulphate-sodium, bicarbonate-sodium and bicarbonate-calcium.

The population, of approximately 200,000 inhabitants, is concentrated in a small southern belt. North of the parallel 14°30' N, the density is 0.06 inhabitant/km^2.

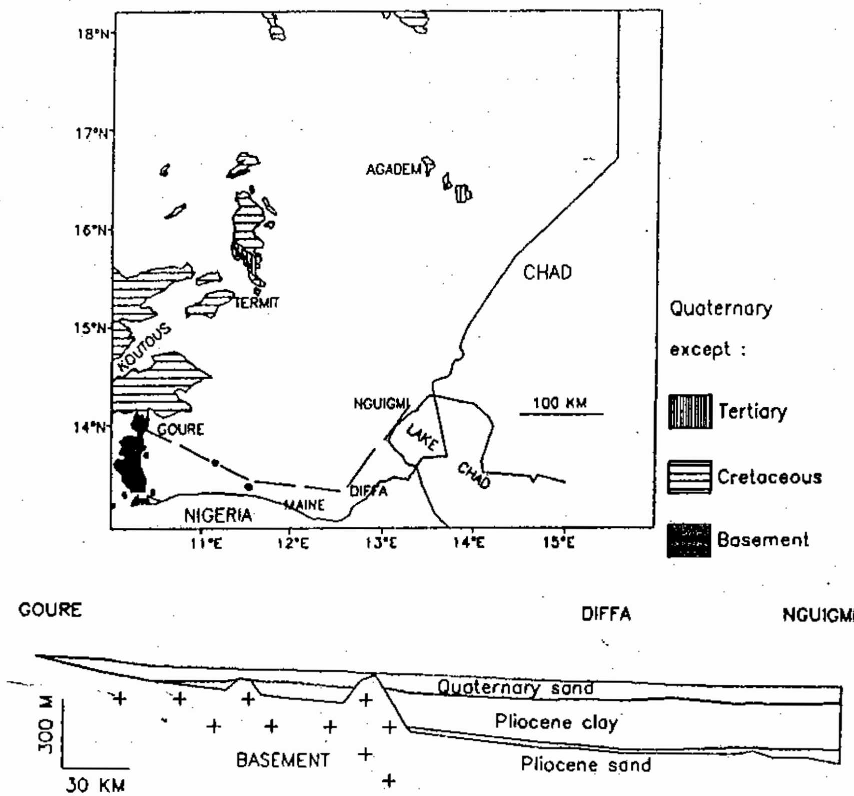

Fig. 1 Geological framework of the Lake Chad basin in Niger and section in the southern belt of the basin

RAINFALL INFILTRATION

The Sahelian climate is characterized by a short rainy season restricted to the summer months. The annual rainfall decreases from south to north and, to a lesser extent, from west to east. The average annual rainfall from 1953-1988 varies between 10 and 350 mm. South of parallel 14° N, there were 20 to 37 rainy days per year and 6 to 12 days per year with rainfall exceeding 10 mm for the same period. In the southern belt, Nguigmi and Maïné-Soroa are representative of extreme values (Fig. 2). The 1970s and 1980s have been much drier, inducing a clear movement of isohyets southwards. Average of 1980-1988 in Figure 3 shows this aggravation.

A simple calculation is made using daily data from the five oldest meteorological stations (27 to 67 years). A storage model represents the soil as a single tank ; the variations of water content are due to rain, evaporation and infiltration. It does not consider the plant transpiration and the delayed evaporation after the end of the rainy season. With a soil storage of 75 mm and a daily evapotranspiration of 6 mm, there is no infiltration at all two years out of three ; the average infiltration is between 11 and 23 mm per year, i.e. about 5 % of the annual rainfall. This rough evaluation, available for the "humid" southern belt, constitutes an upper limit. The real infiltration is probably far less.

In the extreme west of Niger, a detailed survey of recharge to the phreatic aquifer indicates an infiltration of between 5 and 10 % of the annual rainfall (Leduc and Desconnets, 1994). This ratio is assessed in a Sahelian zone more propitious to infiltration (rainfall about 500 mm per year, more pronounced topography which favours the concentration of surface runoff). Infiltration across the Lake Chad basin in Niger is therefore much more limited than this evaluation suggests.

Rainfall infiltration can also be estimated from piezometric fluctuations in the phreatic aquifer. There are only two areas where the annual variation of the water level is significant : along the Komadougou Yobe (up to 2 m, see below) and west of Maïné-Soroa where groundwater is shallow in the centre of many small endoreic basins (0.5 to 1 m). Outside these regions, the piezometric stability throughout the year confirms the extreme weakness of infiltration, even in the south. However, a groundwater recharge exists : water in the aquifer is essentially old but a recent inflow is obvious in some isotopic analyses (PNUD-UNESCO-CBLT, 1972 ; Chouret et al., 1977 ; Roche, 1980).

Despite the scarcity of data, especially from the north, a numerical modelling of the phreatic aquifer up to the parallel 17° N has been carried out. The most judicious calibration implies an average infiltrating flow of about 0.3 mm per year (Leduc, 1994). This inflow is in fact the resultant of real infiltration and evapotranspiration. A similar piezometric reconstitution could be obtained with increased rain infiltration (0.5 mm per year instead of 0.3) and increased permeability (nearly twice more), larger than ground values but still acceptable. On the other hand, an effective rain recharge of 2 to 4 mm per year is completely excessive.

The Kadzell piezometric depression can only be explained by an evapotranspiration larger than infiltration and a very low permeability ; vertical flows surpass horizontal circulation. The clayey soils in this region prevent infiltration during the rainy season. Even if the water table is deep, an infinitesimal evaporation can exist ; the numerical modelling estimates it at about 0.1 mm per year.

Other piezometric depressions in West Africa have already been explained in a like manner (Aranyossi & Guerre, 1990).

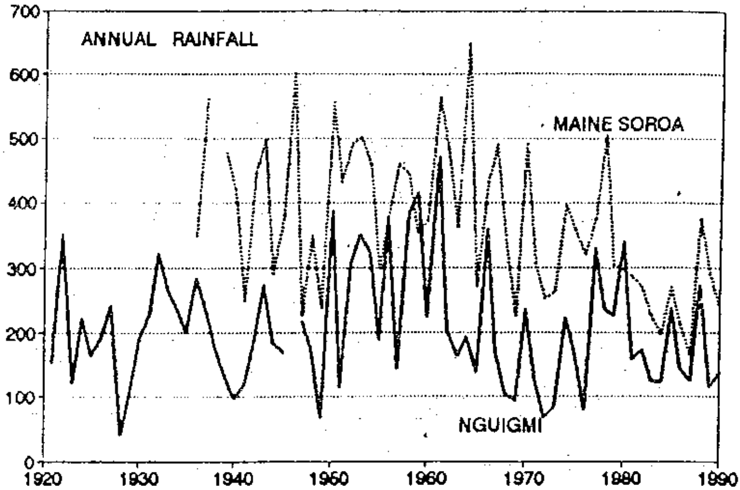

Fig. 2 Annual rainfall in Mainé-Soroa and Nguigmi

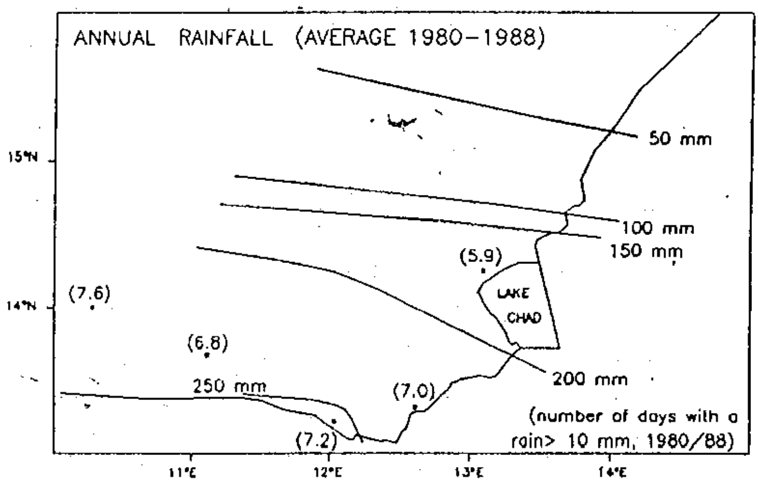

Fig. 3 Rainfall characteristics for 1980-1988

RECHARGE FROM LAKE CHAD

Lake Chad is divided in two basins. The northern one is fed only by the Komadougou Yobe and the overflow from the southern basin. The lowering of the level in the southern lake causes the partial or total drying up of the northern basin. The northern lake had completely disappeared in 1908 ; it is permanently dried up since 1988.

The reconstituted lake level during this century has fluctuated between 278 and 284 m. It is often higher than the phreatic surface. Therefore, in spite of the probable low permeability of clay in its bed, Lake Chad plays a prominent role in regional hydrogeology. Even if more than 90 % of the lake water evaporates, the small percentage available for infiltration is very important to groundwater flow ; Carmouze (1976) estimates it at about 4 10^9 m^3 per year for a mean level of the lake.

In Niger, two zones appear on the 1991 piezometric map (Fig. 4) :

- the northern zone where the piezometric head is close to or higher than the lake level ; groundwater flows from the northwest to the lake ;
- the western zone where the piezometric head is lower than the lake level (up to 30 m in the centre of the Kadzell piezometric depression).

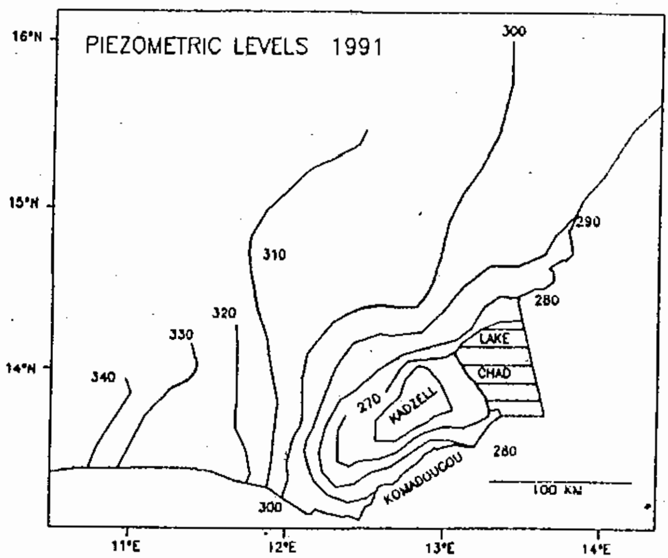

Fig. 4 Piezometric map of the phreatic aquifer

Inflow from the lake to the Kadzell depression is limited by the very low permeability in this part of the aquifer ; it was probably less than 10^6 m^3 per year when there was some water in the northern basin.

The drying up of the lake causes a stop of infiltration towards Kadzell and an important evaporation in the bed of the lake. It is therefore twice negative for the phreatic aquifer.

A comparison of the piezometric levels of 60 wells in 1975 and 1990 has been carried out. After correction because of the pumpings during the measurements, the only clear observation is the lowering of the piezometric level up to 5 m close to the lake. As such a variation is unknown anywhere else in the aquifer, we must assume it is caused by the drying up of the lake. Chouret et al. (1977) had the same explanation for piezometric drop (up to 3.5 m) in Chad along the northern lake after the 1970s drought.

RECHARGE FROM THE KOMADOUGOU YOBE

The Komadougou Yobe is the only river on the western side of Lake Chad. Its flow begins in July, peaks in November and stops several weeks later. The flow duration (10 months in 1962/63 and 4.5 in 1983/84) depends on climatic fluctuations and human activities in the upper basin in Nigeria.

The Komadougou Yobe contributes less than 1% to the total river flow to Lake Chad. The annual discharge decreases downstream : 1.3 10^9 m^3 in Gashua (Nigeria), 525 10^6 m^3 in Diffa and 340 10^6 m^3 at the mouth of the river (IWACO, 1985). This is due to evaporation and infiltration along the banks.

This recharge is clear on Figure 4 : isopiezometric lines are parallel to the river with decreasing head when going away from the Komadougou. Furthermore, piezometric fluctuations throughout the year are just a few centimetres across the major part of the aquifer but rise up to 2 m along the river ; they are very well correlated in time with the river flood.

The recharge from the Komadougou is also confirmed by hydrochemical measurements. With the exception of the area close to Lake Chad, where infiltration from the lake leads to increased salinity, the groundwater mineralization is much lower near the river. Conductivity is 60 $\mu S.cm^{-1}$ in the river, less than 400 $\mu S.cm^{-1}$ near the Komadougou but can reach 3500 $\mu S.cm^{-1}$ farther.

Various indirect methods have been considered for this recharge evaluation (PNUD, 1991). Despite great uncertainty, the amount of 12 10^6 to 20 10^6 m^3 per year can be accepted for the recharge from the Komadougou to the northern aquifer (and the same southwards to Nigeria).

This recharge is threatened by the increasing number of dams in the upper basin in Nigeria : water used upstream for irrigation cannot infiltrate in the lower valley.

RECHARGE FROM OTHER AQUIFERS

The Quaternary aquifer is recharged by three surrounding massifs of Cretaceous sandstone (from northwest to northeast Koutous, Termit and Agadem). Similarly, the aquifer of Plio-quaternary sand and gravel filling the north of the rift discharges towards the studied area. It is difficult to evaluate these contributions because there are very few wells, sometimes dried up, altitudes are approximate, hydrodynamic characteristics are unknown and no spring has ever been measured.

Except for the western border where Quaternary sediments directly overlap the granitic basement, the bottom of the phreatic aquifer in the south is a sequence of Pliocene clay (up to 200 m thick). Below this impervious layer, Pliocene sand contain an artesian aquifer. To the north, clay becomes gradually thinner until the two aquifers join together. When they are separate, the Pliocene head is always higher than the Quaternary head (up to 50 m in the centre of the Kadzell piezometric depression). In spite of such a difference and the large area of contact involved, leakage through the semi-pervious formation must be limited by the very low vertical permeability of Pliocene clay.

A second type of exchange between Pliocene and Quaternary aquifers is the free flowing of artesian boreholes which constitute permanent pools.

WATER BALANCE

A preliminary estimate of the water balance can be proposed in spite of the numerous and large uncertainties surrounding each term. In some cases, the advanced value could be divided or multiplied by ten. Volumes are calculated using different methods when circumstances permit.

Estimates based on ground data

Main inflow to the phreatic aquifer, the rain infiltration is less than 5 % of the annual rainfall, i.e less than 800 10^6 m^3 per year over the southernmost 140,000 km^2. We have no idea of the actual value of the effective infiltration, which must be much lower than this limit.

The calculation of leakage from Pliocene is hazardous as no vertical permeability can be measured (the chosen value, 5 10^{-11} $m.s^{-1}$, is very hypothetical). It is probably between 0 and 4 10^6 m^3 per year, subject to substantial uncertainty. The free flow of artesian boreholes gives between 0.5 10^6 and 10^6 m^3 per year to the phreatic aquifer ; this amount is reliable. Contributions from other surrounding aquifers are estimated from hydraulic gradients at less than 3 millions of m^3 per year, with large uncertainty.

Recharge from Komadougou Yobe is probably between 12 and 20 10^6 m^3 per year.

Outflow is shared out between evaporation, human activities and natural groundwater flow to the phreatic aquifer in Chad. This natural flow to the aquifer in Chad, estimated from hydraulic gradients, is about 2 10^6 m^3 per year ; the accuracy of this calculation, analogous to the evaluation of recharge from surrounding aquifers, is poor.

The water demand for human activities is much more precise. It consists of :

- cattle watering (9 10^6 m^3 per year),
- irrigation (4.5 10^6 m^3 per year),
- village consumption (1.5 10^6 m^3 per year).

A significant portion of this water demand, approximately one third, is met for surface water (the Komadougou Yobe and small temporary pools) during the rainy season. The rest comes from the phreatic aquifer.

The major part of the outflow is due to evapotranspiration, which has never been measured. Over most of the aquifer, the interesting term for the water balance is not the real evaporation but the effective infiltration. In the Kadzell depression and the bed of Lake Chad, evaporation is higher than infiltration. Due to the depth of the water table, evaporation in Kadzell cannot exceed 1 mm per year (10^7 m^3 per year). On the contrary, the uncertainty about evaporation in the dried up Lake Chad is very large : 1 mm to 1 m (3.5 to 3500 10^6 m^3 per year).

The accuracy of these different estimates is highly variable. Unfortunately, the predominant flows (rain infiltration and evaporation) are the less well known. The water balance is therefore very imprecise.

Estimates based on numerical modelling

Numerical modelling uses these elementary evaluations to check their coherence. Given the present information, the chosen calibration seems to be reasonable, even if many values of flow used in the model are lower than the previous estimates based on ground data. They could be increased but this implies an increase of permeability when medians of transmissivity in the present calibration and in situ are very close together (7 10^{-3} and 5 10^{-3} $m^2.s^{-1}$ respectively). Annual amounts detailed below are results from the numerical modelling of 140,000 km^2 south of parallel 16°30' N.

Inflow into the phreatic aquifer is distributed among :
- approximately 35 10^6 m^3 per year from effective rain infiltration over the entire aquifer except in Kadzell and Lake Chad where evaporation prevails,
- 6.5 10^6 m^3 per year from the Komadougou Yobe,
- 2.5 10^6 m^3 per year from surrounding aquifers.

Annual outflow from the aquifer is :
- 12 10^6 m^3 from human activities (man, cattle and irrigation),
- 2.5 10^6 m^3 from natural flow to the phreatic aquifer in Chad,
- 1 10^6 m^3 from evaporation in the Kadzell depression (i.e. 0.1 mm per year),
- 26 10^6 m^3 for evaporation in the Lake Chad bed (i.e. 7.3 mm per year).

In fact, input and output flows of a grid cell could be modified simultaneously without changing their sum. The groundwater balance based on the model is therefore to be considered globally. For example, the value in the centre of Kadzell is the resultant of three very weak phenomena : evaporation, leakage from Pliocene and rain infiltration. Out of them, none can be measured directly. Similarly, the estimate of effective rain infiltration in the model does not reveal the real values of evaporation and infiltration.

Comparison of withdrawal and resources

Whatever the calculation, the total effective inflow seems to be less than 100 millions of m^3 per year. The groundwater resources available in the southernmost 140,000 km^2 can be approximated at 500 billions of m^3 with average values of porosity (10 %) and saturated height (35 m). Even with so many uncertainties in the calculations, the effective recharge is very limited compared to the huge resources.

For the groundwater management, the extreme weakness of replenishment is not problematic with regards to the slight pumpings. The water demand will therefore be satisfied for many decades Nevertheless, attention must be paid to the sound use of Komadougou Yobe, which significantly supplies the southern part of the phreatic aquifer.

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