Hydrogeol J (2016) 24:407–423
DOI 10.1007/s10040-015-1345-z

REPORT

Impacts of a large Sahelian city on groundwater hydrodynamics and quality: example of Niamey (Niger)

Aïssata B. Hassane[1,3] **· Christian Leduc**[2] **· Guillaume Favreau**[3] **·**
Barbara A. Bekins[4] **· Thomas Margueron**[5]

Received: 24 April 2015 / Accepted: 19 November 2015 / Published online: 15 December 2015

Abstract The management of groundwater resources is very important in the semiarid Sahel region, which is experiencing rapid urban development. Impacts of urbanization on groundwater resources were investigated in the unconfined aquifer of the Continental Terminal beneath the city of Niamey, Niger, using water level and chemical data. Hydrodynamic and chemical changes are best described by a combination of factors including the historical development of the city, current land use, water-table depth and topography. Seasonal groundwater recharge occurs with high spatial variability, as indicated by water-level monitoring in all wells, but there was no interannual trend over the 5-year study period. Groundwater salinity shows high spatial variability and a minor rising trend. The highest salinity is in the old city centre, with Na–NO_3 dominant, and it increases seasonally with recharge. Salinity is much lower and more variable in the suburbs (Ca–HCO_3, Ca–NO_3, and Na–NO_3 dominant). Nitrate is the main ionic contaminant and is seasonally or permanently above the international guidelines for drinking water quality in 36 % of sampled wells, with a peak value of 112 mg L^{-1} NO_3–N (8 meq L^{-1}). Comparison of urban and rural sites indicates a long-term increase in groundwater recharge and nitrate enrichment in the urban area with serious implications for groundwater management in the region.

Keywords Urban groundwater · Seasonal recharge · Contamination · Sahel · Niger

Introduction

The Sahel, south of the Sahara desert, is a semiarid region characterized by one of the world's highest population growth rates and strong interannual variability of rainfall in time and space (e.g. Lebel et al. 1997), as exemplified by the exceptionally long drought in the 1970s and 1980s (L'Hôte et al. 2002; Dai et al. 2004; Sheffield and Wood 2007). These two factors affect the whole environment (Leblanc et al. 2008; Boulain et al. 2009) and especially groundwater resources (e.g. Biroue and Schneider 1993; Leduc et al. 2001). This is particularly important because groundwater is often the only permanent water resource, and frequently suffers from low recharge rates and water quality deterioration. The future could be even more problematic according to most climate models which predict a drier Sahel in the 21st century (Held et al. 2005; Kandji et al. 2006); thus, access to a reliable resource for drinking-water supply and irrigation is an ongoing concern.

As in many other semiarid areas (Scanlon et al. 2006), the main sources of groundwater recharge in the Sahel are through depressions and ephemeral stream channels where surface runoff collects causing focused infiltration (Desconnets et al. 1997; Leduc et al. 1997; Favreau et al. 2012). The rapid

Electronic supplementary material The online version of this article (doi:10.1007/s10040-015-1345-z) contains supplementary material, which is available to authorized users.

✉ Aïssata B. Hassane
aissa_hb@yahoo.fr

1 Département de Géologie, Université Abdou Moumouni, BP 10662, Niamey, Niger

2 IRD, UMR G-EAU, BP 64501, 34394 Montpellier, Cedex 5, France

3 IRD, UMR Hydrosciences, Université de Montpellier, 163, rue Auguste Broussonet, 34090 Montpellier, France

4 U. S. Geological Survey, 345 Middlefield Rd., Menlo Park, CA 94025, USA

5 Centre de Recherche Médicale et Sanitaire-CERMES, BP 10887, Niamey, Niger

growth of cities directly impacts groundwater resources (Foster et al. 2011; Foster 2001; Drangert and Cronin 2004) especially in developing countries characterized by limited sanitation and densely populated informal settlements with partial access to safe drinking water (Foster 2001; Xu and Usher 2006). Urbanization contributes to soil compaction along with impervious surfaces (e.g. roads, houses) which may increase runoff and routing of flow into topographic depressions. This changes both intensity and spatial distribution of groundwater recharge—diffuse recharge decreases and localized recharge increases, complemented by leakage from subsurface infrastructure (e.g. storm water drainage and water supply networks; Lerner 2002; Hibbs and Sharp 2012). Urbanization may therefore increase (Lerner 2002; Foster and Chilton 2004; Selim et al. 2014) or decrease (Collin and Melloul 2003; Hoque et al. 2007) groundwater recharge, depending on surface conditions, density and quality of infrastructure, etc. Several studies have shown that groundwater recharge may increase in urban environments even if natural recharge decreases because of lower surface permeability (Lerner 2002). This increase, especially when due to wastewater infiltration (Foster and Chilton 2004), may be very important for future groundwater and wastewater management in rapidly growing cities in arid regions. In unsewered urban areas, recharge waters may transport anthropogenic contaminants to groundwater systems (Lerner 2002; Foster and Chilton 2004; Hoque et al. 2014); however, the effects of urban development on groundwater in the Sahel have received relatively little attention and few studies are available (e.g. Cissé Faye et al. 2004; Yameogo et al. 2006; Ngounou Ngatcha and Djoret 2010; Re et al. 2011). In Dakar, Senegal, groundwater overexploitation led to both water-table declines and seawater encroachment (Re et al. 2011; Madioune et al. 2014), while the lack of sanitation increased the nitrate concentration far above the World Health Organization (WHO) limit of 10 mg L^{-1} NO_3–N, up to 540 mg L^{-1} (122 mg L^{-1} NO_3–N; 8.70 meq L^{-1}) in the suburbs (Cisse Faye et al. 2004; Deme et al. 2006; Diedhiou et al. 2012). A similar increase in nitrate, up to 300 mg L^{-1} (67.77 mg L^{-1} NO_3–N; 4.84 meq L^{-1}), resulted from anthropogenic pollution in N'djamena, Chad (Kadjangaba 2007; Ngounou Ngatcha and Djoret 2010).

This report focuses on the city of Niamey, in southwest Niger, as a typical example of the impacts of urbanization on semiarid groundwater systems. Previous hydrogeological studies in the area mostly concerned the Precambrian basement and focused on recharge processes and the source of nitrate pollution using isotopic techniques (Girard and Hillaire-Marcel 1997; Girard et al. 1997). This current work differs fundamentally from the previous effort as it focuses on the unconfined aquifer of the shallow sedimentary formations of the Continental Terminal (CT, Tertiary) and covers seasonal and interannual variability of groundwater resources. The study incorporates a long-term hydrodynamic and chemical survey over the rural area around Niamey where the CT unconfined aquifer has been observed for two decades, providing a good reference for pre-urbanized conditions. Beyond contributing to better groundwater management in the city of Niamey, this work intends to help other major Sahelian cities with the same sanitation problems by (1) evaluating the variability of groundwater reserves in space and time, and (2) identifying the sources of groundwater salinity, and especially the cause of the nitrate contamination.

Study area

The city of Niamey, located in the Niger River valley, covers an area of 240 km^2 which includes both the city centre and suburbs, mainly made up of old villages like Yantala and informal settlements like Pays-bas, with residential, agricultural and savannah lands (Fig. 1). The study area is the north part of the city, on the north bank of the Niger River. Niamey, the capital of Niger, had 708,000 inhabitants in 2001 (RGPH 2005), and has probably 1.3 million today, with 1.5 million during the dry season due to rural migration (INS 2012). The annual demographic growth rate of 4.5 %, compared with 3.4 % for Niger overall, is due to both the natural increase (birth rates) and migration from rural to suburban areas. The population density is 2,700 inhabitants per km^2 in the city centre. In comparison, the rural population density near Niamey in 2001 was estimated at 30 inhabitants per km^2 (INS 2012). This population growth has led to the expansion of the urban area, increasing the urban infrastructure (e.g. housing, roads) and decreasing both agricultural and savannah lands. Figure 1 shows the expansion of the city of Niamey since the founding of the colonial military post in 1901 and highlights the rapid spread of urbanization following the 1970s' drought.

Two physiographic units are identified in the city area: the "plateau" and the "plain". The plateau is located on the north bank of the Niger River at elevations between 190 and 230 m above mean sea level (amsl). The alluvial plain is mainly located on the south bank of the Niger River, between 180 and 185 m amsl.

The climate is semiarid with an average annual temperature of 29 °C, potential evapotranspiration of 2,500 mm $year^{-1}$, and annual rainfall of 560 mm (1943−2007, Niamey airport data). The rainy season extends from May through September but two thirds of the annual rainfall occurs in July and August. Rainfall is highly variable and irregular from year to year (Lebel et al. 1997). The natural vegetation of the region is a woody savannah mainly composed of *Acacia sp.* (e.g. *Acacia albida*), *Combretum sp.*, and *Balanites sp.* Rain-fed crops (mainly millet fields) have replaced the indigenous vegetation in the suburbs; however, *Acacia albida* is often protected for

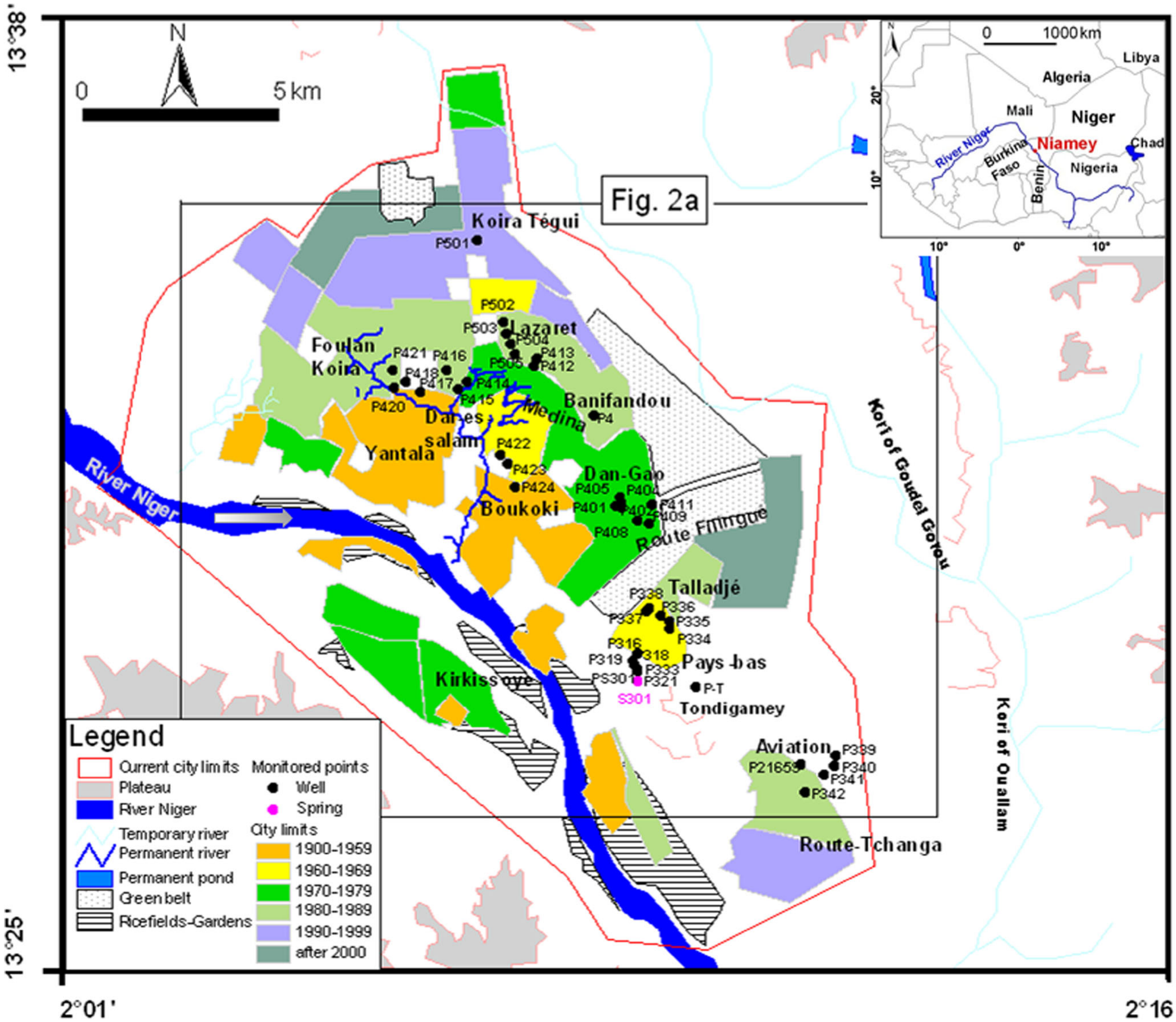


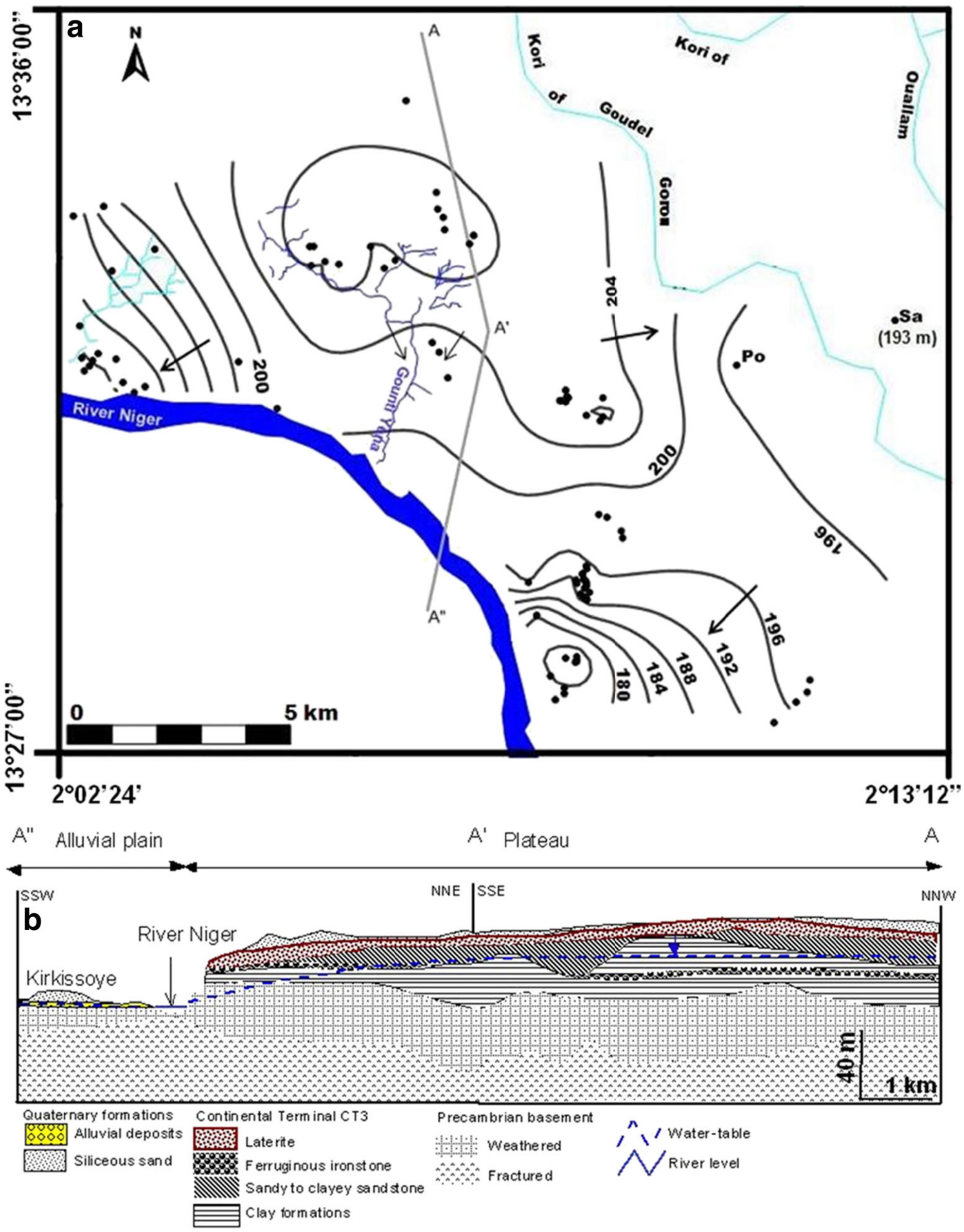
Fig. 1 Study area with sampling points and historical development of the city of Niamey over one century (from 1900s to 2000s; adapted from JICA 2001)

its soil fertilizing properties. The landscape is now a patchwork of fallow and millet fields. Rice fields and gardens are planted along the Niger River. Deep *Eucalyptus sp*. trees, well-known phreatophytes, are planted with *Azadirachta indica* for reforestation campaigns, particularly in areas named "green belts" (Fig. 1).

The Niger River is the only permanent river that drains the city; it flows from northwest to southeast at an elevation of approximately 180 m amsl in Niamey. The Niger River has many small temporary tributaries (locally called *kori*) flowing only during the rainy season, such as Kori of Ouallam and its tributary, Kori of Goudel Gorou (Fig. 2a). Gounti Yena in the city centre is presently a permanent stream mainly fed by the sewage network. The beds of the temporary rivers contain a series of ponds that persist for variable duration in the dry season. In the city of Niamey, increased areas of impervious surfaces associated with urbanization, in addition to low ground slopes and high runoff, create small depressions where rainfall accumulates during the rainy season leading to many ponds which also contain solid waste deposits.

The Niger River has always been the main source of water for Niamey. The urban water supply network officially serves about 65 % of the city residents (Niger PRSP 2008), mostly in the city centre. This supply network is partial or even absent in suburban areas, where groundwater becomes the main source of water, particularly during the dry season due to the increased demand, daily network interruptions lasting for hours, and relatively low cost (Hassane 2010; Hungerford 2012). According to Collignon (1994), groundwater accounted for only 12 % of Niamey's water supply. This estimate was

Fig. 2 **a** Seasonal low water level (March–May 2004) potentiometric map of the city of Niamey (at the north bank of the Niger River; water-table contours in metres above sea level). "Poste police" (*Po*) and "Sagagorou" (*Sa*): wells from a long-term network surveyed by IRD; **b** schematic hydrogeological cross section (modified from Bechler-Carmaux 1998)



surprisingly low, as the city water supply network does not meet the demand. In the heart of the decades of Sahel drought, the complete cessation of the Niger River flow in 1985 led to the drilling of 120 boreholes into the fractured basement to ensure the city water supply (Bernert et al. 1985; Dehays et al. 1986), demonstrating that groundwater is a valuable source for drought impact mitigation. Most hydrogeological studies are from this period or later (Girard 1993; Hassane 2010).

The city of Niamey is at the contact between the Liptako Precambrian basement (mainly granites, schists, and gneisses) outcropping to the west and the first layers of the Iullemmeden sedimentary basin to the east. Figure 2b shows a hydrogeological cross section through the city of Niamey. The Precambrian basement is overlain by a clayey formation that probably continues as a thick layer to the east and north but is not confirmed through drilling. The clayey formation is very thin and even absent near the CT scarp. The CT, which is the upper part of the Iullemmeden sedimentary basin, is composed of primarily sandy to clayey sandstones. Further to the east and north, the CT layers rapidly get thicker and three different aquifers are well identified: two confined aquifers (CT1 and CT2 aquifers) topped by an unconfined aquifer (CT3 aquifer). In Niamey, where they pinch out over the basement, only the unconfined aquifer is present and is mainly composed of clayey to silty sandstones locally interbedded with discontinuous oolithes and clay lenses and overlain by laterites. The CT unconfined aquifer becomes thinner near the Niger River valley with greater hydraulic gradients (1–5 %) and has permanent springs at the contact with hard-rocks (Hassane 2010). During the Holocene succession of dry and humid periods in the region, the area was covered with alternating colluvium and aeolian deposits.

In the study area (the Niamey Plateau and its surroundings), both the CT and the underlying basement store groundwater but the present paper will mainly consider groundwater in the CT unconfined aquifer. Because of shallow drilling depths and easy digging conditions, the CT unconfined aquifer is exploited by the population via numerous wells, particularly in suburban areas. The CT unconfined aquifer has been extensively studied since the beginning of the 1990s in the rural area east of Niamey (cf. the review by Favreau et al. 2009). Transmissivity in two CT wells located in the city is around 2×10^{-4} m^2 s^{-1}; transmissivities from pumping tests in boreholes and wells located east of Niamey range between 6×10^{-5} and 1×10^{-2} m^2 s^{-1} with a median value of 4×10^{-4} m^2 s^{-1} (estimated from a correlation equation between transmissivities and specific flow rates; Favreau 2000).

The lack of a sanitation system for wastewater is considered the major factor contributing to groundwater pollution in the area. According to JICA (2001), only one quarter of houses have a modern toilet and two thirds have a latrine. Other inhabitants discharge human wastes directly to the Niger River or unoccupied areas. Wastewaters are mostly discharged directly on the ground, or in individual septic tanks, wells, and simple pits. Solid wastes are also directly deposited on the ground, in holes, and used as fertilizer for gardens. Rivers and ponds are another frequent solution for waste discharge. Many old wells are transformed to pit latrines mainly in the city centre, some of which are located near in-use wells (distance between well and pit latrine may be less than 10 m). The depth of pit latrines usually reaches 4−5 m and is locally close to the water-table. Moreover, public squares and green belts are transformed into unsewered informal settlements with uncontrolled waste disposal. Contaminants from such sources of pollution are dissolved by seasonal variations of groundwater levels and transferred to aquifers by recharge.

Previous studies in the city focused on groundwater of the fractured Precambrian basement to determine recharge processes (Girard et al. 1997) and the source of nitrate pollution (Girard and Hillaire-Marcel 1997). Results from isotopic analyses of water (^{2}H, ^{18}O, ^{3}H) showed that 'recent' recharge occurs and aquifers are mainly recharged by waters marked by evaporation in the plain area and by meteoric water in the plateau area (Girard 1993; Girard et al. 1997). The groundwater quality deterioration by substantial increases in nitrate concentrations, is attributed to unregulated urbanization (latrines) and deforestation (Girard and Hillaire-Marcel 1997).

Data and methods

Groundwater levels

To evaluate the seasonal variability, groundwater levels were measured in 43 wells on a monthly basis from March 2004 to February 2005 (Figs. 1 and 2a). They all are traditional hand-dug wells (without cementation) that reached only the upper part of the CT saturated zone. The height of standing water in the wells is small (<0.1–6 m). Two other CT wells east of Niamey—Poste police (Po) and Sagagorou (Sa)—were added; they are part of a long-term network surveyed by the Institut de Recherche pour le Développement (IRD; see Lebel et al. 2009 for more details). Twenty-seven wells tapping the Quaternary alluvial and the Precambrian basement aquifers (Hassane 2010) were also included in the monthly survey.

In the study area, groundwater pumping is very weak in the city centre (less than 1 m^3 per day per well) because of the wide urban water supply network and the limited other abstraction needs. However, wells in suburbs are much more exploited, being the main source of water: the domestic demand was estimated at about 20 or 25 L per inhabitant per day (Chene 1984; Bechler-Carmaux 1998). Perturbation of the groundwater level by pumping is then spatially variable, but rather constant throughout the year.

Groundwater geochemistry

Temperature, electrical conductivity (EC) and pH were measured monthly in the wells previously mentioned, simultaneously with groundwater levels. Temperature, EC, and pH were measured in the field on water sampled with a bailer, using a WTW probe with respective uncertainties of 0.1 °C and 1 μS cm^{-1} and a Hanna pH-meter with an uncertainty of 0.01. Groundwater was sampled in 34 wells and one spring (Fig. 1) in four campaigns: June 2004 (beginning of the rainy season); January 2005 (middle of the dry season); August 2005 (middle of the rainy season); and November 2005 (beginning of the dry season), i.e. a total of 84 CT samples for major ion analyses—Table S1 of the electronic supplementary material (ESM). All samples were filtered directly in the field using a Nalgene filtration unit in polysulfone (PSF; 0.45 μm), stored in high-density polyethylene bottles of 125 ml, and kept at 4 °C. Analyses were performed by the University of Montpellier, France. Major ions were determined by ion chromatography and alkalinity was determined using acid titration. Samples were always re-analysed when the ionic imbalance was more than 5 %. Ionic balance errors range from −11 to 7 % (standard deviation, SD=4 %). Among all samples, 83 % had an ionic imbalance smaller than ±5 %, and only one had an error of 11 % (Table S1 of the ESM).

Favreau et al. (2000) discussed the reliability and representativeness of measurements in traditional wells penetrating the

CT unconfined aquifer. In spite of their large diameter, geochemistry of well's water (EC, major ions) is generally not modified, or almost not, by dust contamination or organic matter falling into the well. However, in order to reduce errors linked to groundwater samples in such wells, samples for the present study were systematically taken in in-use wells, regularly pumped for domestic purposes.

Chemical data were explored with Principal Component Analysis (PCA) using the Microsoft EXCEL add-in XLSTAT. The PCA used electrical conductivity, pH, and major ions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-}, Cl^{-}, NO_3^{-}, SO_4^{2-}) as variables.

Recharge estimation

A preliminary estimate of groundwater recharge is based on groundwater level time series by using the water-table fluctuation (WTF) methods that have been widely applied because of their simplicity (e.g. Healy and Cook 2002; Jie et al. 2011; Cuthbert 2014; Dean et al. 2015). However, their simplicity (insensitivity to the mechanism by which water moves through the unsaturated zone and use of directly measurable data) comes together with strong limitations (Healy and Cook 2002) including: (1) the assumption of an exclusive link between groundwater rise and vertical infiltration; (2) the difficulty in identifying the cause of the groundwater level fluctuations and calculating the specific yield value; and (3) the question of applicability of water level data from a given well in a heterogeneous aquifer to the whole catchment. Recharge is the sum of the observed rise of the groundwater level (or actual groundwater rise), and the potential groundwater decline which would have occurred in case of no recharge over the same time period. This second member is difficult to estimate and was discussed in recent studies on improving the WTF method (e.g. Jie et al. 2011; Cuthbert 2014; Dean et al. 2015). The potential groundwater level decline, mainly due to drainage into rivers, is expressed as an extrapolated recession curve (Delin et al. 2007). The estimated recharge is calculated from

$$R = Sy\frac{\Delta h}{\Delta t} \qquad (1)$$

where R is recharge rate ($L\,T^{-1}$), Sy is specific yield (%, porosity parameter), Δh is the peak water-table rise attributed to the recharge period, and Δt is the recharge period (Healy and Cook 2002).

Two approaches are used to calculate Δh in the WTF methods: (1) graphical extrapolation and (2) calculation from a master recession curve (MRC) where the potential groundwater level decline is respectively, extrapolated manually and by regression functions to coincide with the peak of the next recharge event (Delin et al. 2007; Heppner et al. 2007). A third approach used to estimate Δh is the RISE program approach (a computer code developed by A. Rutledge, U. S. Geological Survey, in 2005) which simply assumes that in the absence of recharge, no decline in the water-table occurs (Rutledge 1998; Jie et al. 2011); the potential groundwater rise (Δh) is then equal to the absolute rise in groundwater level. More subjective and empirical than the other WTF methods, the graphical approach is limited to small data sets. Because a potential groundwater-level decline would occur in the absence of recharge, the RISE approach may underestimate recharge. The MRC and RISE approaches require daily water level data. In the present case, recharge is estimated using the water-table rise WTR approach with data acquired monthly, similar to the RISE approach.

Results and discussion

Hydrodynamics

Groundwater flow pattern

The depth to the water-table varied from less than 5 m to about 26 m. The water-table map of the "Niamey aquifers" (i.e. in the city limits) using the seasonal low water-table measurements (March–May) in the basement, alterites and CT has no uniform regional direction of flow (Fig. 2a). Instead, there are several local flow systems driven by topographic gradients. Groundwater is drained by topographic depressions such as the Niger River and much smaller valleys (Gounti Yena, Kori of Ouallam and its tributary the Goudel Gorou). There is a groundwater divide on the highest topographic areas in the city centre from which groundwater flows eastward towards the Kori of Ouallam, and southward towards the Niger River. A potentiometric dome (208−210 m) appears to the northwest, upstream of the Gounti Yena. Hydraulic gradients are small to the east of the groundwater divide, in the direction of the Kori of Ouallam (0.1–0.2 %), and increase in the direction of the Niger River (1–5 %) at the south where the water-table discharges as springs at the border of the CT aquifer and drops into the underlying Precambrian basement aquifers. This water-table configuration is comparable to the seasonal high water level (September−October) potentiometric map (Hassane 2010).

Seasonal variability

In 2004−2005, the groundwater level seasonal variability was between 0.1 and 1.7 m in all wells, indicating recharge all over the study area during the rainy season, mainly by focused recharge. The degree of seasonal variability and the time required for the water-table to rise display the same spatial pattern. In most locations, the water-table rises 3 or 4 months after the beginning of the rainy season, which is consistent with the low permeability of the aquifer (clays and silts overlain by laterites) and the depth to the water-table (Fig. 3). The water-table reaches a maximum in September–October (end of the rainy season) and begins to decrease in October–November (beginning of the dry season) until its lowest level in April. The groundwater seasonal rises are higher (1.1−1.7 m) near the groundwater divide and in the potentiometric dome where water-table depths are less than 15 m (e.g. P415 in Fig. 3). In these areas a water-table rise occurred in response to the exceptional (in intensity and date) rainfall event of 29 April 2004 (129 mm, 20 % of the annual rainfall); but this early water-table rise was sustained only upstream along the Gounti Yena River in the potentiometric dome (shallowest wells) where the water-table lies in sand, oolithe, and silt formations and may be driven by both diffuse and focused recharge processes. Water-table rises are smaller when the water-table depths are greater than 15 m (e.g. P334 in Fig. 3) even when surface elevations and the number of surface ponds are the same. Low water-table rises of 0.1−0.4 m also occur in areas located near the CT scarp where the aquifer is thin even though water-table depths are less than 15 m. This is presumably due to the steep topographic gradient (Fig. 2b).

Estimating recharge from the 2004–2005 monitoring in CT wells is challenging because of the superposition of several processes affecting groundwater levels in space and time, one of which concerns the effect on unsaturated zone transit time of diffuse versus focused infiltration in depressions or via preferential pathways. For instance, the presence of ponds recharging the groundwater may explain some smooth groundwater level declines, whose non-exponential decay excludes the application of the graphical and MRC methods. A second issue concerns the heterogeneity of groundwater hydrodynamic properties in the CT aquifer. Third, boundary

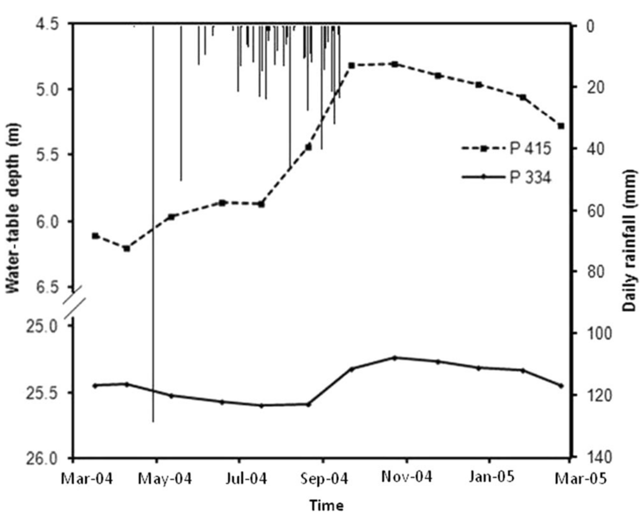


Fig. 3 Seasonal water-table variations with rainfall events (March 2004–February 2005). The first rainfall event of 2004 induced a water-table rise in shallow wells (e.g. *P415*) but had no visible impact on deeper wells (e.g. *P334*)

conditions imposed by the Niger River valley and its temporary tributaries draining the CT aquifer affect 39 wells located at Route Filingue, Pays-bas, Dar es Salam, Route Tchanga, Talladjé (Figs. 1 and 2a). Fourth, the limited frequency of monthly potentiometric measurements may lead to large uncertainties. Finally, there may be vertical fluxes by evapotranspiration, pumping and potentially by exchanges with the underlying semi-confined Precambrian basement aquifer through a semi-pervious layer. This last phenomenon was proposed from chemical data (Hassane 2010), even though pumping tests and chemical data did not show any hydraulic connection in some areas (e.g. Dan-Gao in the city centre where the two aquifers are separated by 36 m of clay). In four wells (P401, P402, P404, P405) near the groundwater divide (Dan-Gao; Figs. 1 and 2a), the absence of vertical leakage is clearly visible in steep and straight recession curves. As a result of these five factors the recharge calculations derived from this study must therefore be taken as a first step.

Interannual variability

Water level data of 10 wells from the 2001 monitoring (Ousmane et al. 2006) at Dan-Gao and Pays-bas were compared with the present study. Apart from the seasonal fluctuations, there is no interannual trend over 5 years, which significantly differs from the long-term rise in the rural surroundings (Leduc et al. 2001; Favreau et al. 2009).

Recharge estimate

To apply the WTF method, groundwater level data from 29 wells, mainly located in the suburbs, were excluded because of perturbations by pumping. Level fluctuations from only 14 wells were undoubtedly attributed to rainfall, and were then used to calculate recharge. They are located at Pays-bas (P316 and P333), Talladjé (P334), Route Tchanga (P339), Dan-Gao (P401, P402, P404), Route Filingue (P408 and P411), and Dar-es-Salam (P414, P415, P416, P418, and P420; Fig. 1) and can be considered as representative of the whole area.

The specific yield and the effective porosity were not directly measured in the study site. In the CT aquifer, east of Niamey, magnetic resonance sounding (MRS) gave water contents between 5 and 23 %, with a mean value of 13 % (Boucher et al. 2009). According to Lubczynski and Roy (2005), the MRS-estimated water content is generally a good approximation of the effective porosity. In Boucher et al. (2009) the MRS water contents (θ_{MRS}) were always higher than pumping test specific yield values. Thus, specific yield (Sy_{MRS}) was calculated between 0.1 and 9 % (mean and median of 3 and 2 %, respectively) from a new model assuming that Sy mainly depends on the median grain size. This range of low values may be surprising, even in silty sandstones, but they are in agreement with the few long duration pumping tests performed in the rural surroundings. A direct application of *Sy* values to the urban area is then assumed.

Recharge rates from the 14 wells calculated with the water table rise WTR approach vary between 4 mm year^{-1} (1 % of the 2004 annual rainfall of 645 mm) near the CT scarp and 50 mm year^{-1} (8 %) near the groundwater divide with median and average rates of respectively 41 mm year^{-1} and 32 mm year^{-1} (6 and 5 %). This probably underestimates actual recharge because it uses the raw rise, without considering a possible natural groundwater decline, and because monthly measurements reduce the total amplitude (up to 50 % in the example by Delin et al. 2007).

For a mean water-table rise of 1.2 m year^{-1} (obtained by averaging $\Delta h = h_{max} - h_{min}$ for all monthly monitored wells), the estimated recharge rate would be 36 mm year^{-1} in 2004. A large-scale estimate of net recharge in the rural surroundings gave 16 mm year^{-1} for the same year 2004 (see Fig. 11 in Favreau et al. 2009).

Hydrochemical changes

Groundwater chemistry

The groundwater temperature ranges from 26.7 to 33 °C and pH from 3.7 to 7.1. The EC is low with large spatial variability (median of 107 µS cm^{-1}, range: 36–1,617 µS cm^{-1}). Using Principal Component Analysis (PCA) three groups were identified (Fig. 4a,b). Factor axis F1 accounts for 62 % of the total variance and is positively correlated to EC, Ca^{2+}, Mg^{2+}, Na^+, NO_3^-, and Cl^-. F2 explains 21 % of the total variance and is closely related to pH and HCO_3^-. Group 1 (23 wells and 1 spring; 57 samples) is composed of low EC waters (median of 87 µS cm^{-1}; range: 36–340 µS cm^{-1}) with low pH (median of 5.9, range: 5.1–7.0). Group 2 (two wells, five samples) has moderate EC (range: 636–1,338 µS cm^{-1}) with low pH (~6 for all samples). Group 3 is composed of two groups of wells (10 wells; 22 samples) which deviate from the F1 axis, one with high NO_3^-, and the other with high HCO_3^-. This group has high EC (median of 904 µS cm^{-1}; range: 321–1,617 µS cm^{-1}), the lowest pH values (median of 5.1, range: 3.7–7.1), and the highest nitrate content (up to 112 mg L^{-1} NO_3–N; 8 meq L^{-1}). All sampled points remain seasonally in the same group except well P333, which moved from group 1 to group 3. These groups form a geographical pattern (Fig. 5). Group 1 is in suburban areas, recently urbanized. In addition, all deeper wells belong to this group. Groups 2 and 3 are located, respectively, upstream along the Gounti Yena River, and in the oldest part of the city centre (urbanization older than 20 years, high concentration of latrines and waste materials). These groups are composed of shallow wells (water-table depths <15 m).

In the Piper diagram (Fig. 6), the old city centre groundwater (groups 2 and 3) is Na–NO_3 water type and has the highest EC, while the suburbs (group 1) are much more variable with three different facies (Ca–HCO_3, Ca–NO_3, and Na–NO_3 water types) and low EC. Groundwater nitrate concentrations range between 0 and 112 mg L^{-1} NO_3–N (8 meq L^{-1}). They are permanently high in the city centre (groups 2 and 3; e.g. Dan-Gao, Boukoki, Route Filingué, Dar-es-Salam) where urbanization was established over 20 years ago, reaching 23 −112 mg L^{-1} NO_3–N (1.7–8 meq L^{-1}), and exceeding the international guidelines for drinking-water quality (10 mg L^{-1} NO_3–N; 0.72 meq L^{-1}) in all sampled wells, whereas in the suburbs (group 1) only two wells (P420 at Foulan Koira, and P333 at Pays-bas; Fig. 1) sporadically exceed this limit. In these areas, nitrate contents range between 0 and 23 mg L^{-1} NO_3–N (0–1.7 meq L^{-1}). Globally, more than 36 % of the samples have nitrate contents higher than the WHO standard for drinking water. Na^+ and NO_3^- are the main ions in the contaminated groundwater.

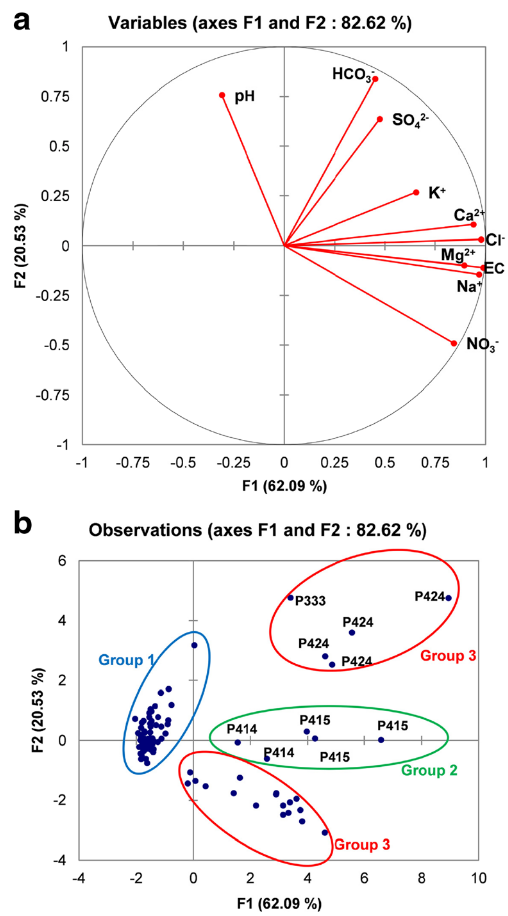


Fig. 4 Principal Component Analysis (PCA) of groundwater chemical data: **a** Correlation between the different analyzed variables and the two first axes of the PCA; **b** Projection according to the two first axes of the PCA (83 % of the covariance)

Variation in groundwater electrical conductivity

There is a clear structuring of EC and depth to the water-table (Fig. 7). The deepest wells (15–30 m) have relatively low EC

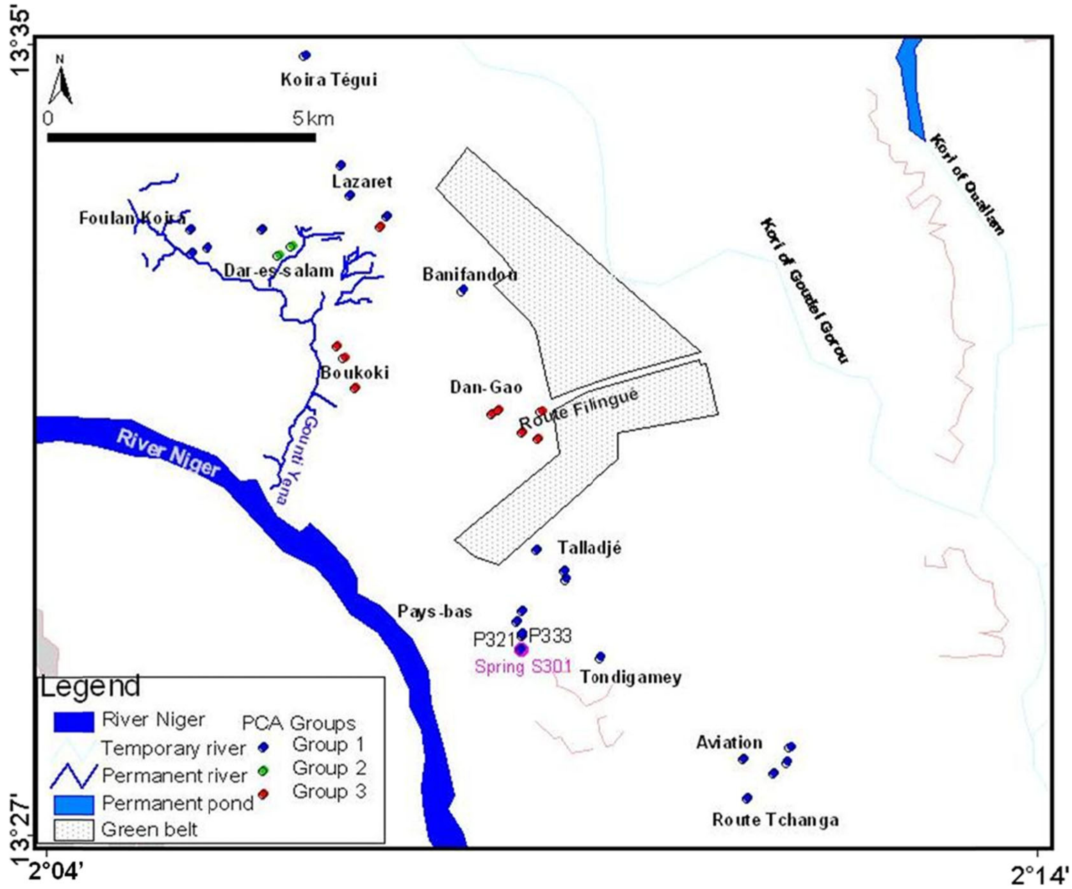


Fig. 5 Location of PCA groups

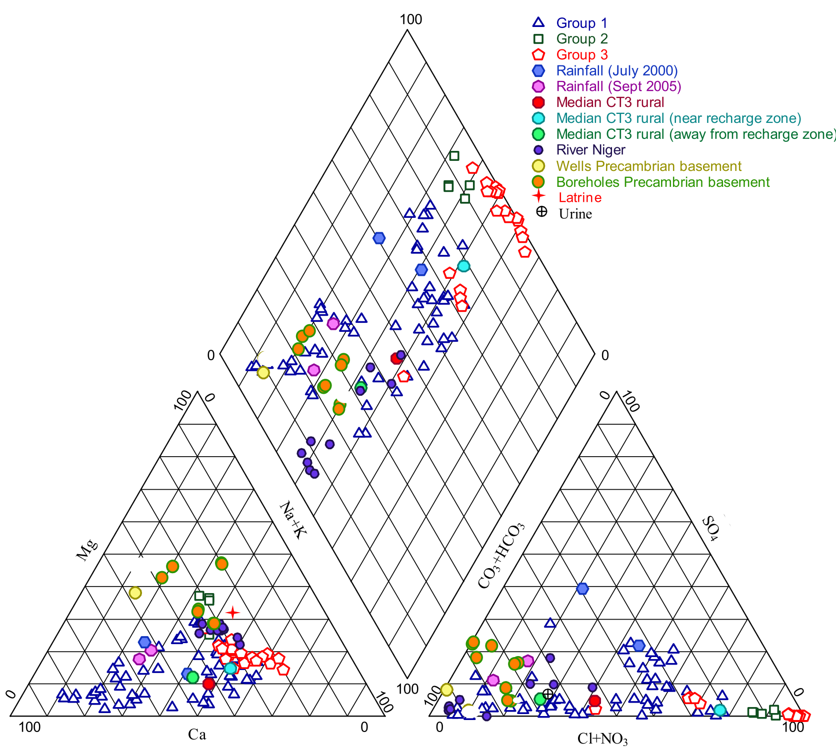


Fig. 6 Piper diagram for groundwaters in urban and rural areas, surface waters, latrines, and rainfall. Niger River data and July 2000 rainwater data from Elbaz-Poulichet (Centre National de Recherche Scientifique-Hydrosciences Montpellier, personal communication 2000)

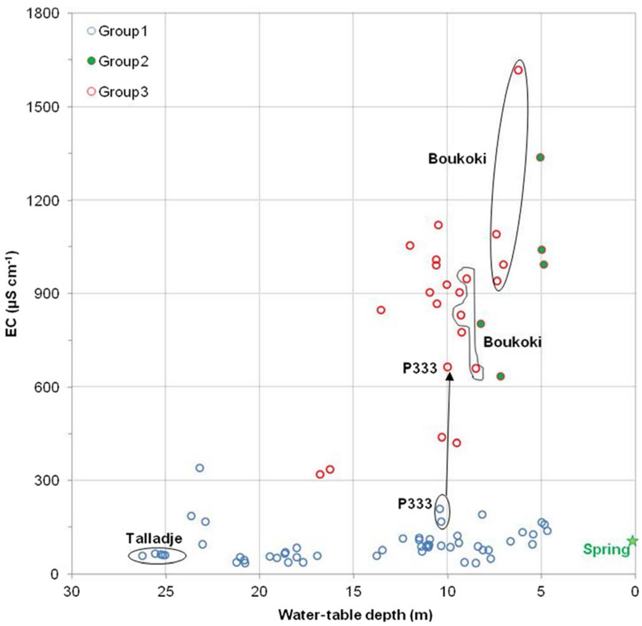


Fig. 7 Relationship between electrical conductivity and water-table depth. *Boukoki* is within the oldest urbanized part (over one century and over 40 years old for, respectively, the upper and lower parts of the groupings). All samples belong to *group 3* (3 wells, 7 samples). Well *P333*, the only well that moved from group 1 to group 3, is located in the suburb settlement of Pays-bas. *Talladje* has the deepest wells

(36–340 µS cm^{-1}), whereas shallow wells (5–15 m) show high and variable EC values (36–1617 µS cm^{-1}). For shallow wells in groups 2 and 3 located in the city centre, the small water-table rise following the heavy rainfall of 29 April, 2004 is associated with an increase in EC at the beginning of the rainy season (Fig. 8a), suggesting that recharge waters at the start of the rainy season have high EC in these locations. In arid and semiarid areas, a prolonged dry season accumulates salts at the soil surface and in the unsaturated zone due to high evapotranspiration rates (Massuel et al. 2006). These salts are leached to groundwater by the new recharge flux each year, which usually explains the high increase in EC at the beginning of the rainy season. Later, in the middle of the rainy season, the significant rise of water-table associated with a decrease in EC reflects the massive input of low EC recharge water, closer to rainfall mineralization. In two wells (P411 at Route Filingue and P415 at Dar-es-Salam in Fig. 1), the increase of both EC and water-table are concomitant and sustained (e.g. P415 in Fig. 8b). In these wells recharge waters have high EC throughout the rainy season. The 1-month time lag between the rise of water-table and EC indicates that leaching and vertical transport of solute takes more time than the rainwater infiltration. During the dry season, EC increases in all wells as the water-table drops. The seasonal EC increase is linked to increases in the anions NO_3^-, and Cl^-, and cations Ca^{2+}, Mg^{2+}, Na^+. In suburban areas (group 1), no significant seasonal variation in EC was observed. However, variations are evident in waters sampled near contaminant sources. For example, well P333 in the suburb settlement of Pays-bas exhibited significant seasonal increases in ion concentrations (Fig. 7): HCO_3^- concentration increases from 18 % at the beginning of the rainy season (June 2004) to 54 % of the total anions after the rainy season (November 2005), whereas (Cl^- + NO_3^-) concentration decreases from 78 to 45 % of the total anions.

Electrical conductivity, water level and chemical data collected in 2000 (T. Margueron, Centre de Recherche Médicale et Sanitaire-CERMES, unpublished data, 2000) and 2001 (Ousmane et al. 2006) are used together with the present data to evaluate the interannual variability of groundwater quality from 2000 to 2005. No interannual variation in groundwater EC was observed (Fig. 8a). Only well P401 shows an interannual increase in nitrate content (Fig. 9). This well belongs to group 3 and is located at Dan-Gao (Figs. 1 and 5). In comparison, the suburb well P333 located at Pays-bas, which seasonally moved from group 1 to group 3 due to a high increase in HCO_3^- content and relatively high NO_3^- content, shows no interannual increase in nitrate content (Fig. 9). Nitrate concentration increases by a factor close to 5 over 5 years in well P401. It is worth noting that nitrate shows little or no change in well P404 (Table S1 of the ESM) located only a few metres from well P401 and which has the same water-table depth (~10 m; Fig. 8a).

These results are comparable to the findings for the rural area where shallow wells (10–20 m deep) near recharge areas show seasonal EC fluctuations linked with high nitrate concentrations (Elbaz-Poulichet et al. 2002) and either no long-term trend or small increases (1991–1999; Favreau 2000). Most of the wells with nitrate content higher than the international guidelines for drinking-water quality of 10 mg L^{-1} NO_3–N were found in the valley bottoms and near ponds. This high nitrate concentration is linked to the nitrogen leaching from the soil due to land clearing. The sources of nitrate in the area are atmospheric deposition (high nitrogen content in rain; Galy-Lacaux and Modi 1998) and biological fixation of nitrogen in soils by native vegetation.

Impacts of urbanization on groundwater quantity

The rural area around Niamey provides a reference for comparison with the city groundwater dynamics because the topographic and geological conditions before urbanization are similar. A long-term increase in the CT3 water-table was identified in the entire region around Niamey as a consequence of changes in land-use and land cover (Leduc et al. 2001; Favreau et al. 2002). This phenomenon started at least 50 years ago and is still going on (Favreau et al. 2009). The massive land use changes are the consequence of both extensive development of rain-fed agriculture (conversion of the native vegetation to cropland) and severe drought. The intense land clearing causes the formation of impervious clayey surface

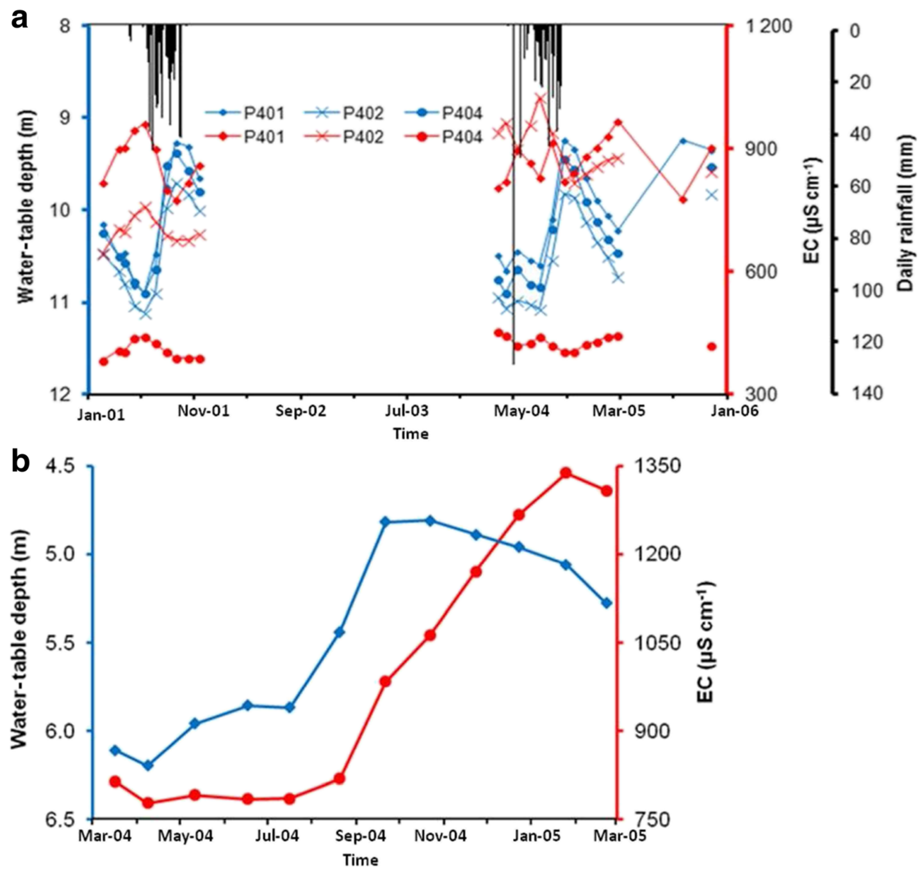


Fig. 8 Relationship between seasonal variations of water-table (*blue lines*) and electrical conductivity (*red lines*) in groups 2 and 3 wells: **a** Example of wells (*P401*, *P402*, and *P404*) with the general pattern (January 2001 −November 2005); **b** Example of well (*P415*) showing consecutive rise in EC and water-table near a solid waste deposit (March 2004–February 2005)

crusts on sandy soils; less permeable ground surfaces lead to larger runoff, and greater accumulation of runoff water in temporary ponds where it mainly infiltrates and recharges the CT3 aquifer. The average rate of water-table rise over more than 5, 000 km^2 was 0.20 m year^{-1} (0.01–0.45 m year^{-1}; Leduc et al. 2001) during the 1990s and 0.18 m year^{-1} (<0.1–0.4 m year^{-1}; Favreau et al. 2009) for the 1991−2007 period. These recent water-table rises are much higher than the recharge of few mm year^{-1} calculated for wetter periods (1950s and 1960s; Leduc et al. 2001; Favreau et al. 2002). The distance to the nearest pond is a major determinant for the seasonal fluctuation of the water-table, with up to 4–6 m in locations less than 50 m from a pond and almost no seasonal variation in very remote locations. North of Niamey, the presence of large fossil

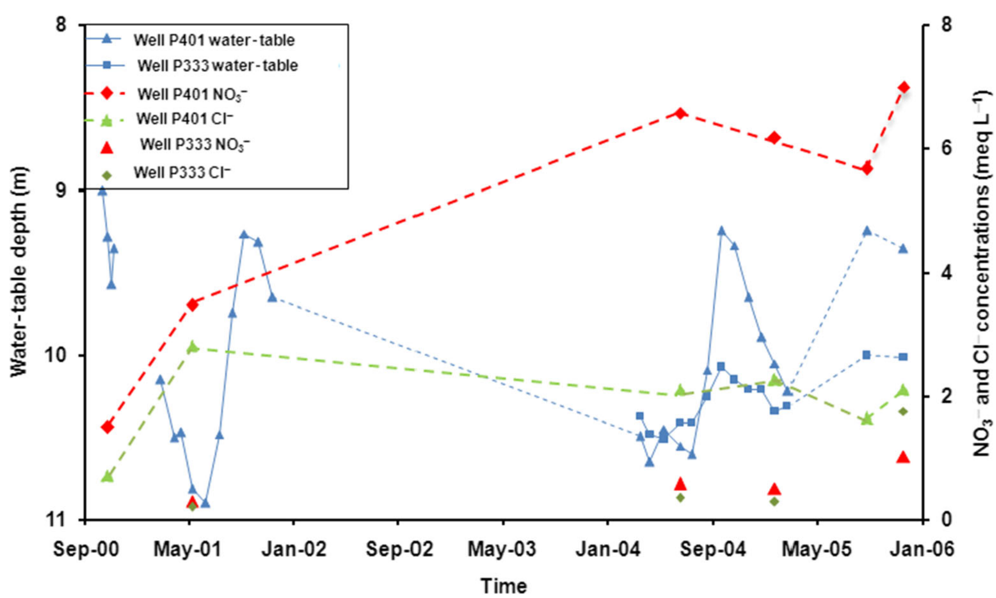


Fig. 9 Variations of water-table, nitrate and chloride concentrations over 5 years (December 2000−November 2005)

valleys with numerous temporary or nearly permanent ponds makes the surface and underground landscape a bit more heterogeneous. These processes are described and quantified in detail by Leduc et al. (2001) and Favreau et al. (2002, 2009).

Contrasting with the rural surroundings, the lack of inter-annual trend between 2000 and 2005 in Niamey does not mean that recharge is steady when urbanization increases. In fact, two specific features of the city of Niamey make its hydrogeology different from the rest of the CT area: (1) the presence of many small and big valleys creates a series of strong hydraulic constraints on the water-table (e.g. drainage boundaries—River Niger, Gounti Yena, and Kori of Ouallam—where groundwater discharges as baseflow; Fig. 2), limiting its possible variations; and (2) the rapid wedging out of the CT layers results in discharge to springs. Therefore, the apparent stability is not necessarily an artificial balance of higher recharge with higher pumping for domestic use. The long-term groundwater recharge increase observed in the rural area and recharge rates calculated for the year 2004 in the city (32 mm year^{-1}) and the rural area (16 mm year^{-1}) suggest that a long-term increase in groundwater recharge has probably also occurred in the urban area linked to urbanization processes. Urbanization and land clearing in rural areas induce similar increases in the groundwater recharge. As they increase impervious surfaces areas, the quantity of runoff reaching the topographic depressions increases, subsequently enhancing focused recharge and groundwater resources. By increasing runoff and concentrating it in highly permeable stream beds and post-urbanization depressions, urbanization increases recharge. In addition, as a result of urbanization the shallow aquifer recharge is supplemented by: (1) increased wastewater discharged directly into the soil and surface-water bodies; and (2) losses from the water supply network, estimated at 30−60 % in developing countries by Garcia-Fresca (2007), and not precisely known in the case of Niamey.

Impacts of urbanization on groundwater quality

Impacts of urbanization on groundwater chemistry were investigated by comparing chemical data from the city and the rural surroundings (Figs. 6 and 10). This shows that (1) the chemical composition of the groundwater in the old city centre (groups 2 and 3 waters) is highly enriched in NO_3^-, and Na^+, and (2) groundwater within the suburban areas (group 1 waters) reflects the same variability in water types (Ca–HCO_3, Ca–NO_3, and Na–NO_3) as groundwater in the rural area (Elbaz-Poulichet et al. 2002) where groundwater near recharge zones is Na–NO_3 dominant, while away from the recharge zones, groundwater is Ca–HCO_3 dominant (Favreau 2000). These results are consistent with changes in land use and land cover in the urban and rural areas, respectively. This trend towards nitrate enrichment after urbanization was noted in the region by Girard (1993) for the Precambrian basement aquifer of Niamey compared to nitrate content of the rural area (Ousmane 1988).

Piper diagram, scatter diagrams, and ionic ratios of chemical data from groundwaters, rainwaters, surface waters, and latrines (Table S2 of the ESM, Figs. 6 and 10) are used together to investigate major ion origins and processes affecting groundwater quality. Compared to the meteoric line of Niamey (Taupin et al. 1997; Fig. 10a,b), Na–Cl and NO_3–Cl in group 1 have a significant sodium and nitrate enrichment and a wider range of Na^+:Cl^- ratios (1−20) than the rainfall (1.67). Compared to groups 2 and 3, group 1 is depleted in Na^+ and NO_3^-; thus, group 1 reflects uncontaminated groundwater. Groups 2 and 3 are enriched in Na^+ and NO_3^- and have Na^+:Cl^- ratios close to rain and thus probably reflect a surface contribution (natural and anthropogenic inputs). (Ca^{2+} + Mg^{2+}) is correlated with HCO_3^- in the majority of group 1 waters, indicating possible congruent dissolution of calcite (Fig. 10d). These group 1 waters reflect therefore the natural composition of the aquifer. Ca^{2+} and Mg^{2+} come partly from atmospheric fallout (Saharan dust and rainfall; Elbaz-Poulichet et al. 2002) which have Ca, Mg, Na, and K-rich compounds (Galy-Lacaux and Modi 1998). In addition, Ca^{2+} and Mg^{2+} may also be released from upward leakage from the semi-confined Precambrian basement aquifer as shown by group 2 composition in cations which is significantly different from group 3 and close to the Precambrian basement groundwater composition (Hassane 2010) in the ternary diagram of cations (Fig. 6). Exchangeable cations (Na−Ca, Na−Mg) show high positive correlation suggesting that cation exchange processes on clay layers may be masked by the other processes which take place in the aquifer.

Effect of latrines

The median concentrations of nitrate in groups 2 (5.6 meq L^{-1}) and 3 (5.0 meq L^{-1}) are more than 20 times the median of group 1 (0.2 meq L^{-1}). The (Ca^{2+} + Mg^{2+}):HCO_3^- ratio shows an excess of alkali earths in groups 2 and 3 (Fig. 10d). Concentrations of (Ca^{2+} + Mg^{2+}) and NO_3^- are well correlated within each group when the HCO_3^- concentration relative to (Ca^{2+} + Mg^{2+}) is removed (Fig. 10e), showing that the excesses of alkali earths and nitrate come from the same sources. Moreover, strong positive correlations between NO_3^- and Na^+, Cl^-, Ca^{2+}, and Mg^{2+} (R^2=0.95, 0.86, 0.71, and 0.70, respectively) in the study area suggest that groundwater with high NO_3^-, Na^+, Cl^-, Ca^{2+}, and Mg^{2+} contents were recharged from the same sources. The concentrations of Ca^{2+} and Mg^{2+} in groups 2 and 3 are in the same ranges as the concentrations obtained in the latrines of the rural area, east of Niamey (G. Favreau, personal communication, 2002; Fig. 10f) suggesting that Ca^{2+}, Mg^{2+}, and NO_3^- are partly released from latrines in areas with groups 2 and 3 groundwater compositions.

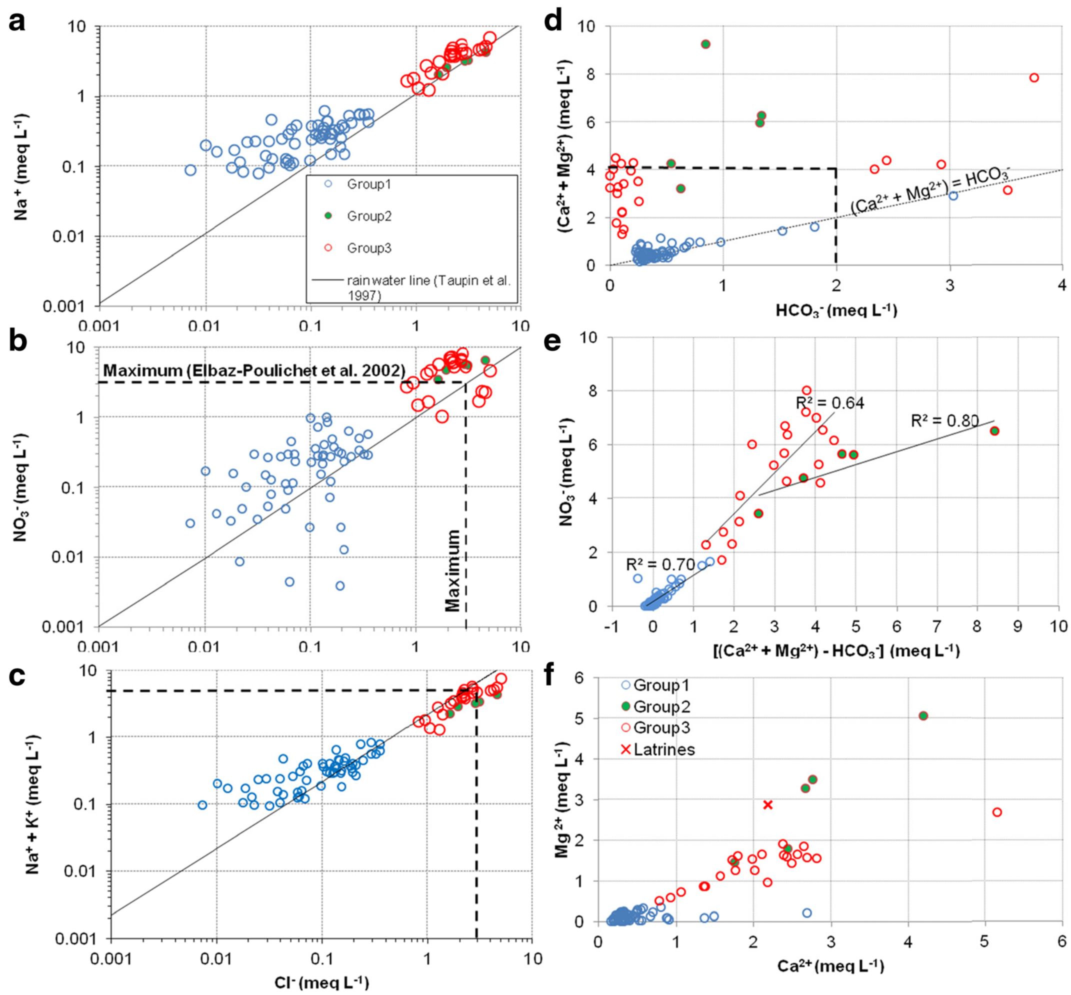


Fig. 10 Correlation diagrams between chloride content and **a** Na^+, **b** NO_3^-, and **c** $Na^+ + K^+$; **d** $(Ca^{2+} + Mg^{2+})$ versus HCO_3^- for groundwater samples; **e** Excess of $(Ca^{2+} + Mg^{2+})$ versus NO_3^- for groundwater samples; **f** Ca^{2+} versus Mg^{2+} in groundwater and latrine samples

Effect of solid wastes

A rapid rise in pH and EC are observed in well P333 (Fig. 11a, b). Well P333 is located at Pays-bas, 9 m away from a quarry filled with solid wastes. pH and EC rise when the water-table rises in the middle of the rainy season (August 2004; Fig. 11b), and drop at the end of the rainy season (September 2004), whereas the water-table keeps on rising. For comparison, the temporal evolution of EC in well P321 located 46 m from well P333 and 37 m from the quarry (Fig. 11a) is presented in Fig. 11c. The small fluctuation of EC during the rainy season indicates that the influence of the quarry is spatially limited, confirming the point source nature of the groundwater contamination. The solid waste degradation in the quarries may behave like a landfill in which organic matter degradation under reducing conditions results in a significant increase in pH as described by Jorstad et al. (2004). When methanogenic conditions are established during the waste stabilization process in an anaerobic environment, the CO_2 generated in the landfill is converted to HCO_3^- with a progressive increase in pH. These methanogenic conditions, beneath and immediately downstream the landfill, are also characterized by a NO_3^- reducing zone. These processes may increase HCO_3^- and pH of recharge waters leading to their increase in groundwater, and may deplete NO_3^- concentration in groundwater. They are hidden at the end of the rainy season by the massive input of low mineralized recharge water.

Effect of land clearing

The NO_3^-:Cl^- ratio (median of 2.1) is rather uniform (1.9, 2.0, and 2.6 respectively for groups 1, 2, and 3), suggesting that nitrate and chloride sources are common. These ratios are higher than the rainfall ratio (1.67). Group 1 appears to be enriched in nitrate relative to rain and ponds of the rural areas (median of 0.05 meq L^{-1}; Favreau 2000). Therefore, rainfall is not the only source of nitrate in group 1 groundwater. Massuel et al. (2006) highlighted a nitrate accumulation area in a sandy valley soil, which they attributed to nitrate from infiltrated

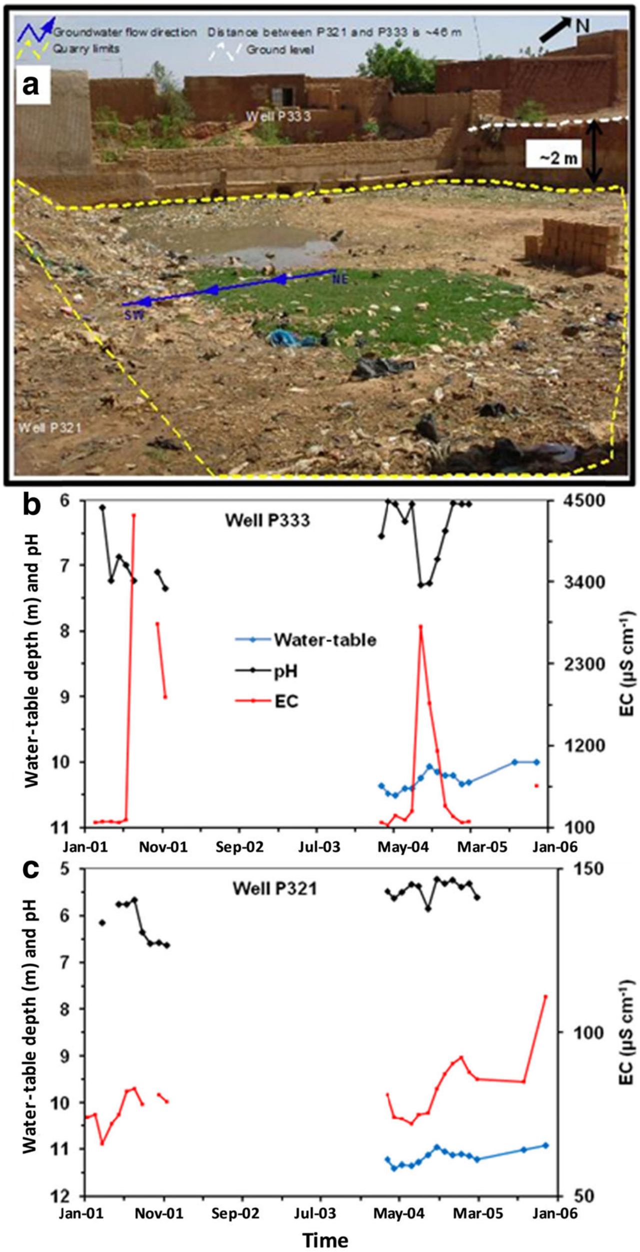


Fig. 11 **a** July 2004, former clay quarry filled by solid wastes in January 2001; **b**–**c** Temporal evolution of water-table, electrical conductivity, and pH (January 2001–November 2005) in **b** well P333 (Pays-bas) at 9 m away from the quarry; **c** well P321 at 46 m away from well P333

rainfall concentrated by evaporation, or accumulation of nitrate by perturbation of the nitrogen cycle following land clearance (Girard and Hillaire-Marcel 1997; Elbaz-Poulichet et al. 2002).

Variations in nitrate content and transformation of nitrogen compounds

In the rural area, nitrate concentration (between 0.56 and 40.26 mg L^{-1} NO_3–N) is always low (about 1 mg L^{-1} NO_3–N) in "natural" conditions and increases near ponds (median of 10 mg L^{-1} NO_3–N in 28 sites within a distance of 500 m to ponds), linked to land clearing and focused recharge (Elbaz-Poulichet et al. 2002; Favreau et al. 2009). The seasonal changes in nitrate concentrations indicate a leaching of nitrate naturally accumulated in the unsaturated zone by atmospheric deposition with high nitrogen content in rain (Galy-Lacaux and Modi 1998) and N fixation by native trees, as other sources (fertilizer, latrines in villages) are not significant.

In comparison, nitrate concentrations in this study range between 0 and 112 mg L^{-1} NO_3–N. The highest EC values are mainly linked to the highest nitrate values. The urban nitrate contamination can be explained by seasonal and inter-annual processes (Fig. 9). The nitrate content in well P401 was only 21 mg L^{-1} NO_3–N (1.50 meq L^{-1}) in October 2000, and rose to 48.74 mg L^{-1} NO_3–N (3.48 meq L^{-1}) in May 2001 (beginning of the rainy season). The exceptional rainfall event of 29 April, 2004 resulted in a groundwater nitrate peak of 92 mg L^{-1} NO_3–N (6.57 meq L^{-1}). Nitrate content was lower in the middle of the rainy season (79.7 mg L^{-1} NO_3–N; 5.69 meq L^{-1} in August 2005) when an inverse relationship between the groundwater level and EC occurred. This correlation suggests that nitrogen is leached from a common and permanent sub-surface soil source. The permanent high nitrate concentrations observed in this study also suggest that inter-annual increases in nitrate contents occurred in the past. The aquifer Eh values measured at the rural site show well oxygenated water (Eh between 300 and 500 mV and high dissolved O_2 values with saturations >50 %), indicating denitrification is not a significant sink for nitrate (Favreau et al. 2003, 2009). Correlation between nitrate and pH is weak and inverse ($r=-0.54$) in the study area. The correlation is higher ($r=-0.7$) for group 3 waters. The negative correlation between pH and nitrate suggests that the decrease of pH (acidification) is linked to an increase of nitrate concentrations (Fig. 12). The decrease of pH with the increase of both water-table depth and EC (Fig. 12a) suggests that nitrification (microbial oxidation of ammonium) takes place in the unsaturated zone during recharge. Ammonium probably originates from infiltration of urban wastes, mainly from pit latrines, in which urea and NH_4^+ prevail, and their later transformation in the unsaturated zone either by relatively fast hydration of urea or by slow mineralization of soil organic matter. Nitrification is described by the equation:

$$NH_4^+ + 2O_2 = NO_3^- + 2H^+ + H_2O \tag{2}$$

If nitrification is important in the area, nitrate concentrations will continue to increase, potentially inducing groundwater acidification in this poorly buffered sandy to clayey sandstone aquifer. In addition to the prevailing anthropogenic origin, nitrate may also come from the atmosphere (rainfall and dust) and the release of nitrogen fixed by mycorrhizas on

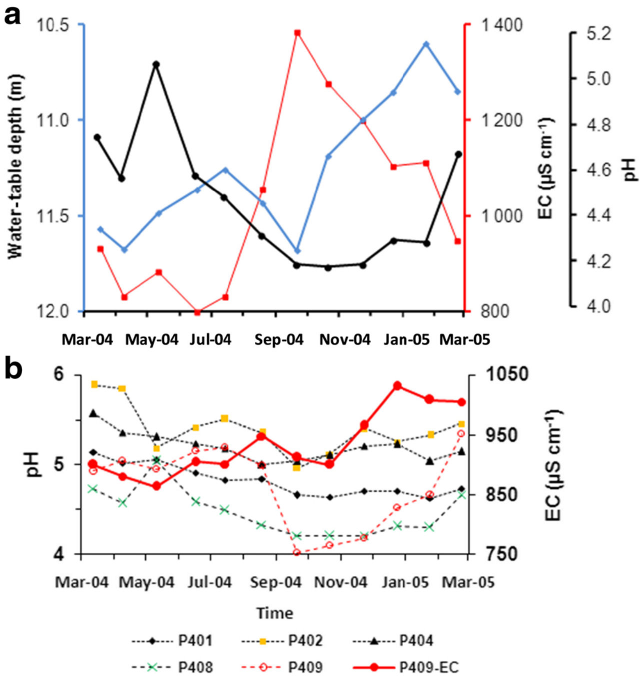


Fig. 12 pH variations (March 2004–February 2005): **a** temporal evolution of water-table (*blue line*), electrical conductivity (*red line*), and pH (*black line*) in well P408 at Dan-Gao; **b** temporal evolution of pH at Dan-Gao and Route Filingue (city centre, over 20 years old); well P409 electrical conductivity variation is plotted as a reference for EC variations in the area

roots of the native vegetation (surely less active in the urban area than in the rural surroundings).

Conclusions

This paper evaluates the impacts of urbanization on groundwater resources in a Sahelian environment and provides the first regular survey (over 3 years) of the CT aquifer in the urban area of Niamey. Recharge has increased in the urban area as a consequence of urbanization in parallel with the long-term groundwater recharge increase observed in the rural area due to land clearing. Processes increasing recharge in urban and rural areas are similar, and involve an increase of impervious surfaces, and then enhanced focused recharge. In addition, recharge in the urban area is supplemented by urban wastewater and losses from the water supply network. Urbanization also impacted groundwater quality by increasing seasonally and/or permanently nitrate concentrations, with current levels exceeding the WHO limit of 10 mg L^{-1} NO_3–N in 36 % of sampled wells, and up to 112 mg L^{-1} NO_3–N.

Urbanization in Niamey affects groundwater quantity and quality on the short- and long-term. Because the seasonal variability of groundwater flow has led to seasonal degradation of groundwater quality, the waste management practices of the city of Niamey need to be improved to protect the shallow groundwater resources. The results of this study can help to design future groundwater monitoring programs in this study area where long-term surveys are needed. The groundwater quantity and quality modifications driven by urbanization indicate the need to protect semiarid aquifers, especially shallow unconfined aquifers of Sub-Saharan African cities with the same sanitation problems, by better waste management practices and long-term groundwater surveys.

Acknowledgements The authors dedicate this paper to late Professor François Brissaud (Université Montpellier 2, France). This study was supported by the Agence Française de Développement (AFD) and IRD through, respectively, a research grant and a PhD fellowship to the first author. The authors thank the local residents for access to private wells, and their colleagues Abassa Alhassane, Abdoulaye Koné, Anne Laure Besnier, Maman Sani Babaye, Maimouna Ibrahim, and Sami Boubé for their contribution to the field campaigns. Thorough comments of Gary P. Curtis (U.S. Geological Survey, USA), Pibgnina Bazié (AGRHYMET Regional Centre at Niamey, Niger) and Todd Jarvis (Oregon State University, USA) before submission, and later remarks of the associate editor, Matthew Currell, and the two anonymous reviewers significantly helped to improve the manuscript.

References

Bechler-Carmaux N (1998) Les risques liés à l'eau dans une capitale sahélienne: pénurie et excès d'eau à Niamey (Niger) [Risks related to water in a Sahelian capital: water shortage and excess in Niamey (Niger)]. PhD Thesis, Univ Strasbourg I, France, 288 pp

Bernert G, Dehays H, Garin H, Zunino C (1985) Programme d'urgence pour le renforcement de l'alimentation en eau potable des quartiers périphériques de Niamey (Niger): exécution de 50 forages productifs [Emergency program to strengthen the supply of drinking water in suburban areas of the city of Niamey (Niger): execution of 50 productive boreholes]. Technical report BRGM/MHE, BRGM, Orléans, France, 52 pp

Biroue WK, Schneider JL (1993) Vers l'assèchement de la nappe phréatique au Sahel? [Towards the drying of the water-table aquifer in the Sahel?] C R Acad Sci Ser II 317:89–92

Boucher M, Favreau G, Vouillamoz J-M, Nazoumou Y, Legchenko A (2009) Estimating specific yield and transmissivity with magnetic resonance sounding in an unconfined sandstone aquifer (Niger). Hydrogeol J 17:1805–1815

Boulain N, Cappelaere B, Seguis L, Favreau G, Gignoux J (2009) Water balance and vegetation change in the Sahel: a case study at the watershed scale with an eco-hydrological model. J Arid Environ 73:1125–1135

Chene J (1984) Programme d'urgence pour le renforcement de l'alimentation en eau des quartiers de la périphérie de Niamey. Implantation de 50 forages [Emergency program to strengthen the supply of drinking water in suburban areas of the city of Niamey (Niger): execution of 50 productive boreholes]. Technical report BRGM, BRGM, Orléans, France, 17 pp

Cissé Faye S, Faye S, Wohnlich S, Gaye CB (2004) An assessment of the risk associated with urban development in the Thiaroye area (Senegal). Environ Geol 45:312–322

Collignon B (1994) Impact des activités humaines sur les ressources en eau souterraine en Afrique sahélienne et soudanienne [Impact of human activities on groundwater resources in Sahelian and Soudanian Africa]. In: Maire K (ed) Enregistreurs et indicateurs de l'évolution de l'environnement en zone tropicale [Recorders and

indicators of environmental changes in the tropics]. University of Bordeaux Press, Bordeaux, France
Collin ML, Melloul AJ (2003) Assessing groundwater vulnerability to pollution to promote sustainable urban and rural development. J Clean Prod 11:727–736
Cuthbert MO (2014) Straight thinking about groundwater recession. Water Resour Res 50:2407–2424
Dai A, Lamb PJ, Trenberth KE, Hulme M, Jones PD, Xie P (2004) The recent Sahel drought is real. Int J Climatol 24:1323–1331
Dean JF, Webb JA, Jacobsen GE, Chisari R, Dresel PE (2015) A groundwater recharge perspective on locating tree plantations within low-rainfall catchments to limit water resource losses. Hydrol Earth Syst Sci 19:1107–1123
Dehays H, Garin H, Zunino C (1986) Programme d'urgence pour le renforcement de l'alimentation en eau potable des quartiers périphériques de Niamey (Niger): deuxième phase—exécution de 68 forages [Emergency program to strengthen drinking water supply in suburban areas of the city of Niamey (Niger): second phase—execution of 68 boreholes]. Technical report BRGM/MHE, BRGM, Orléans, France, 30 pp
Delin GN, Healy RW, Lorenz DL, Nimmo JR (2007) Comparison of local- to regional-scale estimates of ground-water recharge in Minnesota, USA. J Hydrol 334:231–249
Deme I, Tandia AA, Faye A, Malou R, Dia I, Diallo MS, Sarr M (2006) Management of nitrate pollution of groundwater in African cities: the case of Dakar, Senegal. In: Xu Y, Usher BH (eds) Groundwater pollution in Africa. Balkema, Leiden, The Netherlands, pp 181–192
Desconnets JC, Taupin JD, Lebel T, Leduc C (1997) Hydrology of the Hapex-Sahel Central Super-Site: surface water drainage and aquifer recharge through the pool systems. J Hydrol 188–189:155–178
Diedhiou M, Cisse Faye S, Diouf OC, Faye S, Faye A, Re V, Wohnlich S, Wisotzky F, Schulte U, Maloszewski P (2012) Tracing groundwater nitrate sources in the Dakar suburban area: an isotopic multi-tracer approach. Hydrol Process 26:760–770
Drangert JO, Cronin AA (2004) Use and abuse of the urban groundwater resource: implications for a new management strategy. Hydrogeol J 12:94–102
Elbaz-Poulichet F, Favreau G, Leduc C, Seidel JL (2002) Major ion chemistry of groundwaters in the continental terminal water table of southwestern Niger (Africa). Appl Geochem 17:1343–1349
Favreau G (2000) Caractérisation et modélisation d'une nappe phréatique en hausse au Sahel: dynamique et géochimie de la dépression piézométrique naturelle du kori de Dantiandou (sud-ouest du Niger) [Characterization and modelling of a rising water table in the Sahel: dynamics and geochemistry of the Dantiandou kori natural piezometric depression (southwest Niger)]. PhD Thesis, Univ Paris XI, Orsay, France, 258 pp
Favreau G, Leduc C, Marlin C (2000) Reliability of geochemical and hydrodynamic sampling in a semi-arid water table. J Afr Earth Sci 31:669–678
Favreau G, Leduc C, Marlin C, Guero A (2002) Une dépression piézométrique en hausse au Sahel (Sud-Ouest du Niger) [A rising piezometric depression in the Sahel (southwestern Niger)]. C R Geosci 334:395–401
Favreau G, Leduc C, Seidel JL, Ousmane SD, Mariotti A (2003) Land clearance and nitrate-rich groundwater in a Sahelian aquifer, Niger. In: Servat E et al. (eds) Hydrology of the Mediterranean and Semiarid Regions, IAHS Publ. 278, IAHS, Wallingford, UK, pp 163–167
Favreau G, Cappelaere B, Massuel S, Leblanc M, Boucher M, Boulain N, Leduc C (2009) Land clearing, climate variability and water resources increase in semiarid southwest Niger: a review. Water Resour Res 45:W00A16
Favreau G, Nazoumou Y, Leblanc M, Guero A, Goni IB (2012) Groundwater resources increase in the Iullemmeden Basin, West Africa. In: Treidel H, Martin-Bordes JL, Gurdak JJ (eds) Climate change effects on groundwater resources: a global synthesis of findings and recommendations. International Contributions to Hydrogeology 27, CRC, Leiden, The Netherlands, pp 113–128
Foster SSD (2001) The interdependence of groundwater and urbanization in rapidly developing cities. Urban Water 3:185–192
Foster SSD, Chilton PJ (2004) Downstream of downtown: urban wastewater as groundwater recharge. Hydrogeol J 12:115–120
Foster SSD, Hirata R, Howard KWF (2011) Groundwater use in developing cities: policy issues arising from current trends. Hydrogeol J 19:271–274
Galy-Lacaux C, Modi A (1998) Precipitation chemistry in the Sahelian Savanna of Niger, Africa. J Atmos Chem 30:319–343
Garcia-Fresca B (2007) Urban-enhanced groundwater recharge: review and case study of Austin, Texas, USA. In: Howard KWF (ed) Urban groundwater: meeting the challenge, 32nd International Geological Congress (IGC), Florence, Italy, 2007, Balkema, Leiden, The Netherlands, pp 3−18
Girard P (1993) Techniques isotopiques (^{15}N, ^{18}O) appliquées à l'étude des nappes des altérites et du socle fracturé de l'Ouest Africain: l'Ouest du Niger [Isotopic techniques applied to groundwaters of alterites and fractured basement aquifers in West Africa: the Western Niger]. PhD Thesis, Univ of Quebec at Montreal, Canada, 141 pp
Girard P, Hillaire-Marcel C (1997) Determining the source of nitrate pollution in the Niger discontinuous aquifers using the natural ^{15}N/^{14}N ratios. J Hydrol 199:239–251
Girard P, Hillaire-Marcel C, Oga MS (1997) Determining the recharge mode of Sahelian aquifers using water isotopes. J Hydrol 197:189–202
Hassane AB (2010) Aquifères superficiels et profonds et pollution urbaine en Afrique: cas de la communauté urbaine de Niamey (Niger) [Shallow and deep aquifers and groundwater pollution in Africa: the case of the urban community of Niamey (Niger)]. PhD Thesis, Univ Abdou Moumouni, Niamey, Niger, 249 pp
Healy RW, Cook PG (2002) Using groundwater levels to estimate recharge. Hydrogeol J 10:91–109
Held IM, Delworth TL, Lu J, Findell KL, Knutson TR (2005) Simulation of Sahel drought in the 20th and 21st centuries. Proc Natl Acad Sci 102:17891–17892
Heppner CS, Nimmo JR, Folmar GJ, Gburek WJ, Risser DW (2007) Multiple-methods investigation of recharge at a humid region fractured rock site, Pennsylvania, USA. Hydrogeol J 15:915–927
Hibbs BJ, Sharp JM (2012) Hydrogeological impacts of urbanization. Environ Eng Geosci 18:3–24
Hoque MA, Hoque MM, Ahmed MK (2007) Declining groundwater level and aquifer dewatering in Dhaka metropolitan area, Bangladesh: causes and quantification. Hydrogeol J 15:1523–1534
Hoque MA, McArthur JM, Sikdar PK, Ball JD, Molla TN (2014) Tracing recharge to aquifers beneath an Asian megacity with Cl/Br and stable isotopes: the example of Dhaka, Bangladesh. Hydrogeol J 8:1549–1560
Hungerford HB (2012) Water, cities, and bodies: a relational understanding of Niamey, Niger. PhD Thesis, University of Kansas, USA, 210 pp
INS (2012) Annuaire statistique-démographie [Statistical demographic yearbook]. National Institute of Statistics of Niger, Niamey, Niger
JICA (2001) Etude sur l'amélioration de l'assainissement de la ville de Niamey [Study on improving the sanitation of the city of Niamey, vol 1]. Report, JICA, Tokyo
Jie Z, Heyden J, Bendel D, Barthel R (2011) Combination of soil-water balance models and water-table fluctuation methods for evaluation and improvement of groundwater recharge calculations. Hydrogeol J 19:1487–1502
Jorstad LB, Iankowsky J, Ackworth I (2004) Analysis of the distribution of inorganic constituents in a landfill leachate-contaminated aquifer Astrolabe Park, Sydney, Australia. Environ Geol 46:263–272

Kadjangaba E (2007) Etude hydrochimique et isotopique du système zone non saturée–nappe: impact de la pollution [Hydrochemistry and isotopic study of the unsaturated zone–groundwater system: impact of the pollution]. PhD Thesis, Univ d'Avignon et des Pays du Vaucluse, France, 193 pp

Kandji ST, Verchot L, Mackensen J (2006) Climate change and variability in the Sahel region: impacts and adaptation strategies in the agricultural sector. Report ICRAF/UNEP, UNEP, Nairobi, Kenya, 58 pp

L'Hôte Y, Mahé G, Some B, Triboulet JP (2002) Analysis of a Sahelian annual rainfall index from 1896 to 2000: the drought continues. Hydrol Sci J 47:563–572

Lebel T, Taupin JD, D'Amato N (1997) Rainfall monitoring during HAPEX-Sahel, 1: general rainfall conditions and climatology. J Hydrol 188–189:74–96

Lebel T, Cappelaere B, Galle S, Hanan N, Kergoat L, Levis S, Vieux B, Descroix L, Gosset M, Mougin E, Peugeot C, Seguis L (2009) AMMA-CATCH studies in the Sahelian region of West-Africa: an overview. J Hydrol 375:3–13

Leblanc M, Favreau G, Massuel S, Tweed S, Loireau M, Cappelaere B (2008) Land clearance and hydrological change in the Sahel: SW Niger. Global Planet Chang 61:135–150

Leduc C, Bromley J, Schroeter P (1997) Water table fluctuation and recharge in semi-arid climate: some results of the HAPEX-Sahel hydrodynamic survey (Niger). J Hydrol 188–189:123–138

Leduc C, Favreau G, Schroeter P (2001) Long-term rise in a Sahelian water-table: the Continental Terminal in south-west Niger. J Hydrol 243:43–54

Lerner DN (2002) Identifying and quantifying urban recharge: a review. Hydrogeol J 10:143–152

Lubczynski M, Roy J (2005) MRS contribution to hydrogeological system parametrization. Near Surf Geophys 3:131–139

Madioune DH, Faye F, Orban P, Brouyère S, Dassargues A, Mudry J, Stumpp C, Maloszewski P (2014) Application of isotopic tracers as a tool for understanding hydrodynamic behavior of the highly exploited Diass aquifer system (Senegal). J Hydrol 511:443–459

Massuel S, Favreau G, Descloitres M, Le Troquer Y, Albouy Y, Cappelaere B (2006) Deep infiltration trough a sandy alluvial fan in semiarid Niger inferred from electrical conductivity survey: vadose zone chemistry and hydrology modeling. Catena 67:105–118

Ngounou Ngatcha B, Djoret D (2010) Nitrate pollution in groundwater in two selected areas from Cameroon and Chad in the Lake Chad basin. Water Policy 12:722–733

Niger PRSP (2008) Accelerated development and poverty reduction strategy, 2008–2012. In: Combating poverty, a challenge for all. International Monetary Fund, Niamey, Niger

Ousmane B (1988) Etude géochimique et isotopique des aquifères du socle de la bande sahélienne du Niger (Liptako, Sud-Maradi et Zinder-est) [Geochemical and isotopic study of basement aquifers in the Sahelian belt of Niger (Liptako, Southern Maradi, eastern Zinder)]. PhD thesis, Abdou Moumouni Univ, Niger, 152 pp

Ousmane B, Daddy A, Soumaila A, Margueron T, Boubacar A, Garba Z (2006) Groundwater contamination in the Niamey urban area, Niger. In: Xu Y, Usher BH (eds) Groundwater pollution in Africa. Balkema, Leiden, The Netherlands, pp 169–180

Re V, Cissé Faye S, Faye A, Faye S, Gaye CB, Sacchi E, Zuppi GM (2011) Water quality decline in coastal aquifers under anthropic pressure: the case of a suburban area of Dakar (Senegal). Environ Monit Assess 172:605–622

RGPH (2005) Recensement général de la population et de l'habitat (RGP/H-2001): résultats définitifs [General census of population and housing (RGP/H-2001): final results]. Ministry of Finance and Economy, Niamey, Niger, 25 pp

Rutledge AT (1998) Computer programs for describing the recession of groundwater discharge and for estimating mean groundwater recharge and discharge from streamflow records: update. US Geol Surv Water Resour Invest Rep 98-4148

Scanlon BR, Keese KE, Flint AL, Flint LE, Gaye CB, Edmunds WM, Simmers I (2006) Global synthesis of groundwater recharge in semiarid and arid regions. Hydrol Process 20:3335–3370

Selim S, Hamdan A, Rady A (2014) Groundwater rising as environmental problem, causes and solutions: case study from Aswan city, Upper Egypt. Open J Geol 4:324–341

Sheffield J, Wood EF (2007) Characteristics of global and regional drought, 1950–2000: analysis of soil moisture data from off-line simulation of the terrestrial hydrologic cycle. J Geophys Res 112: D17115

Taupin JD, Gallaire R, Arnaud Y (1997) Analyses isotopiques et chimiques des précipitations sahéliennes de la région de Niamey au Niger: implications climatiques [Isotopic and chemical analysis of Sahelian precipitations in Niamey area, Niger: climatic implications]. In: Hydrochemistry, Rabat Symposium, 1997, IASH Publ. 244, IAHS, Wallingford, UK, pp 151−162

Xu Y, Usher BH (2006) Issues of groundwater pollution in Africa. In: Xu Y, Usher BH (eds) Groundwater pollution in Africa. Balkema, Leiden, The Netherlands, pp 3–13

Yameogo S, Savadogo AA, Nakolendousse S, Koussoube Y (2006) Spatial and temporal variation of groundwater pollution in Ouagadougou City, Burkina Faso. In: Xu Y, Usher BH (eds) Groundwater pollution in Africa. Balkema, Leiden, The Netherlands, pp 157–167