Groundwater recharge increase induced by land-use change: comparison of hydrodynamic and isotopic estimates in semiarid Niger

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Abstract In southwest Niger the Continental Terminal water table has been intensively studied over about 4000 km^2. In this semiarid context, a surprising long-term water-table rise is evident; the mean rise was 0.20 m year^{-1} for the 1990s, and present levels are the highest ever measured (+3.5 m since the early 1960s). This increase in groundwater reserves is explained by the heavy land clearing observed during recent decades. Hydrodynamic data were considered first. The mean recent rise of 0.20 m year^{-1} implies a recharge rate of at least 10 to 30 mm year^{-1} during the 1990s, whereas numerical modelling of a steady state in the early 1960s requires a much lower recharge. Radioisotope data were also considered. Taking into account the progressive increase in groundwater resources, the modelling of ^{14}C and ^{3}H contents gives a low pre-clearing value for recharge of between 0.6 and 5.0 mm year^{-1}. All these estimates agree with an increase of groundwater recharge due to land clearing by about one order of magnitude in 40 years.

Key words environmental isotopes; groundwater; land use; natural recharge; Niger; semiarid

INTRODUCTION

Changes in water resources are linked with climatic fluctuations and also with environmental changes, the relative importance of these two factors depending on time and place. In semiarid regions, hydrological processes are more sensitive to small changes. Recent decades in the Sahel were marked by severe droughts and by a rapid increase in population, both having an impact on the environment. A detailed study of hydrological change in the Sahel therefore deserved consideration. Our study near Niamey (southwest Niger) was based on a very large amount of hydrodynamic and geochemical data. We could therefore estimate groundwater recharge rates for recent years and its change during the past forty years.

REGIONAL FEATURES

The study area (2°20′–2°50′E, 13°20′–14°00′N, Fig. 1) is located at the southwest boundary of the Continental Terminal aquifer, that extends over 150 000 km^2. Outcropping sediments, mainly silty sandstones, belong to the Continental Terminal, dated

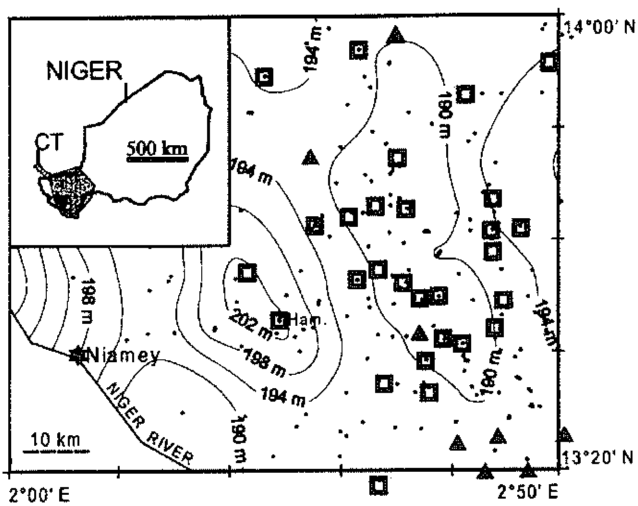

Fig. 1 General map of Niger with the Continental Terminal (CT) outcrops, and potentiometric map (1998) of the water-table elevation in the study area (• regular potentiometric survey, □ sampled well, ▲ sampled borehole).

Eocene to Pliocene, and to the Quaternary. The upper surface is formed by a laterite plateau cut by sandy valleys inherited from former wetter conditions during the Quaternary; the difference in altitude never exceeds 100 m. The Niger River flows directly over the Pre-Cambrian basement. The mean annual precipitation in Niamey is 567 mm with 90% of rainfall concentrated between June and September. The mean annual temperature is 29°C and the potential evapotranspiration is about 2500 mm $year^{-1}$. The natural vegetation consists of a wooded savanna, but much of the area is now mainly a patchwork of fallow and millet fields on the sandy slopes of dry valleys.

The main features of the hydrological system are well established (Desconnets *et al.*, 1997). Due to the degradation of the drainage network, the region is made up of small juxtaposed endoreic catchments; their areas are of the order of 1 km^2. During the rainy season the intense rainfall events produce surface runoff, which reaches the lowest part of each catchment and fills temporary pools, always much higher than the water table. Most of the concentrated water rapidly infiltrates, creating temporary groundwater mounds below the pools (e.g. Fig. 2). At a distance from the pools, infiltration into the soil below 3 m is nil or very limited, and no seasonal water-table fluctuation is observed (Leduc *et al.*, 1997). At the whole study area scale, groundwater hydraulic gradients are low, less than 1‰ and there is no preferential direction of flow (Fig. 1). The median depth to the water table is 35 m for a mean saturated thickness of 30 m in the aquifer. The groundwater geochemistry was detailed in Favreau (2000). The groundwater temperature is around 30°C; the water is acid (pH between 5.0 and 6.0) and circulates in an oxidizing medium (Eh between 300 and 500 mV). Total dissolved solid values are low, consistent with the quartzic, carbonate-free nature of the aquifer (median of 50 mg l^{-1}). Two deeper aquifers exist in the Continental Terminal but geological, hydrodynamic and isotopic data do not show any leakage with the water table.

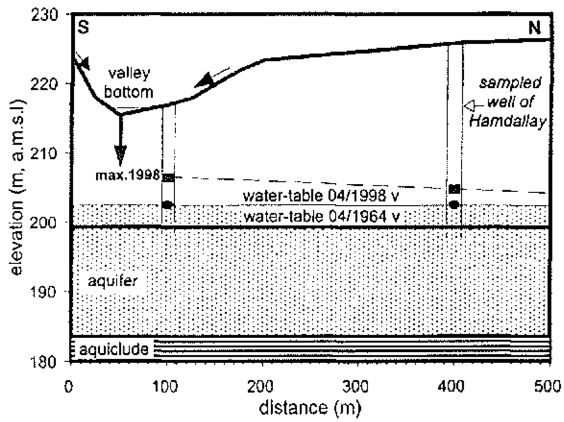

Fig. 2 Schematic cross-section of recharge in Hamdallay (located as Ham in Fig. 1) with the long-term water-table rise since the beginning of the 1960s.

HYDRODYNAMIC APPROACH

Over 10 000 water table level measurements were made during the past decade in about 150 wells with a bimonthly to annual frequency. Seven automatic level recorders added to the monitoring network. The reliability of the data was discussed by Favreau *et al.* (2001); the influence of pumping did not exceed 2.0 m, but natural water-table fluctuations can be up to 5 m near recharge areas during the rainy season (Fig. 2).

The second part of the dataset was one hundred older measurements made between the 1950s and the 1980s (e.g. Boeckh, 1965). They gave a long-term view of changes in the aquifer. The major difficulty when dealing with the old, isolated data was to connect them with recent measurements. Exact dates and locations of the wells were checked. Other uncertainties, like possible changes in the reference for measurement, were overcome by enquiries in the field.

The comparison of old and recent measurements shows a systematic increase in water-table levels, of between 0.5 m and 12.5 m since the early 1960s. The average rise is 3.5 m (Fig. 3(c)), i.e. an increase of 10% in the groundwater reserve. The long-term rise accelerated during the last decade to between 0.05 and 0.45 m year^{-1}, with a mean rise of 0.20 m year^{-1}. Rise intensities are not linked with proximity to a recharge area, nor with the potentiometric level, but rather with the aquifer porosity (Leduc *et al.*, 2001).

Explanation for the water-table rise

Some easy explanations of the long-term rise must be excluded. There is no artificial recharge due to irrigation. Overflow from artesian boreholes could only be important on a local scale; such boreholes are rare and the rise often began before their drilling. We must also eliminate a reduction in pumping; because of population growth (4% per year) there is a higher number of wells, both increasing groundwater abstraction.

A first real explanation could be a link with variation in rainfall; the 1990s, which were wetter than the 1980s, could have resulted in greater infiltration (Fig. 3(a)). However, previous variations in rainfall and groundwater levels refute such a simple correlation. The relative decrease in rainfall of 20% between 1950 and 1970, and 1970 and 1990, should have had a significant impact but in fact the recent groundwater levels are higher than during the 1960s. This lack of a simple relationship does not mean that rainfall has no influence on water-table fluctuations. For instance, the enhancement of the rise during the past decade can also be interpreted as a positive combination of a long-term process and greater infiltration due to a return to wetter years. However, the main process at work in the hydrological change appears to be poorly influenced by rainfall.

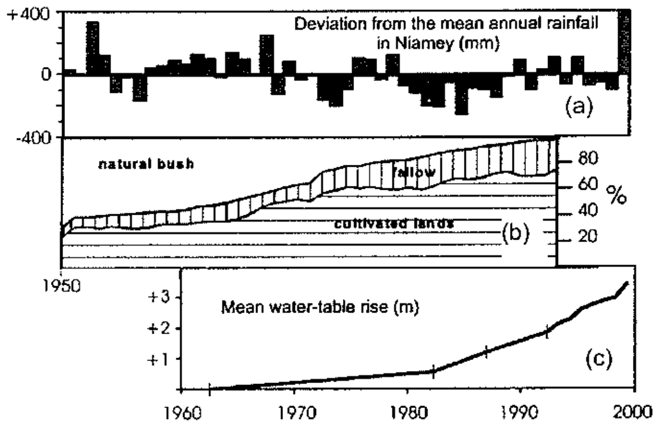

Fig. 3 Comparison of changes in rainfall (a), in land use (b) and in water table level (c) between 1950 and 1998. Deviation from mean annual rainfall in Niamey (567 mm) is expressed in mm; land use is expressed as a percentage of the total cultivable area (i.e. with the exception of lateritic plateaux); the mean rise in the water table is calculated from over 50 points.

A second explanation is the change in land use. Since the 1950s, land-clearing has increased due to rapid population growth. Using Loireau's (1998) ground survey based on aerial photographs, Fig. 3(b) shows the landscape changes over about 600 km^2 of the study area for the 1950–1992 period. Cultivated areas (millet fields and associated fallows) increased from about 27% of the total cultivable area to nearly 100%, and the natural savanna almost disappeared. A direct consequence is a reduction of the transpiration loss and of direct water uptake from the water table but, because of the thick unsaturated zone (median of 35 m), this has probably little impact on the groundwater budget. As recharge is essentially indirect, the most reliable hypothesis is that recent deforestation enhanced surface runoff and so the volume of water reaching endoreic ponds and so the groundwater recharge. Other evidence for this change includes a comparison of aerial photographs between 1950 and 1992, which shows a widening of the gullies (Valentin, 1994) and the substitution of wooded areas in valley bottoms by endoreic pools. Such an increase in erosion and runoff after land-clearing is observed elsewhere in the Sahel (e.g. Albergel, 1987).

Recharge estimates

An estimate of the present recharge is provided by the mean water-table rise over the last decade. Assuming a porosity between 5 and 15%, the mean rise of 0.20 m year^{-1} implies a recharge of at least 10 to 30 mm year^{-1}. These figures are consistent with previous estimates based on the water balance of endoreic pools, where inferred recharges ranged from 10 to 80 mm year^{-1} depending on the catchment and year (Desconnets *et al.*, 1997).

The presence of a natural closed potentiometric depression in the centre of the study area (Fig. 1) allows a second estimate of the groundwater recharge. Such aquifers, common in the Sahel, can be explained by a local water deficit, i.e. infiltration lower than evaporation (Aranyossy & Ndiaye, 1993). Their existence implies weak lateral flows and low recharge rates to balance evapotranspiration. In the study area, the potentiometric depression is presently rising but was probably in steady equilibrium in the 1960s (Fig. 3(c)). Hydrodynamic numerical modelling of it (Favreau, 2000) suggests a regional recharge of about 1 mm year^{-1} in the 1960s under quasi-natural vegetation.

RADIOISOTOPE APPROACH

Isotopic data

Groundwater samples of ^{14}C and ^{3}H were taken from 28 wells and 8 boreholes (Fig. 1). When necessary, for wells open to the atmosphere, the water column was renewed before sampling in order to obtain representative water. Stable isotope contents ($\delta^{18}O$, $\delta^{2}H$) were also analysed. Their values confirm that deep infiltration occurs quickly after rain (no evaporative feature) and suggest a good vertical mixing in the aquifer (no difference between samples from wells or boreholes). The $\delta^{13}C$ contents of the dissolved inorganic carbon (DIC) in groundwater are consistent with the present vegetation and confirm the biogenic origin of the DIC (soil carbon).

The ^{3}H content in groundwater is low: maximum of 4.0 ± 1.0 TU, with more than half of the samples below the detection limit (~2 TU). The ^{14}C activities of DIC range from 60.4 ± 0.5 to 102.6 ± 0.7 pmC, for a mean value of 84.4 ± 0.8 pmC. As for stable isotopes, there is no statistical difference between ^{3}H and ^{14}C values obtained from wells or boreholes (Fig. 4).

Recharge estimates

Hydrodynamic observations prove that deep infiltration is localized in space but significant in volume and speed when it occurs; in addition, the isotopic features of the groundwater suggest a good vertical mixing within the aquifer. The model used to estimate the renewal rate is thus a good mixing model, which appears to be the most suitable for estimating recharge in this study area. Considering the regional increase of the groundwater reserve over the last decades, the radioisotope concentration in the aquifer at year *i* can be expressed as:

$$Ca_i = \left[(1 - Rr_i) Ca_{i-1} e^{-\ln 2/T} \left(1 + \sum_{n=1}^{i-1} S_n \right) + (Rr_i + S_i) Cr_i \right] \Big/ \left[1 + \sum_{n=1}^{i} S_n \right]$$

where Ca_i is the radioisotope (^{3}H or ^{14}C) concentration in the aquifer during year i, Rr_i the renewal rate for the year i (i.e. the ratio between annual recharge and groundwater reserve), T the radioisotope half-life (12.43 years for ^{3}H, 5730 years for ^{14}C), Cr_i the atmospheric input of ^{3}H or ^{14}C at year i and S_n is the relative groundwater reserve increase during year n, compared to the initial reserves before the beginning of the water-table rise.

In southwest Niger, there is no regular sampling of ^{3}H in rain or of tropospheric $^{14}CO_2$. The ^{3}H input function was reconstructed from annual means (1960–1997) weighted with rainfall data of African stations north of the equator (IAEA/WMO, 1998). For ^{14}C, annual means of west African sites reported by Nydal & Lövseth (1996) were used.

We first considered a local approach. Figure 4 shows ^{3}H/^{14}C ground measured values and modelled values for different types of groundwater reserve increase and for different annual renewal rates. For most of the samples with ^{3}H above the detection limit, ^{3}H contents are higher than expected for a stable reserve but fit with exponential or linear increases in reserve of up to +20%. The radioisotope results thus validate both the conceptual model considered, and the mean long-term increase in groundwater reserve. The ^{3}H/^{14}C couples suggest pre-clearing annual renewal rates (Rr) between 0.02 and 0.30% (Fig. 4). However, as geological heterogeneities exclude any accurate quantification of local groundwater reserves, this approach provides only a rough estimate of the renewal rates.

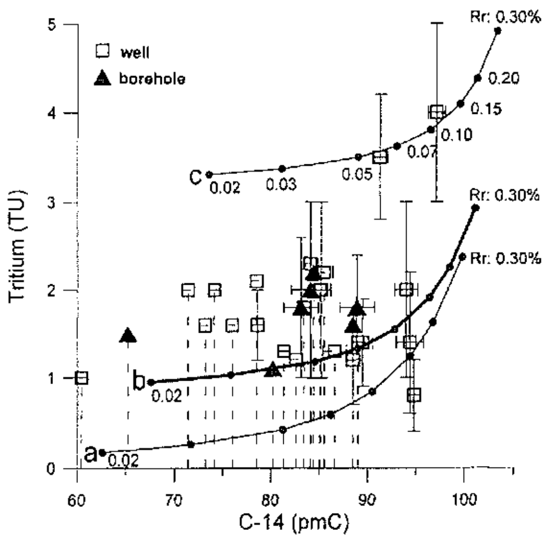

Fig. 4 ^{3}H contents and ^{14}C activities in groundwater. The curves represent the ^{3}H/^{14}C couples modelled for various annual renewal rates (Rr between 0.02 and 0.3%) and different rises in groundwater reserve for the period 1960–1998 (**a**: stable water-table; **b**: exponential rise of +10%; **c**: linear rise of +20%). Vertical lines represent the uncertainty for ^{3}H contents (dotted for values below the detection limit). Squares and triangles show the measured values in wells and boreholes.

A second approach considers the mean characteristics of the whole aquifer to calculate an average renewal rate. An increase in groundwater reserve of +10% is chosen for all samples, in agreement with the potentiometric change in the area. The inferred mean annual renewal rate in the 1950s ranges between 0.04 and 0.05% for the mean ^{14}C activity in groundwater and fits in with the ^{3}H results (Rr < 0.20%). This convergence of two independent tracers can be considered as a crossed validation. However, the initial model assumptions require a sound examination of the model sensitivity.

The first uncertainty is due to the reconstructed history of atmospheric input. ^{3}H in rainfall is highly variable in time and space; this results in an uncertainty of about 1 TU for the ^{3}H content in present groundwater. Atmospheric ^{14}C fluctuated between 98 and 110 pmC during the past thousand years (Suess, 1971); the consequent uncertainty for present groundwater is of about 3.5 pmC. A second source of uncertainty is the increase in the reserve. An increase of ± 2% around 10%, the average chosen for the past 40 years, results in differences of about 0.3 TU for ^{3}H and near 1 pmC for ^{14}C. Other sources of uncertainty, such as variability of the recharge as a function of the annual rainfall, and the time-lag in the ^{14}C input via the soil were also tested. The weighting of the renewal rates with annual rainfall does not modify groundwater contents by more than 0.2 TU for ^{3}H, and 0.2 pmC for ^{14}C. A possible time lag of 3 years for the $^{14}CO_2$ transit from the atmosphere to groundwater through the soil influences activities by less than 0.3 pmC. Cumulated uncertainties vary between 1 and 2 TU for ^{3}H and 3.5 and 5 pmC for ^{14}C in groundwater. Therefore, calculations based on ^{3}H are very sensitive to uncertainties (Rr < 0.35%), whereas ^{14}C provides more robust and accurate results, with a range of possible values between 0.03 and 0.06%. For the mean aquifer parameters (30 m of saturated thickness, porosity between 5 and 15%), these figures lead to pre-clearing recharge rates of between 0.6 and 5.0 mm year^{-1}. These rates are consistent with the long-term regional recharge of about 1 mm year^{-1} suggested by the hydrodynamic modelling of the aquifer (Favreau, 2000).

CONCLUSION

The hydrodynamic information is clear; the Continental Terminal water table near Niamey is obviously rising. This phenomenon, due to land-clearing, probably started in the early 1960s. Recent recharge, calculated from the present interannual rise in the groundwater reserve, is greater than 10 to 30 mm year^{-1}. Recharge calculated by numerical modelling of the 1960s (assumed to be representative of a steady equilibrium), was of the order of 1 mm year^{-1}. The isotopic information is also clear. ^{3}H and ^{14}C contents are more consistent when interpreted with an increase in the groundwater reserve. Because of the low ^{3}H contents, ^{14}C provides more detailed results: the long term recharge is of the order of 1 mm year^{-1}. Both the hydrodynamic and isotopic data show that the transient state must be taken into account. Both data lead to an estimate of the annual recharge in the 1960s of about 1 mm year^{-1}. This value is much lower than recent recharge, by at least one order of magnitude.

In semiarid environments few estimates of increase in recharge following deforestation have been reported and, to the best of our knowledge, they only concern semiarid Australia. Among others, Allison *et al.* (1990) calculated an increase of about two orders of magnitude in the western Murray basin (from 0.1 to between 5 and 30 mm year^{-1}) using unsaturated zone chloride profiles. These results are consistent with our estimate in Niger. Because our study area is very representative of semiarid African environments (endoreic runoff and localized recharge, land-clearing for past decades), it is suggested that increased recharge due to land-clearing may be a common process in Africa, even if not well documented as yet.

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