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Land clearing, climate variability, and water resources increase in semiarid southwest Niger: A review

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[1] The water table in southwestern Niger has been rising continuously for the past decades (4 m rise from 1963 to 2007), despite a ~23% deficit in monsoonal rainfall from 1970 to 1998. This paradoxical phenomenon has been linked with a change in land use from natural savannah to millet crops that have expanded in area sixfold since 1950 and have caused soil crusting on slopes that has, in turn, enhanced Hortonian runoff. Runoff concentrates in closed ponds and then recharges the aquifer; therefore, higher runoff increases aquifer recharge. At the local scale (2 km^2), a physically based, distributed hydrological model showed that land clearing increased runoff threefold, whereas the rainfall deficit decreased runoff by a factor of 2. At a larger scale (500 km^2, 1950–1992 period), historical aerial photographs showed a 2.5-fold increase in the density of gullies, in response to an 80% decrease in perennial vegetation. At the scale of the entire study area (5000 km^2), analytical modeling of groundwater radioisotope data (^{3}H and ^{14}C) showed that the recharge rate prior to land clearing (1950s) was about 2 mm a^{-1}; postclearing recharge, estimated from groundwater level fluctuations and constrained by subsurface geophysical surveys, was estimated to be 25 ± 7 mm a^{-1}. This order of magnitude increase in groundwater fluxes has also impacted groundwater quality near ponds, as shown by a rising trend in groundwater nitrate concentrations of natural origin (75% of δ^{15}N values in the range +4 to +8‰). In this well-documented region of semiarid Africa, the indirect impacts of land use change on water quantity and quality are much greater than the direct influence of climate variability.

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1. Introduction

[2] Hydrological processes and groundwater balance are often difficult to evaluate in semiarid areas, as a result of a combination of factors specific to these regions. These include (1) low rainfall, high potential evapotranspiration (PET), and seasonal rainfall events of high intensity but low frequency [*Kalma and Franks*, 2003; *Warner*, 2004]; (2) redistribution of surface water that is highly sensitive to soil surface characteristics, with frequently occurring localized infiltration and/or indirect or focused recharge at different scales [e.g., *Wood and Sanford*, 1995; *Heilweil et al.*, 2007]; (3) a strong influence of vegetation on groundwater recharge and discharge, to depths of up to a few tens of meters within the unsaturated zone [e.g., *Canadell et al.*, 1996; *George et al.*, 1999; *Scanlon et al.*, 2005a]; and (4) influence of past decadal to millennial recharge events on groundwater dynamics and quality, implying frequent disequilibrium with present environmental conditions [e.g., *De Vries et al.*, 2000; *Leblanc et al.*, 2007].

[3] Land use change in semiarid areas has often resulted in dramatic modifications in the water balance. For instance, increases in recharge and long-term rising water tables were reported in SE Australia [*Allison et al.*, 1990] and in SW USA [*Scanlon et al.*, 2005b], following replacement of natural ecosystems by rain-fed agriculture at the beginning of the 20th century. In both cases, changes in groundwater fluxes resulted primarily from areally distributed increases in drainage below the root zone. Conversely, afforestation by deep rooted *Eucalyptus sp.* trees reduced drainage and lowered the water table in semiarid SW Australia [*Bari and Schofield*, 1992], in temperate Argentina [*Engel et al.*, 2005], and resulted in a decrease in groundwater-fed river flows in South Africa [*Le Maitre et al.*, 1999].

[4] The Sahel region south of the Sahara desert combines semiarid characteristics with one of the world's highest population growth. The annual population increase, ~1.5% (1950s) to ~3% (1990s), increased the population by a factor of 2 to 3 over this time (1950–1990) [*Raynaut*,

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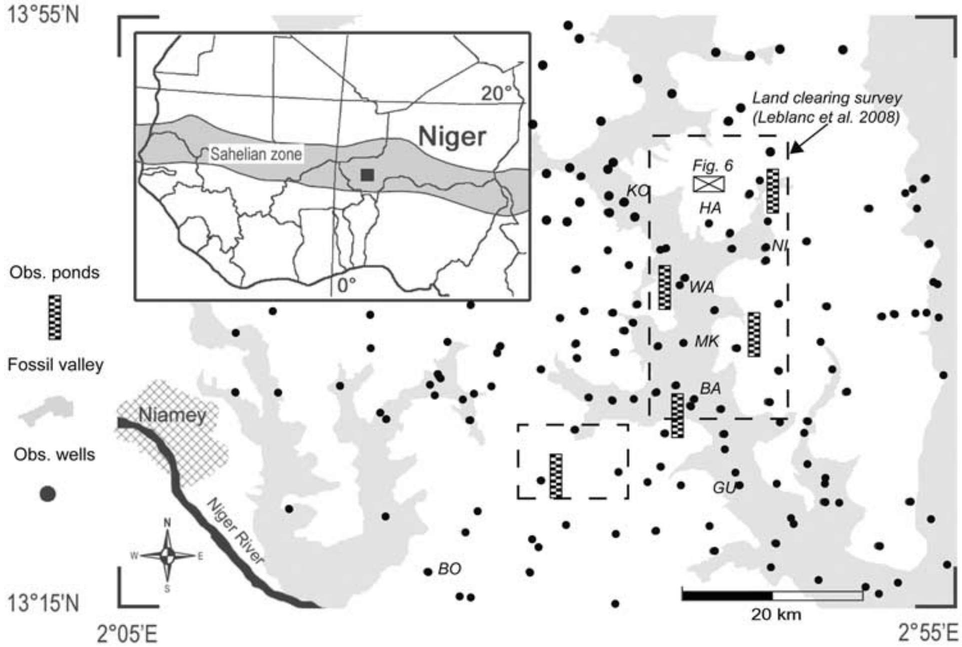

Figure 1. The study area in West Africa (black square, small inset) and location of the main study sites. The 500 km^2 area surveyed by aerial photographs [cf. *Leblanc et al.*, 2008] is delineated by dotted lines. Initials refer to the sites discussed in the text (e.g., "WA" for "Wankama").

2001]. This demographic growth has been mainly supported by an increase in the surface area of rain-fed cultivated lands at the expense of the natural woody savannah [*Reenberg et al.*, 1998; *Mortimore et al.*, 2005]. In contrast, conversion of land to irrigation has remained limited to only 1% of the cultivated area [*Siebert et al.*, 2005], mostly located in large river plains [*Siebert et al.*, 2005; *Vandersypen et al.*, 2007]. At a global scale, land clearing in the Sahel is among the most recent in the semiarid tropics, related to a relatively late increase in population [*Lambin et al.*, 2003].

[5] The monsoon-dominated West African climate has experienced a lasting drought since the early 1970s, which culminated in the 1980s with a rainfall deficit of 25–40% compared to the 1930s–1960s [*Nicholson et al.*, 2000; *L'Hôte et al.*, 2002]. This rainfall anomaly was considered the longest climatic signal at a global scale recorded in the 20th century [*Eltahir and Gong*, 1996; *Le Barbé et al.*, 2002]. Lower rainfall amounts had a marked impact on the regional hydrology, with, for instance, lower discharge to the Atlantic Ocean [*Mahé and Olivry*, 1999], lower evapotranspiration fluxes to the atmosphere [*Taylor et al.*, 2002], and long-term drops in the water table in some regional aquifers [*Biroue and Schneider*, 1993]. At a smaller scale, contradictory effects were also described as a result of environmental changes, with increases in river discharge for catchments of up to 21,000 km^2 [*Mahé et al.*, 2005] or rises in the water table for aquifers of up to 8000 km^2 [*Leduc et al.*, 2001].

[6] The purpose of this review paper is to provide a synthesis of the various hydrogeological and long-term hydrological surveys performed in SW Niger over the past two decades. The studies show that in this region, land clearing, resulting in soil crusting has increased runoff on sandy slopes, enhancing indirect recharge through ponds and gullies. This recharge pathway differs from those reported in SE Australia and in SW USA, where increased drainage below the root zone is the primary mechanism increasing recharge after cultivation [*Scanlon et al.*, 2007]. This study is also unique because an unusually large set of independent approaches (hydrodynamics monitoring, subsurface geophysics, environmental tracers, remote sensing and hydrological modeling) were combined to decipher the impacts of climate and land clearing on the terrestrial part of the water cycle. Changes in water quantity and water quality are both estimated at a multidecadal time scale, providing valuable results that could be used for improving water resources management at the aquifer scale. This study represents, to the best of our knowledge, one of the most detailed examples of the consequences of recent land use change on water resources in semiarid Africa.

2. Study Area

[7] The main features of SW Niger were described in previous papers presenting research projects on land surface–atmosphere interactions in this region [e.g., *Goutorbe et al.*, 1997; *Redelsperger et al.*, 2006]. The study area is located east of Niamey, on the left bank of the Niger River (Figure 1). The predominantly rural population mainly lives on rain-fed crops, and spreads over numerous small villages of a few hundreds inhabitants; in 2001 (last census), the population density was $\sim$30 inhabitants per km^2. The demographic growth was 1.5% a^{-1} in the 1950s, increasing to 3% a^{-1} in the 1980s–1990s; locally, higher rates were reported (e.g., up to 7.5% for the 1977–1988 period; [*Loireau*, 1998]). Groundwater pumping from the unconfined aquifer was estimated from census data and field inquiries to have remained <1 mm a^{-1}, and is mostly dedicated to domestic use and to livestock watering [*Leduc and Loireau*, 1997; *Favreau*, 2000].

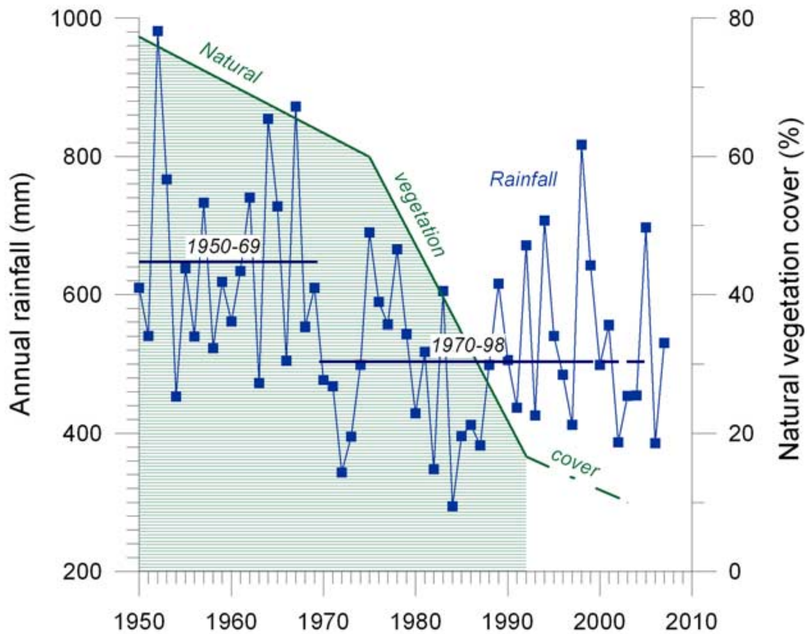

Figure 2. Annual rainfall at Niamey airport (1950–2007) and computed trend in natural vegetation cover for the 1950–1992 period (land cover data from *Leblanc et al.* [2008]). Horizontal lines refer to mean rainfall values for the 1950–1969 and 1970–1998 periods (−23% decrease in rainfall).

[8] The climate is typically semiarid, with an average annual temperature of 29°C, PET ~2500 mm a^{-1} (Penman's equation) and annual rainfall of 557 mm (1943–2007, Niamey airport data). The monsoonal rainfall deficit computed for 1970–1998 was ~23% compared to 1950–1969, with strong interannual variability (standard deviation is 145 mm, Figure 2). This deficit resulted mainly from a decrease in the mean number of events per year, whereas mean rainfall amount per event and rainfall intensity remained almost unchanged [*Balme et al.*, 2006a]. At the seasonal scale, 90% of annual precipitation falls from June through September, with short but intense rainfall events that are convective in origin and spatially heterogeneous [*Lebel et al.*, 1997].

[9] The natural vegetation was a woody savannah (dominant species: *Acacia sp., Combretum sp.*) but over the past decades, nearly 80% of the area has been cleared for cropping. Most of the landscape now appears as a patchwork of fallow with small shrubs dominated by *Guiera senegalensis*, and rain-fed millet fields. On the plateaus (27% of the area), ~60% of the natural banded vegetation pattern ("tiger bush") has also been cleared, mainly for firewood harvesting [*Leblanc et al.*, 2008]. Downslope, in the clayey valley bottoms, the original bushy vegetation has been largely replaced by specific water-demanding crops (cassava, groundnut, or sorghum).

[10] The geology of the region consists of shallow (<300 m) sedimentary formations that belong to the Continental Terminal (CT, Tertiary), made of loosely cemented clays, silts and sands. The CT crops out over a 150,000 km^2 area in SW Niger and extends further into West Africa [*Lang et al.*, 1990]. The landscape reflects a succession of former drier and wetter periods during the Quaternary, when the lateritic plateau was incised by numerous sandy valleys (Figure 1) [*D'Herbès and Valentin*, 1997]. Differences in altitude are <100 m, with ground slopes of ~1 to 3%. The water table is a continuous, smooth surface, with hydraulic gradients ≤0.1%, and little seasonal variation, except near ponds (Figure 3) [*Leduc et al.*, 1997]. The water table depth varies from 75 m below the lateritic plateau to less than 10 m below the valley bottoms, with a mean water table depth near to 50 m [*Massuel*, 2005]. The aquiclude underlying this unconfined aquifer consists of a 15 to 80 m thick, continuous gray clayey layer that prevents any significant leakage with the deeper confined aquifers [*Favreau*, 2000; *Le Gal La Salle et al.*, 2001]. Westward, the Niger River flows directly over Precambrian basement and acts as a regional groundwater discharge area.

3. Data and Methods

[11] The variety of methods used and intensity of data for quantifying long-term changes in water resources in SW Niger is unparalleled in semiarid Africa. A detailed description of the data and methods can be found in the cited literature, and only a brief description is included in this review.

3.1. Hydrodynamics Surveys

[12] Groundwater levels were measured manually with dippers at a bimonthly to quarterly frequency in ~150 wells over an 8000 km^2 area from 1991 to 2007 (Figure 1) [*Leduc et al.*, 1997, 2001]. In addition, groundwater levels in seven piezometers were recorded at a 3-hourly interval from 1993 through 2007 (e.g., Figure 3). For surface water, five temporary ponds were monitored at 3-hourly to twice-daily intervals, providing estimates of focused recharge through the ponds (Figures 1 and 3) [*Desconnets et al.*, 1997; *Martin-Rosales and Leduc*, 2003]. The database includes about 50 to 200 measurements for each of the observation wells, and quasi-continuous records for ponds and piezom-

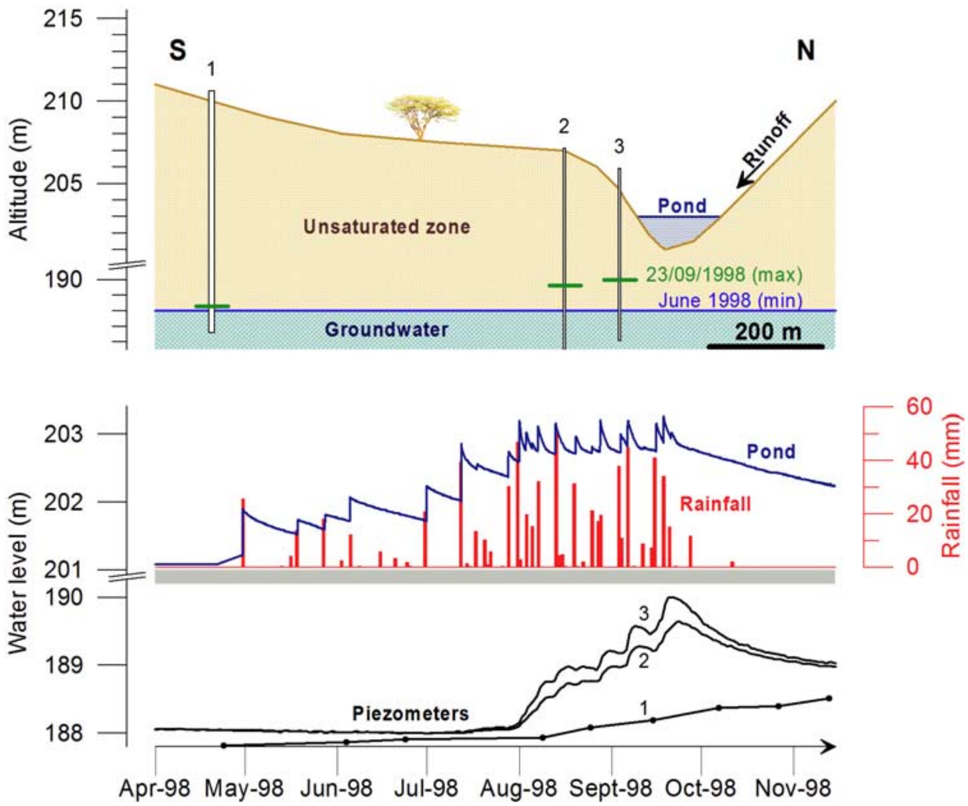

Figure 3. Focused recharge through an endorheic pond (Banizoumbou, 1998). Pond water levels show a quasi-immediate response to rainfall events (recorded in the same site). Piezometric fluctuations confirm the rapid, indirect recharge process identified by computing the surface water balance of the pond (90% infiltration, 10% evaporation).

eters for the 1993–2007 period. A few tens of accurate groundwater level measurements from the 1950s–1960s were available in technical reports [e.g., *Boeckh*, 1965], and these data were included in the piezometric time series [*Favreau and Leduc*, 1998; *Leduc et al.*, 2001].

3.2. Environmental Tracers

[13] A broad spectrum of environmental tracers were analyzed in rainwater [*Taupin et al.*, 2002], in surface water [*Desconnets et al.*, 1997], in the unsaturated zone water [*Massuel et al.*, 2006], and in groundwater [*Elbaz-Poulichet et al.*, 2002]. Electrical conductivity of water (EC), pH, and temperature were measured simultaneously with water table depth in wells and boreholes; the reliability of these measurements, mostly performed in bores open to the atmosphere, was discussed in *Favreau et al.* [2000]. Surveys of major ion concentration were performed at various times from 1991 through 2001 [*Leduc and Taupin*, 1997; *Elbaz-Poulichet et al.*, 2002]. This whole data set represents ~150 chemical analyses over ~80 sampling sites. Environmental isotopes of water (^{18}O, ^{2}H) were analyzed to constrain evaporation rates in a few selected ponds [*Desconnets et al.*, 1997] and groundwater recharge processes (^{18}O, ^{2}H and ^{3}H) at the aquifer scale [*Favreau et al.*, 2002a; *Favreau et al.*, 2004a]. In addition, the isotopic signature of the dissolved inorganic carbon (^{14}C and ^{13}C) was determined in ~30 groundwater samples to estimate aquifer recharge rate [*Le Gal La Salle et al.*, 2001; *Favreau et al.*, 2002a]. Analyses of nitrogen and oxygen isotopes of nitrate (^{15}N-NO$_3$ and/or ^{18}O-NO$_3$) were also performed in 2001 on ~20 groundwater samples and 22 soil samples (total nitrogen, 0–20 cm deep) to determine the source of nitrate in groundwater [*Favreau et al.*, 2003; *Favreau et al.*, 2004b].

3.3. Subsurface Geophysics

[14] Subsurface geophysical methods were used to constrain groundwater flow paths and aquifer parameters. At the watershed scale (0.1 to 2 km^2), electromagnetic mapping (EM-34), 2-D electrical resistivity tomography, and resistivity logging to depths of up to 25 m within the unsaturated zone were conducted in 2002 and 2003 to map differences in resistivity and drainage [*Massuel et al.*, 2006]. At a larger scale (~3000 km^2), time domain electromagnetic soundings (TDEM) and magnetic resonance soundings (MRS) [*Legchenko et al.*, 2004] were performed at 23 sites in 2005 and 2006 to better estimate the depth to the conductive clayey aquiclude (using TDEM) [*Favreau et al.*, 2007] and the transmissivity and water content of the aquifer (using MRS) [*Vouillamoz et al.*, 2008; *Boucher et al.*, 2009].

3.4. Remote Sensing and GIS

[15] A time series of aerial photographs was used to quantify land clearing and hydrological changes since 1950 [*Leblanc et al.*, 2008]; these data were supplemented with some ancillary GIS data (digital elevation model, SPOT-derived land cover map) to describe hydrological changes, and by field surveys to better constrain the

interpretation. Panchromatic aerial photographs (provided by IGN, France and IGNN, Niger) were radiometrically corrected and georectified, providing a normalized time series at different dates (1950, 1960, 1975 and 1992) over 500 km^2 (Figure 1). The ground resolution of the aerial panchromatic images varied from 1.05 m to 1.32 m, a resolution sufficient to detect the land cover and hydrological changes (average width of gullies varies from ~1 to 5 m [*Massuel*, 2005]). Ancillary data included a 1991 digital topographic map of the region at a scale of 1:200,000 with a vertical resolution of ~20 m, a set of topographic maps at a scale of 1:50,000, a land cover map at a scale of 1:50,000 derived from an October 1992 SPOT image [*D'Herbès and Valentin*, 1997], and a SPOT image from May 2005, with a ground resolution of 2.5 m. A digital elevation model was specifically produced for the study area at a 40 m horizontal resolution using the methodology in *Elizondo et al.* [2002].

3.5. Hydrological Modeling

[16] A physically based, 2-D-distributed hydrological model was used to simulate the surface runoff response to land use and climate change [*Cappelaere et al.*, 2003]. In this model, time and space are discretized consistently and finely enough to represent the water flow dynamics of individual storm events over the entire catchment (2 km^2, grid resolution 20 m). Infiltration, runon/runoff production, and routing functions (kinematic wave with Green-Ampt and Manning equations) are fully coupled and solved concurrently using finite elements in space and finite differences in time. The model was calibrated and validated for the Wankama catchment on the basis of rainfall events that occurred from 1992 to 2000 and reproduced the observed catchment behavior satisfactorily [*Cappelaere et al.*, 2003].

4. Results

4.1. Hydrological Processes

[17] The indirect or focused recharge process in SW Niger can be viewed as water harvesting at the soil surface, following formation of impervious, clayey surface crusts on sandy soils [*Valentin et al.*, 2004]. During the rainy season, intense rainfall events (half of the annual rain falling at rates >35 mm h^{-1}; [*Lebel et al.*, 1997]) produce Hortonian runoff on slopes that rapidly (within 1–3 h) concentrates in gullies and temporary ponds, natural outlets of endorheic watersheds of a few km^2, where groundwater recharge was shown to occur (Figure 3). Elsewhere in the landscape, neutron probe logging and soil moisture surveys showed that drainage is restricted to the upper 5 m soil zone [*Peugeot et al.*, 1997], with the exception of banded vegetation on the plateau [*Galle et al.*, 1999] and main gullies in sandy slopes [*Esteves and Lapetite*, 2003] where deeper drainage could occur. As a result, the soil moisture is low in the deeper (5 – 25 m) part of the unsaturated zone, with matric potential ≤ -250 m and gravimetric water content as low as 2–3% (Figure S1 in the auxiliary material) [*Massuel et al.*, 2006].[1]

[18] Deep drainage of surface water to the aquifer was estimated using several independent methods. Infiltration and evaporation volumes for ponds and gullies were computed using recorded water levels or stream discharge. In the upstream part of catchments, flow measurements showed a reduction in runoff coefficient by up to 24% between two gauging stations of a 0.2 km^2 watershed, attributed to water losses by infiltration through the sandy bed of the gullies [*Esteves and Lapetite*, 2003]. In a larger catchment (2 km^2), subsurface electrical surveys, combined with unsaturated zone water chemistry, indicated deep (>10 m) drainage below large sandy gullies [*Massuel et al.*, 2006]. In the downstream part of catchments, infiltration accounted for 80–95% of the surface water that reached the ponds, on the basis of water level, water chemistry, and water isotope (^{18}O, ^{2}H) surveys [*Desconnets et al.*, 1997]. A marked increase in infiltration rates was shown at the event scale for water stages above the clayey bottom of the pond [*Desconnets et al.*, 1997]. A clogging trend was also shown, with lower infiltration rates with time, as a result of clay input from runoff water feeding the ponds [*Martin-Rosales and Leduc*, 2003]. Bulk infiltration below ponds was usually ~10,000 m^3 a^{-1} but could reach 100,000 m^3 a^{-1} in some places or during rainy years. Expressed as a function of the surface area of the ponds (a few hectares), this represents locally up to 2600 mm a^{-1} of infiltration. Most of this infiltration occurs during a few days, after rapid inputs of surface water to the ponds (Figure 3). High drainage rates below the ponds result in low ionic concentrations in groundwater (median value of 100 μS cm^{-1}), and little or no fractionation of water isotopes in pond water [*Desconnets et al.*, 1997] and within the aquifer [*Favreau et al.*, 2002a].

[19] Piezometric fluctuations recorded in wells with water table depths of up to 50 m, and located at distances <500 m from the ponds showed seasonal mounds of up to a few meters in amplitude following flood events (Figure 3) [*Leduc et al.*, 1997; *Favreau*, 2000]. Transient groundwater modeling confirmed that the measured piezometric fluctuations were in accordance with the computed infiltration of surface water from the pond to the aquifer [*Favreau*, 1996; *Massuel*, 2005]. Elsewhere in the landscape, there was no seasonal piezometric fluctuation at distances >500 m from infiltrating ponds or gullies and only long-term rises in the water table were monitored (Figure 4).

4.2. Impact of Land Use Change and Climate on Runoff

4.2.1. Hydrological Modeling

[20] In SW Niger, there are no data on long time series of surface runoff. To overcome this lack of field data, a first estimate of the impact of land clearing on runoff was obtained by hydrological modeling at the scale of a small experimental watershed [*Séguis et al.*, 2004]. Rainfall events and the water level of the pond in the Wankama catchment (2 km^2) were intensively monitored from 1992 through 2007. The catchment has a mean slope of 1.5% from west to east. At the downstream end, the closed, temporary pond acts as the natural outlet of water runoff from the basin. Hillslope soils are mainly sandy, weakly structured, and can be classified as Cambic Arenosols or Psammentic Haplustalfs [*D'Herbès and Valentin*, 1997]. Further details about the hydrological survey and data analysis are available in work by *Peugeot et al.* [2003].

[21] The physically based, distributed hydrological model [*Cappelaere et al.*, 2003] was used to simulate runoff, using a long-term rainfall series at a daily resolution (1950–1998)

[1]Auxiliary materials are available in the HTML. doi:10.1029/2007WR006785.

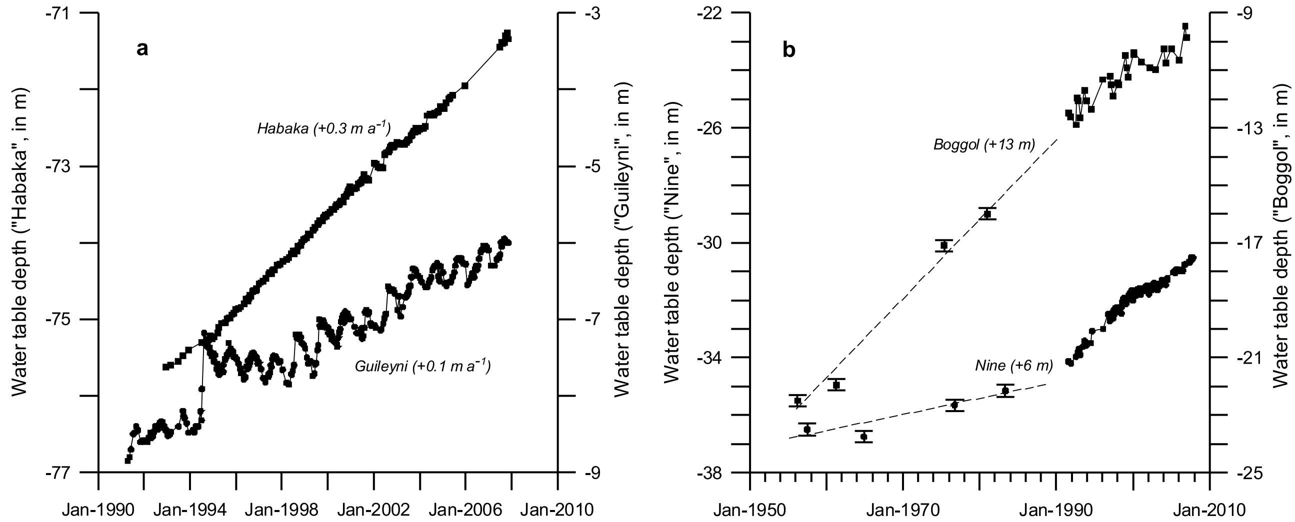

Figure 4. Monitoring of the long-term rise in the water table (a) for the 1991–2007 period and (b) for the 1956–1957 to 2007 period. Measured differences in the rise intensities are due to changing aquifer properties (Figure 4a) and/or differences in the onset of increased land clearing (Figure 4b).

and three land surface states (1950, 1975 and 1992) [*Séguis et al.*, 2004]. This model allowed the effects of land use change and climate variability to be separated. The catchment evolution through time was shown to be representative of the regional change in land use, with a marked increase in the cultivated land (from 6% in 1950 to 56% in 1992) and an increase in the extent of eroded lands (from 7 to 16%). Simulated runoff volumes showed that, irrespective of the land cover, mean annual runoff decreased by about 40% when climate changed from the wet period (1950–1969) to the dry period (1970–1998). Within wet and dry period, land use change increased the mean annual runoff by a factor of 2.8 (Figure 5) [*Séguis et al.*, 2004]. Additional analysis of the model outputs of the internal catchment behavior (N. Boulain et al., Water balance and vegetation change in the Sahel: A case study at the watershed scale with an ecohydrological model, submitted to *Journal of Arid Environments*, 2008) showed that in sandy gullies (3 to 4% of the surface area), the volume of water that infiltrated with depths >2 m a^{-1} increased by a factor of 3 for the 1950–1992 period (Figure S2). In this respect, a typical dry year was shown to produce more concentrated infiltration with the current land use (mostly millet crop) than a wet year under previous land use (natural savannah).

4.2.2. Changes in Drainage Network

[22] Analysis of a time series of aerial photographs, validated by field inquiries, showed that the drainage network and pond systems changed dramatically over the past decades. The first major change was the spectacular development of the gully network; gullies continuously increased in number and length from 1950 to 1992, resulting in a 2.5-fold increase in drainage density [*Leblanc et al.*, 2008]. A detailed example of the increase in connectivity of the gullies and development of the drainage system over the 1950–1992 period is shown in Figure 6. Visually, an increase in the surface area of millet fields is obvious between 1950 and 1975; however, changes in drainage network are more significant between 1975 and 1992, with development of large, connected drainage systems. Comparison of the 1992 aerial photograph with a high-resolution

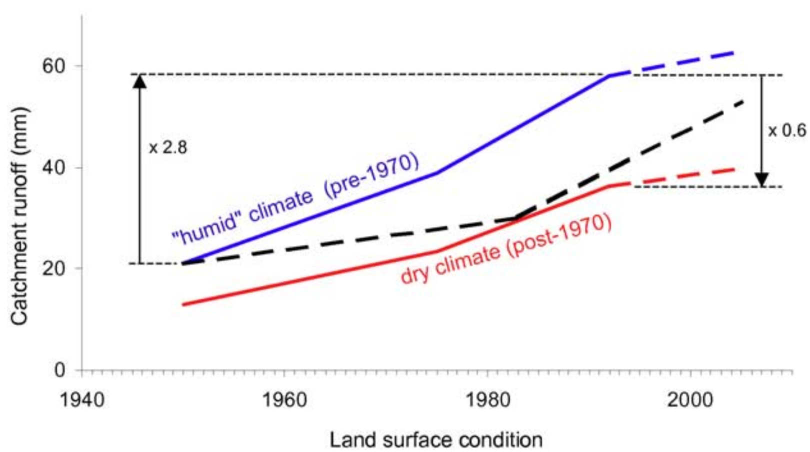

Figure 5. Simulated variations of runoff with land use and rainfall (Wankama catchment). The black dashed curve shows the historical evolution, combining land use and rainfall fluctuations (computed data from *Séguis et al.* [2004]).

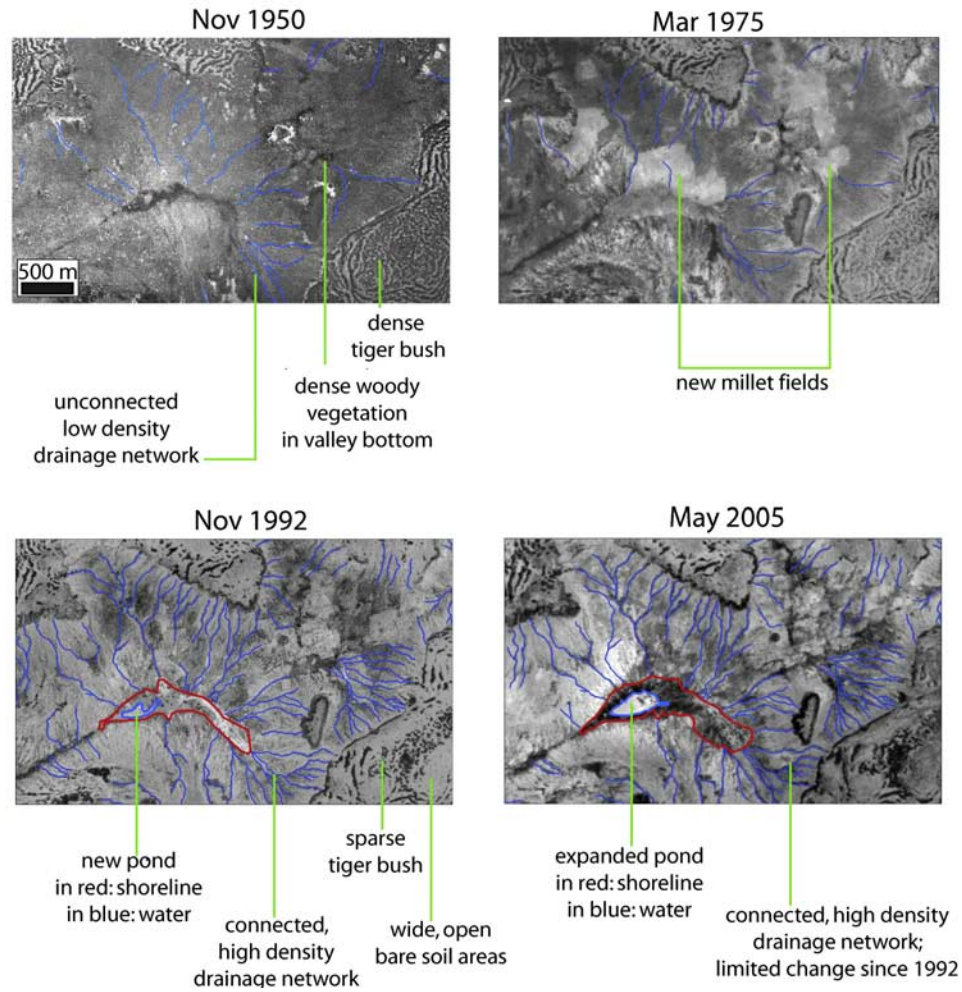

Figure 6. Changes in land cover (plateaus), land use (millet fields), and drainage network (gullies and ponds) for the 1950–2005 period. Aerial photographs from IGNN, Niger, for the 1950–1992 period and high-resolution SPOT image from 20 May 2005. (Copyright 2008 CNES. Distribution Spot Image Corp., USA. All rights reserved.)

2005 SPOT image showed that little change occurred in land cover between the two dates, whereas the pond expanded in surface area (Figure 6). Larger gullies and upslope shifts in sandy midslope alluvial fans were also noted elsewhere, as well as larger ponds and/or appearance of new ponds [*Leblanc et al.*, 2008]. Because there is evidence that in alluvial fans and temporary ponds most of the run-on water recharges the aquifer [*Massuel et al.*, 2006], the long-term changes in the drainage network result in higher groundwater recharge rates.

4.3. Long-Term Groundwater Dynamics

4.3.1. Piezometric Surveys

[23] Groundwater records obtained from ~150 sites in SW Niger (Figure 1) showed a continuous rise in the water table for the entire 1990s [*Leduc et al.*, 1997, 2001]. More recent data (2000–2007, surveys performed by the Ministry of Hydraulics, Niger Republic, and IRD) confirmed the rise, with current groundwater levels being the highest ever recorded (Figure 4). Local rise intensities vary from <0.1 m a^{-1} to 0.4 m a^{-1}, with an average rise of ~0.18 m a^{-1} for the 1991–2007 period (Figure 7). Local differences in intensity of the water table rise were shown to depend more on local aquifer characteristics, rather than distance from ponds or water table depth [*Leduc et al.*, 2001; *Vouillamoz et al.*, 2008]. For each considered chronicle, the seasonal fluctuation in the water table can vary interannually from 0 to 6.2 m depending on the local rainy season characteristics (Figures 4a and 8).

[24] Older measurements, dating back to the late 1950s (1956–1957) and/or to the early 1960s (1961–1964) provided a less continuous but long-term view of changes in aquifer reserves. The estimated average increase in the water table from 1963 to 1999 was 3.2 m [*Leduc et al.*, 2001] and was 4.1 m from 1963 to 2007, because of the ongoing rise in the water table (Figure 7). A marked acceleration in the water table rise in the early 1980s relative to the 1960s to the 1970s was obvious at the scale of the entire 5000 km^2 study area (Figure 4b, Figure 7) [*Leduc et al.*, 2001]. At smaller scales (500 km^2), the increase in the water table was more abrupt, in close relationship with increased connectivity of the drainage network (Figure 7). The observed discrepancy between the long-term dynamics at different spatial scales can be explained by a more consistent

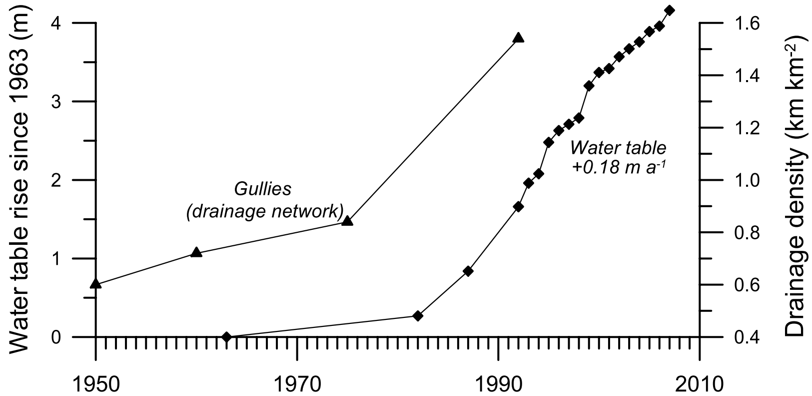

Figure 7. Computed changes in groundwater levels for the 1963–2007 period [after *Favreau*, 2000; *Massuel*, 2005] (reprinted with permission from Elsevier) and comparison with change in the drainage density (km km^{-2}, data from *Leblanc et al.* [2008]). Dynamics of the changes show similar trends, indicating a rapid response of groundwater levels to gully connectivity and increased focused recharge.

timing of land clearing for smaller areas (Figure 4b) [*Leblanc et al.*, 2008].

4.3.2. Changes in Groundwater Discharge

[25] The measured long-term change in groundwater reserves implies a persistent disequilibrium in the recharge-discharge aquifer balance. The main cause for the disequilibrium is, following land clearing higher runoff increased groundwater recharge through ponds, whereas groundwater discharge remained comparatively low. The increase in runoff and focused recharge was shown by the increase in gully density (km km^{-2}) and by the appearance of new ponds in the landscape (Figure 6). Natural spring discharge along the Niger River showed little evidence of change since the 1960s (B. Hassane, Niamey University, personal communication, 2008); low potentiometric gradients (<0.1%) combined with low aquifer permeability ($\leq 10^{-3}$ m s^{-1}) [*Boucher et al.*, 2009] have resulted in a minimal impact of the water table rise on aquifer discharge fluxes.

[26] The amount of groundwater pumping for domestic water use, small-scale irrigation, and/or livestock watering was estimated by repeated field surveys over 12 villages for one year (G. Favreau, unpublished data, July 2002 to August 2003). Results showed that most (75%) of the groundwater is used for domestic purposes (whole year), and second for cattle watering (dry season), with only 5% of groundwater used for irrigation (dry season, small gardens). The groundwater domestic use was estimated to be of ~20 L per inhabitant per day, in accordance with other estimates obtained in rural West Africa [*Hadjer et al.*, 2005]. In terms

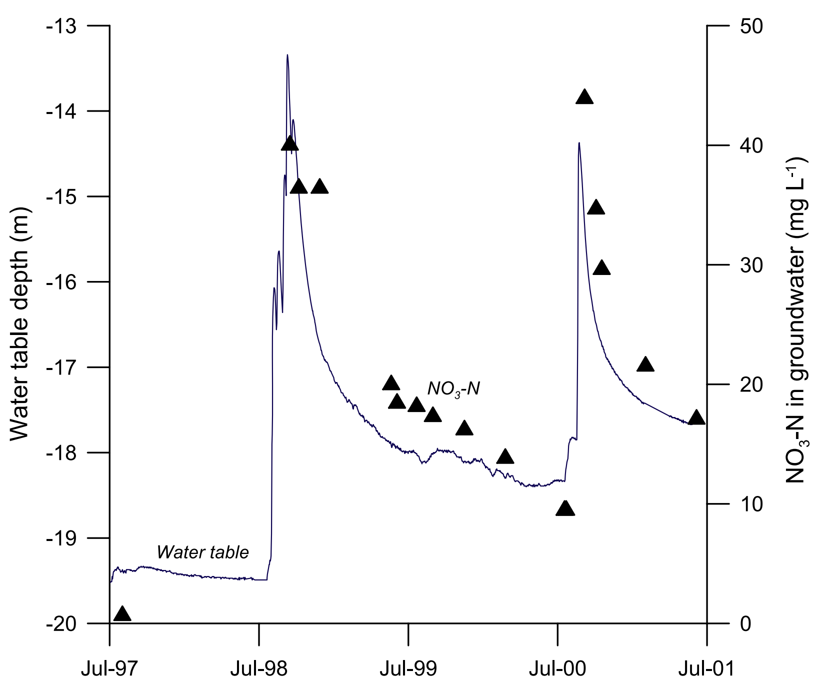

Figure 8. Fluctuations of the nitrate content (NO_3-N) and groundwater level recorded during the 1997–2001 period (Maourey Kouara Zeno) [after *Favreau et al.*, 2004b]. Screen depth is 21 to 24 m.

of water extracted from the aquifer, this represents about 0.3 mm a^{-1} of pumping from the unconfined aquifer. On a long-term perspective, considering the threefold increase in population density and the unchanged water use, groundwater pumping could be inferred to be $\sim$0.1 mm a^{-1} during the 1950s.

[27] A complementary explanation for the increase in groundwater reserves could lie in reduced transpiration, following large-scale clearing. Several local savannah trees, such as *Faidherbia albida or Acacia sp.*, are known to have roots to a few tens of meters depth [*Canadell et al.*, 1996]. Field surveys revealed, however, that land clearing has affected some large trees much less than small shrubs, because of their positive impact (*Faidherbia albida*) on the nutrient input to millet fields [*Buerkert and Hiernaux*, 1998; *Kho et al.*, 2001]. Local shrubs (e.g., *Guiera senegalensis*) were shown in the study area to have a much shallower root system, extracting water from the first 4 m of the soil [*Brunel et al.*, 1997; *Gaze et al.*, 1998]. Because the average depth to the water table is 1 order of magnitude greater than the root system of these shrub species (average water table depth of 50 m, 94% of the surface area with depths >10 m) the influence of a decreasing woody cover on groundwater discharge by transpiration was considered negligible, compared to the observed increase in recharge.

4.3.3. Increase in Recharge

[28] The long-term rise in groundwater reserves during the piezometric survey period (1992–2007) represents an excess of recharge over discharge that can be quantified using the water table fluctuation method (WTF) [*Healy and Cook*, 2002; *Crosbie et al.*, 2005]:

$$R = Sy \times \Delta h \tag{1}$$

where R is recharge rate (L T^{-1}), Sy is specific yield (%, porosity parameter), and Δh is measured water table fluctuation for a given time unit (L T^{-1}). The specific yield is the volume of water that can be released by gravity or that is stored in the aquifer when the water table rises [*Healy and Cook*, 2002]. For this aquifer, only $\sim$5% of the land surface area is seasonally flushed by recharge, below ponds and gullies [*Massuel*, 2005]. As a result, most ($\sim$95%) of the unsaturated zone displays very low residual water content at depth (Figure S1). The average specific yield for the Continental Terminal aquifer (1–2% in work by *Leduc et al.* [1997] and <10% work by *Boucher et al.* [2009]) may therefore represent a lower estimate of the porosity parameter to be used in equation (1). For the $\sim$95% of the aquifer where only bound water remains at depth, a modified equation of the WTF method is given by [after *Vouillamoz et al.*, 2008]:

$$R_n = (\theta_a - \theta_0) \times WTR \tag{2}$$

where R_n is net recharge rate (L T^{-1}), θ_a is total porosity (%), θ_0 is mean residual volumetric water content above the saturated zone, or bound water (%), and WTR is mean interannual water table rise, or net groundwater storage (L T^{-1}). Net recharge rate (R_n) is lower than the recharge rate (R) because R_n is computed at the annual time scale, and takes into account the aquifer discharge [*Healy and Cook*, 2002]. Estimates of total porosity (θ_a) of the aquifer from mercury porosimetry ranged from 25 to 36% (six data in work by *Favreau* [2000]); the residual volumetric water content of the unsaturated zone (θ_0; matric potential = −250 m) was estimated to range from 3.6 to 23.7% (gravimetric water content from 1.8 to 11.3% [*Massuel et al.*, 2006]; apparent density of $\sim$2.0 in the work by *Favreau* [2000]). Assuming full connectivity of the pores, the volume that would be refilled by the water table rise can be estimated to be equal, to the total porosity minus bound water ($\sim$effective porosity), i.e., 1 to 32%.

[29] Estimates of aquifer water content obtained by magnetic resonance soundings (MRS) were considered as proxy values for determining effective porosity [*Lubczynski and Roy*, 2005]. The MRS-determined mean water content over the entire saturated aquifer thickness was 13% (range: 5.4 to 22.6%) (e.g., Figure 9 and *Boucher et al.* [2009]). In terms of net aquifer recharge, this implies, considering an effective porosity of 13% for the dry unsaturated zone ($\sim$95% of the area), an estimated specific yield of 3% ($\sim$5% of the area), and an interannual rise in the water table of 0.18 m a^{-1} (WTR), a mean value of 23 mm a^{-1} (R_n). This MRS-based estimate of net recharge rate is more accurate than previous computations based on literature values of effective porosity (10–25%), with estimated recharge rates from 20 to 50 mm a^{-1} [*Leduc et al.*, 2001; *Favreau et al.*, 2002a]. Considering the mean relative uncertainty in water content (20%) and estimated uncertainty in the mean water table rise (10%), the total uncertainty in recharge is estimated to be about ±7 mm a^{-1}.

[30] Environmental radioisotopes (^{14}C and ^{3}H) measured in $\sim$30 groundwater samples from various depths within the saturated zone, were used to estimate preclearing recharge rates [*Favreau et al.*, 2002a]. Use of ^{14}C of the dissolved inorganic carbon as an atmospherically derived tracer was shown to be feasible for this sandstone aquifer [*Le Gal La Salle et al.*, 2001; *Favreau et al.*, 2002a] because of the absence of carbonates along the flow path of recharging waters, as shown by low ionic contents (median value of 45 mg L^{-1}), and low-saturation indices with respect to carbonate minerals (−3 to −5). An analytical model for correcting (1) for changes in the atmospheric radioisotope content through time and (2) for the increase in groundwater reserves was considered to determine the natural renewal rate of the aquifer in 1950:

$$d/dt(CV) = RCr - QC - \lambda CV \tag{3}$$

where C is radioisotope aquifer content, V is saturated aquifer volume (L^3), R is aquifer recharge (L^3 T^{-1}), Cr is atmospheric radioisotope content input, Q is outflow from the aquifer (L^3 T^{-1}), λ is radioisotope decay constant (T^{-1}), and R > Q [*Favreau et al.*, 2002a]. The average long-term (preclearing) renewal rate (R_0/V_0) was estimated to be 0.05% a^{-1}; this implies, considering representative characteristics of the aquifer (mean saturated thickness of about 30 m, mean effective porosity of $\sim$13%), a mean recharge rate of $\sim$2 mm a^{-1} for preclearing conditions. Sensitivity analyses were performed to determine the reliability of this estimate. Uncertainty related to the reconstructed atmospheric radioisotope chronicles, the computed increase in groundwater reserves and possible time lags to the aquifer showed that the renewal rate should lie between 0.03 and

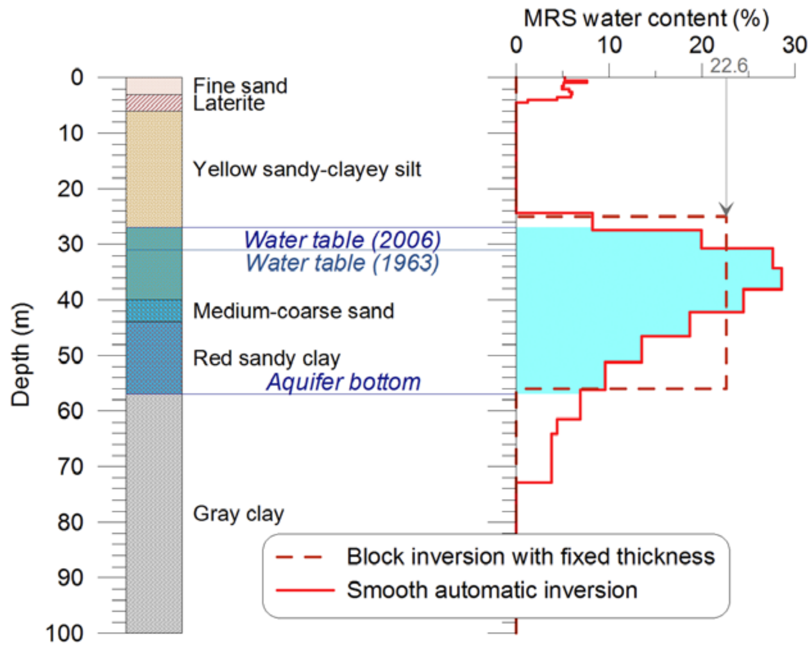

Figure 9. Magnetic resonance sounding (MRS) in the unconfined aquifer (Kolo Bossey; see M. Boucher, unpublished data, November 2006). (right) The MRS volumetric water content (22.6%) is used to estimate (left) the increase in groundwater reserves through time (1963–2006).

0.08% a^{-1} [*Favreau et al.*, 2002a]. When taking into account the estimated uncertainty in the mean saturated aquifer thickness (10%) and in the effective porosity (20%), the preclearing recharge rate should lie between 1 and 4 mm a^{-1}. Using this estimate of recharge ~2 mm a^{-1} at steady state (R_0, with R_0 = Q) and considering (1) the estimated net recharge rate of 23 mm a^{-1} (R_n) and (2) little change in groundwater discharge rates, postclearing recharge (R) should be ~25 mm a^{-1} ($R = R_n + R_0$).

[31] Groundwater modeling of the aquifer was conducted to assess the sensitivity of groundwater levels to aquifer recharge characteristics. Steady state (1960s) and transient (1992–2003) inverse modeling of the potentiometric levels (MODFLOW code) were conducted, using natural flow boundaries and aquifer properties estimated from pumping tests as input parameters [*Favreau*, 2000; *Massuel*, 2005]. Groundwater recharge was spatially distributed as a function of the survey of the endorheic catchments and ponds over the study area [*Massuel*, 2005]. At steady state, simulations showed that recharge rates of 0.5 to 1.0 mm a^{-1} were sufficient to reproduce the potentiometric levels to within ±2 m. Transient modeling (1992–2003) was performed using the intensity in the water table rise as a calibration data set. A lumped conceptual runoff model, applicable to the large number of ungauged endorheic catchments, was derived from the existing fine-scale model [*Cappelaere et al.*, 2003] to simulate runon to the ponds [*Massuel*, 2005]. Groundwater recharge rates =5.0 mm a^{-1} (areally averaged) were able to reproduce the measured rise intensities in the water table [*Massuel*, 2005]. This confirmed that the process of localized recharge was able to reproduce the overall measured dynamics of water table rise, for the estimated range in aquifer properties (permeability from 10^{-3} to 10^{-6} m s^{-1}, storativity from 1 to 35%). However, because the calibration procedure is a spatially distributed trade-off between transmissivity, storativity, and recharge, large uncertainties in the distribution of the aquifer parameters result in large uncertainties in the simulated recharge rates.

4.4. Impact of Land Clearing on Groundwater Quality

4.4.1. Increase in Groundwater Nitrate

[32] Major ion analyses of groundwater from wells with screen depths up to 40 m below the water table consistently showed low ionic concentrations (EC median value is 100 μS cm^{-1}), slightly acidic waters (pH: 5 to 6), dominated by Na or Ca cations and NO_3 or HCO_3 anions [*Leduc and Taupin*, 1997; *Favreau*, 2000; *Le Gal La Salle et al.*, 2001]. Increases in EC were most often linked with an increase in nitrate, with nitrate concentrations exceeding the recommended World Health Organization (WHO) limit of 10 mg L^{-1} NO_3-N in water from ~25% of the wells. Median nitrate-nitrogen concentration in wells <500 m from ponds (tritium content above the detection limit or seasonal piezometric fluctuation observed) was 10 mg L^{-1} (28 sites), 1 order of magnitude higher that median nitrate-nitrogen concentration (1 mg L^{-1}, 50 sites) in water from wells at greater distance from ponds. As denitrification processes can be excluded in this unconfined aquifer (Eh values from +300 to +500 mV, dissolved oxygen from 4.6 to 7.3 mg L^{-1}), this suggested a recent increase in the nitrogen flux to the aquifer beneath the ponds [*Favreau et al.*, 2003].

[33] Geochemical surveys were conducted on selected wells to estimate changes in ionic fluxes through time. Comparison of groundwater chemical analyses from wells sampled prior to clearing (1963–1964) and more recently (1990s) showed either similar low ionic concentrations (three wells) or increased nitrate values (four wells). Chemical surveys performed for the 1996–2001 period also

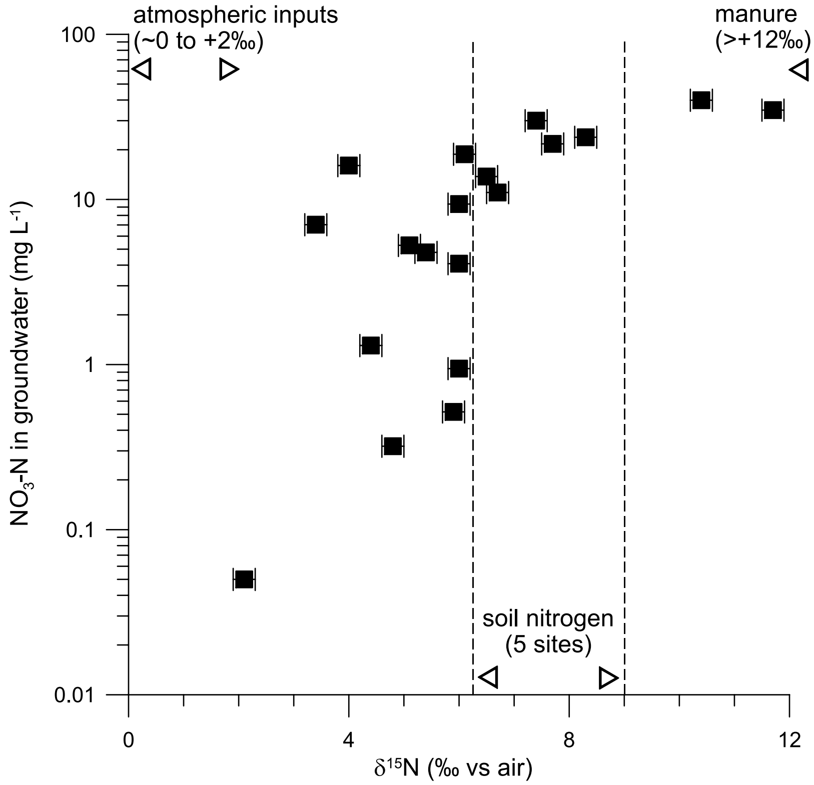

Figure 10. Isotopic values of nitrate in groundwater for a wide range of contents (0.05–40 mg L^{-1}, NO_3-N). The local range in the mean $\delta^{15}N$ values of five sampled soils (0–20 cm, 22 samples, total nitrogen) is also reported.

showed large seasonal changes in nitrate concentrations, correlated with plurimetric piezometric fluctuations (Figure 8). Seasonal changes in nitrate concentrations up to 2 orders of magnitude, and up to 45 mg L^{-1} (NO_3-N), indicate a current nitrogen flux to the aquifer [*Elbaz-Poulichet et al.*, 2002]. In SW Niger, there is a lack of nitrogen pollution sources (no fertilizer used, few or no latrines in villages) and the primary source of nitrogen is atmospheric deposition, as shown by relatively high nitrogen contents in precipitation (e.g., 172 mg m^{-2} in 1996) [*Galy Lacaux and Modi*, 1998]. Another source of nitrate in the Sahel is from N fixation by native trees (*Faidherbia albida*) [cf. *Deans et al.*, 2005] and/or cyanobacteria at the soil surface [*Malam Issa et al.*, 2001]. Because groundwater near ponds had NO_3-N/Cl molar ratios (median: 4.9) exceeding NO_3-N/Cl molar ratios in rainfall (~3 to ~4) [*Freydier et al.*, 1998; *Galy Lacaux and Modi*, 1998], biological fixation of nitrogen in soils represents a likely secondary source for nitrate in groundwater.

4.4.2. Nitrogen and Oxygen Isotopes of Nitrate

[34] Nitrate-rich groundwaters are frequently found in semiarid regions [*Kendall and Aravena*, 2000]. In this environment, groundwater nitrate is often shown to be derived from a natural soil source, using ^{15}N as a tracer for constraining the nitrogen cycle [e.g., *Kreitler and Jones*, 1975; *Heaton*, 1984; *Gates et al.*, 2008]. In the studied aquifer, ~20 groundwater samples, with NO_3–N concentrations between 0.05 and 40 mg L^{-1}, were analyzed for $\delta^{15}N$ to determine the origin of dissolved nitrate. High levels of dissolved O_2 (>60% saturation) confirmed the absence of any significant denitrification process within the unconfined aquifer. The $\delta^{15}N$ data ranged from +2.1 up to +11.7‰, with 75% of the values between +4.0 and +8.3‰ (Figure 10). This range is typical of that in nitrate derived from mineralization of soil organic nitrogen (SON) [*Kendall and Aravena*, 2000], higher than for industrial fertilizer (~0 to +2‰), and lower than that reported for groundwater polluted by manure or septic tanks effluent (>+12‰ near Niamey) [*Girard and Hillaire-Marcel*, 1997]. The analysis of a few nitrogen-rich valley bottom soils showed similar $\delta^{15}N$ values between +6.6 to +8.8‰ (total nitrogen), a range consistent with $\delta^{15}N$ values of nitrate in groundwater (Figure 10). These values are also consistent with the range of +4.9 to +8.0‰ found by *Heaton* [1984] for mineralization of SON in Namibia. For higher (>+9‰) and lower (<+3‰) $\delta^{15}N$ values, manure or naturally high atmospheric inputs [*Galy Lacaux and Modi*, 1998] may locally represent a significant nitrogen source to the system. However, the narrow range of $\delta^{15}N$ values, for a 2-order range in the nitrate content, strongly suggests that natural soil nitrogen is the main source for dissolved nitrate in the aquifer.

[35] In addition to ^{15}N isotope, ^{18}O of dissolved nitrate represents a complementary tracer to elucidate mineralization processes of nitrogen in the subsurface. Analyses of $\delta^{18}O$ of nitrate were performed in 12 wells, where $\delta^{15}N$ analyses were also performed [*Favreau et al.*, 2004b]. Results showed $\delta^{18}O$ values within the range of +7 to +14‰, a range consistent with mineralization of SON, with

Table 1. Synopsis of the Respective Impacts of Rainfall, Land Clearing, and Population Changes on Water Resources in SW Niger

	Changes 1950–1990s	Runoff	Drainage Density	Groundwater Recharge	Groundwater Discharge	Groundwater Quality, NO_3
Rainfall	−23%[a]	−40%[a]	-	−50%[b]	-	-
Land clearing	−80% in natural vegetation cover[a,c]	×2.8[a]	×2.5[c]	×10[d,e,f,g]	negligible[e]	nitrogen input to the aquifer[h,i]
Population	×3[j]	-	-	no irrigation	×3[d]	no fertilizer used

[a]*Séguis et al.* [2004].
[b]*Massuel* [2005].
[c]*Leblanc et al.* [2008].
[d]*Favreau* [2000].
[e]*Leduc et al.* [2001].
[f]*Favreau et al.* [2002a].
[g]*Vouillamoz et al.* [2008].
[h]*Elbaz-Poulichet et al.* [2002].
[i]*Favreau et al.* [2003].
[j]*Loireau* [1998].

little fractionation of water molecules contributing to nitrification in the soil system [*Kendall and Aravena*, 2000; *McMahon and Böhlke*, 2006].

5. Discussion

5.1. Impact of Rainfall Changes Versus Land Clearing

[36] Reduction in surface water runoff from rainfall decrease was quantified by hydrological modeling to be about twice (−40%) the measured long-term decrease in annual rainfall (−23%, 1970–1998 versus 1950–1969, Table 1). At the scale of the modeled 2 km^2 watershed, this decrease in runoff was mainly due to a cumulative effect during the rainy season, and a lower number of rainfall events implying a longer dry period between successive rainfall events [*Séguis et al.*, 2004]. The impact of rainfall variability on groundwater recharge was shown to be a complex process, with strong influence of the seasonal distribution of intense rainfall events on the pond dynamics and water table fluctuations (Figure 3). At the site scale, large interannual changes in groundwater dynamics were found, with high-magnitude recharge events following some years with no recorded recharge (e.g., Figure 8). At the scale of the entire study area, water table rises show lower interannual variability than at the site scale, with rises from 0.05 to 0.41 m a^{-1} during the 1992–2005 period (Figure 11). During this 14 year time period, ~50% of the groundwater reserve increase (2.3 m) occurred during only 3 years (Figures 7 and 11). Using the annual rainfall-recharge relationship built for the 1992–2005 period (R^2 of 0.76, Figure 11), the measured decrease in rainfall since 1970 (23%) could be translated to a 50% decrease in groundwater recharge, considering no change over this time period in the relationship between precipitation and groundwater recharge (Table 1).

[37] Land clearing was shown to significantly increase surface runoff. At the watershed scale, simulations showed a threefold increase in runoff, irrespective of the considered climate [*Séguis et al.*, 2004]. At larger scales, an increase in drainage density (×2.5) was shown to have occurred in response to land clearing of ~80% of the landscape [*Leblanc et al.*, 2008]. A time lag of ~30 years was determined between the onset of the increase in land clearing and the beginning of the water table rise. The explanation for this time lag, as shown by aerial photographic surveys, is that recharge has become more efficient with increasing connectivity of the drainage network, and hence, with increasing runon to the ponds (Figures 3 and 6). The discrepancy between the simulated increase in runoff (~×3) and the estimated increase in recharge (~×10, from ~2 mm a^{-1} up to 25 ± 7 mm a^{-1} for recharge) can be partly related to the development of new ponds (Figure 6), although this increase remains difficult to estimate by remote sensing because most ponds disappear during the dry season [*Massuel*, 2005; *Leblanc et al.*, 2008]. A second possible explanation may lie in increasing infiltration through alluvial fans and sandy gullies, as suggested by subsurface geophysics [*Massuel et al.*, 2006] and hydrological modeling (Figure S2).

[38] Climate has remained mostly similar to modern semiarid conditions during the past ~3 to 2.5 ka in the Sahel with little change in pollen records during this period [*Lézine*, 2007]. The aquifer renewal rate (recharge/volume) prior to land clearing was estimated at about 0.05% a^{-1} and groundwater distant from the ponds dates back to this period of the late Holocene [*Favreau et al.*, 2002a]. Low groundwater nitrate concentrations distant from the ponds (median: 1 mg L^{-1}, NO_3-N) imply that natural rainfall variability has resulted in low nitrogen flux to the aquifer. By contrast, land clearing for the second half of the 20th century has resulted in a break in the nitrogen cycle and rapid nitrate flux to the aquifer (Figure 8). Land clearing in SW Niger obviously has a much greater impact on groundwater resource quality than natural rainfall variability (Table 1).

5.2. Representativity

5.2.1. Increased Runoff From Land Clearing

[39] Land clearing represents the main factor driving long-term changes in surface water resources in semiarid Niger. Land use is also recognized as a key parameter in explaining decadal changes in river flow in West Africa [*Li et al.*, 2007; *D'Orgeval and Polcher*, 2008]. Higher runoff as a long-term consequence of land clearing and soil crusting was described at various scales in the Sahel, from small watersheds of a few tens of square kilometers [*Albergel*, 1987] to larger catchments of up to 21,000 km^2 [*Mahé et al.*, 2005]. Important factors for determining soil crusting in West Africa include rainfall intensity [*Hoogmoed and Stroosnijder*, 1984], soil

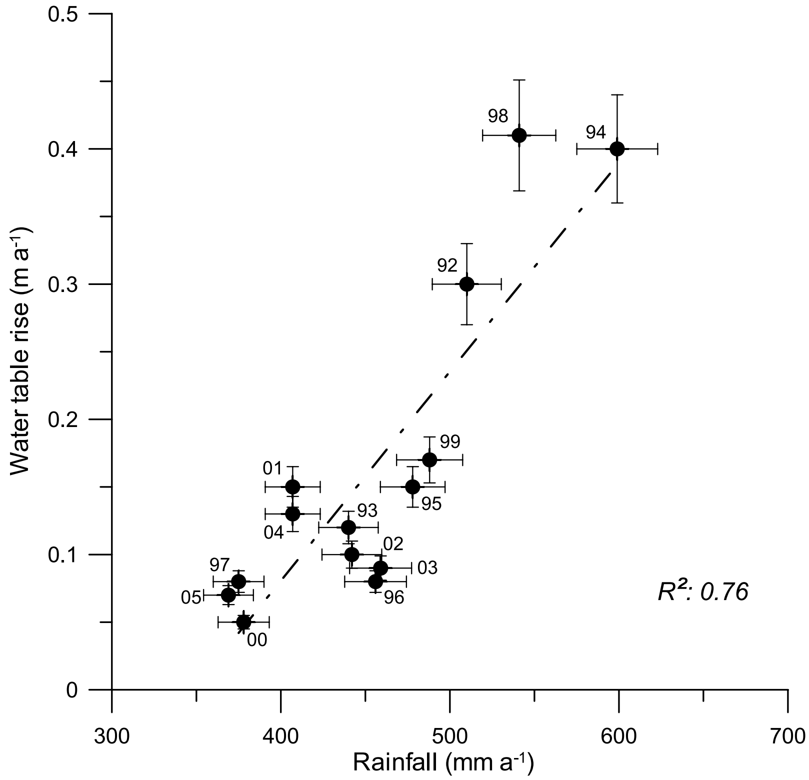

Figure 11. Computed annual water table rise (WTR, net recharge) as a function of mean annual rainfall over the study area (5000 km^2) for the 1992–2005 period. Years are reported as labels for each year (e.g., 92 for 1992). Uncertainty in the computed WTR is 10%. Annual rainfall averaged by kriging over 15 rainfall stations [after *Massuel*, 2005] with areal rainfall estimation error of 4% [*Balme et al.*, 2006b].

texture [*Casenave and Valentin*, 1992], microbial development at the surface [*Valentin et al.*, 2004], chemical properties of the soil [*Barbiéro and Van Vliet-Lanoë*, 1998; *Igwe*, 2005], and land use practices [*Peugeot et al.*, 1997; *Hiernaux et al.*, 1999]. In the Sahel, these factors may be variable in time and space; land degradation may also have resulted in additional processes, such as revitalization of small sand dunes [e.g., *Nickling and Wolfe*, 1994; *Tengberg*, 1995] where preferential infiltration of rainwater was shown to occur [*Ribolzi et al.*, 2006]. Elsewhere in semiarid Africa, rural development did not systematically entail increased surface runoff, when land use changes consisted of crop substitution [*Lørup et al.*, 1998]. At a global scale, contrasting hydrological responses to land clearance were described, with, for instance, weak increases in runoff but decreasing time lag in the hydrological response to rainfall events in semiarid Mexico from 1970 to 1998 [*Viramontes and Descroix*, 2003] or strong increases in runoff on easily eroded soils in China over a 14 year period [*Wei et al.*, 2007]. For semiarid areas, a given change in land use may lead to different hydrological responses, depending on the initial land cover characteristics; conversely, for a given landscape, different types of land cover "degradation" may lead to different responses in streamflow [*Wilcox*, 2007].

5.2.2. Increasing Recharge Following Land Clearing

[40] Long-term rises in groundwater levels following changes in land use have not been frequently reported in semiarid areas (see review by *Scanlon et al.* [2006]). Possible explanations lie in frequent overexploitation of aquifer reserves, and/or land use change having occurred much earlier than the onset of piezometric surveys. As a consequence, a rising water table can be considered as direct evidence of increased recharge; however, a drop in the water table can conceal an increase in recharge, if groundwater pumping offsets increased recharge rates. To the best of our knowledge, the few existing examples of rising water tables in West Africa are for older periods of the 20th century. In northern Nigeria, water table rises of up to 20 m from 1932 to 1964 were reported as a result of land clearing and were attributed to reduced transpiration and increased surface runoff that, in turn, increased groundwater recharge [*Carter and Barber*, 1958; *Barber and Dousse*, 1965]. In southern Senegal, *Charreau and Fauck* [1970] reported a water table rise of a few meters over 20 years following land clearance for cultivation. Elsewhere at a global scale, increases in direct recharge of up to 2 orders in magnitude were reported in the Murray Basin in SE Australia, following clearing of native woody vegetation for pasture [*Allison et al.*, 1990; *Leaney et al.*, 2003; *Cartwright et al.*, 2007]. In SW USA, long-term rises in the deep water table were also reported, as a consequence of a change from discharge through evapotranspiration in natural ecosystems to recharge (median: 24 mm a^{-1}) following conversion to cropland [*Scanlon et al.*, 2005b]. Whereas land clearing appears to consistently increase groundwater recharge by at least 1 order in magnitude, different recharge processes (direct or indirect) lead to various time lags in the water table response

to land cover changes. These case studies, although well documented, are few when compared to those reporting changes in surface water fluxes as a consequence of land use change; more groundwater-oriented research is needed for a better assessment of the variety of water table responses to land clearing in semiarid regions.

5.2.3. Land Clearing and Nitrate-Rich Groundwater

[41] Nitrate is a major component of biogeochemical cycles in semiarid regions, with frequently high values both in the unsaturated and saturated zones. In SW USA, high nitrate values were interpreted to result from atmospheric deposition and accumulation during the late Pleistocene and early Holocene periods ($\sim$10 to $\sim$18 ka BP) [e.g., *Stonestrom et al.*, 2004; *McMahon et al.*, 2006]. In Africa, various studies reported high nitrate values within the deep unsaturated zone [e.g., *Edmunds et al.*, 1992] and were locally reported to be linked with in situ production by natural N fixation [*Deans et al.*, 2005]. High nitrate levels in aquifers were reported for regions where human pollution was unlikely and were interpreted as a consequence of natural processes in Texas [*Kreitler and Jones*, 1975], in Namibia [*Heaton*, 1984], in Mali [*Fontes et al.*, 1991], in central Australia [*Barnes et al.*, 1992], and in northern China [*Gates et al.*, 2008]. Although recognized as a widespread phenomenon [*Scanlon et al.*, 2007], natural nitrogen flux from the subsurface to groundwater was rarely monitored simultaneously with land clearing. For instance, in SW USA, *McMahon et al.* [2006, paragraph 36] concluded that "establishing links between land use and groundwater quality in areas with thick unsaturated zones is complicated by the presence of large subsoil chemical reservoirs and long transit times to the water table." However, in areas where focused (indirect) recharge processes dominate, this link may be more likely to be recorded, as shown by the rapid response of groundwater quality to land use change in semiarid Niger (Figure 8).

5.3. Lessons Learned From a Long-Term Survey

[42] Combining various approaches and long-term records are basic prerequisites for fully understanding the impact of land use change on the terrestrial water balance. In Africa, most studies described changes in land use, in water chemistry, in surface runoff or in groundwater dynamics separately, for different places and different periods; this has resulted in a complex picture of time frames and changes in water resources. However, a comprehensive understanding of changes in water resources requires integration of the various components of the water cycle. In SW Niger, using the chloride mass balance method, *Bromley et al.* [1997] estimated the long-term recharge to be of about 13 mm a^{-1} below the plateaus. More recently, using noble gas tracers, *Peeters et al.* [2003] obtained short residence times, of a few tens of years, for the same aquifer. Although these estimates may relate to different time scales or different places, both approaches considered the single assumption of direct (slow motion) recharge through the deep unsaturated zone, a process that was shown not to be dominant in the area [*Favreau et al.*, 2002b, 2004a]. Another complexity lies in the steady rise in the water table over the past decades; for radioisotope interpretation, considering a priori stable groundwater reserves would have led to a discrepancy between isotopic long-term estimates of groundwater recharge (1–4 mm a^{-1}) and recharge estimates obtained using hydrodynamic methods and data from recent surveys (25 $\pm$ 7 mm a^{-1}). The long-term record of groundwater levels allows this discrepancy to be interpreted as a result of the recent increase in groundwater recharge. As pointed out by *Simmers* [1997], preliminary knowledge on the hydrodynamic processes can greatly help in estimating the relevance of the computed groundwater balances. This implies, for semiarid areas, long-term monitoring of water fluxes.

5.4. Implications for Groundwater Management

[43] This study encompasses several key issues for rural development in the Sahel. Our results show that the net recharge available for agriculture and domestic use is $\sim$23 mm a^{-1}. Increasing crop yield, by using renewable groundwater resources for irrigation ("blue water") would be feasible in the study area and could greatly help reduce the impact of rainfall variability on crop production, which is the primary concern of farmers in the Sahel [*Rockström and Barron*, 2007]. Because the impact of global warming on rainfall in the Sahel is much debated, with models predicting contradictory trends for the 21st century [*Haarsma et al.*, 2005; *Held et al.*, 2005], relying more on groundwater for crop production could represent a reliable answer to mitigate the expected increase in temperature and potential evapotranspiration [*Hulme et al.*, 2001].

[44] Land clearing of valley bottoms has resulted in nitrogen leaching from the soil into the aquifer. Because most of the wells with nitrate concentration exceeding the WHO recommended limit of 10 mg L^{-1} (NO_3-N) were found near ponds and/or in the downstream part of catchments, groundwater pumping for consumption by humans and cattle should be located upgradient of ponds. Conversely, groundwater near ponds should be considered as a target for wells dedicated to irrigation, being significantly enriched in nitrate, one of the limiting nutrients for millet production in the Sahel [*Buerkert and Hiernaux*, 1998]. Most fields located on the downslope part of catchments were also reported as more productive [*Rockström et al.*, 1999]; increasing crop yield in these more favorable parts of the landscape by conjunctive use of irrigation and fertilizers may help to reduce the need to cultivate crops in the upstream part of catchments, where most of the gully development occurred as a result of more recent land clearing [*Loireau*, 1998; *Leblanc et al.*, 2008].

[45] In the lower part of the landscape, in a few valley bottoms, the water table was shown to have risen above the soil surface, creating permanent "blue" ponds [*Favreau*, 2000]. Although these ponds were shown to be of recent origin (<20 years in 2007) and of very limited areal extent (less than $\sim$20 in 2007, each of a few ha, over the entire 5000 km^2 CT aquifer study area), the steady rise in the water table implies that they will grow in number and in surface area as the groundwater level continues to rise. Because of high evaporation rates, these groundwater discharge areas may eventually result in increased salinity of groundwater and soils, making them less suitable for sustainable irrigation [e.g., *Valenza et al.*, 2000]. Permanent, instead of seasonal, ponding may also create a more favorable environment for malaria vectors, as shown for *Anopheles funestus* in SW Niger [*Labbo et al.*, 2004]. Limiting the extent of groundwater discharge ponds by

stabilizing the water table level would represent a positive side effect of increased groundwater pumping for irrigation.

6. Conclusions

[46] This paper synthesized one of the most comprehensive set of long-term studies (1950–2007) combining surface water and groundwater dynamics and groundwater quality to infer the impacts of land clearing on water resources in a semiarid part of Africa. The main conclusions are as follows.

[47] 1. A few decades after the onset of increasing intensity in land clearing (1950s), changes in land use have largely offset the negative climatic signal that prevailed at the regional scale (23% reduction in mean annual rainfall, 1970–1998 versus 1950–1969). Land clearing increased surface water resources by a factor close to 3 (runoff volume), with a 2.5-fold increase in drainage density (gullies) and more numerous ponds in the landscape.

[48] 2. Land clearing resulted in 1-order of magnitude increase in groundwater recharge relative to preclearing levels, from $\sim$2 mm a^{-1} to $\sim$25 mm a^{-1}. After 5 decades of continuous clearing, a new equilibrium has not been yet achieved and the aquifer reserves are still increasing in volume.

[49] 3. Land clearing and focused recharge beneath ephemeral ponds have degraded groundwater quality by increasing nitrate concentrations with current levels exceeding the recommended WHO limits in about 25% of pumped wells. Nitrate was shown to be of natural origin, with atmospherically derived and soil organic nitrogen as the main sources for nitrate in groundwater near ponds.

[50] With proper management, the measured changes in water quantity and quality could be used advantageously for water supply and food production. Degradation in water quality is a negative aspect for safe drinking water supply, but is limited in space to the vicinity of ponds. Increased groundwater resources could be used for irrigated agriculture to mitigate long-term variability in rainfall and climate change impacts on crop yield.

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References

Albergel, J. (1987), Sécheresse, désertification, et ressources en eau de surface: Application aux petits bassins du Burkina-Faso, in *The Influence of Climate Change and Climate Variability on the Hydrologic Regime and Water Resources*, edited by S. I. Solomon, M. Beran, and W. Hogg, *IAHS Publ.*, *168*, 355–365.

Allison, G. B., P. G. Cook, S. R. Barnett, G. R. Walker, I. D. Jolly, and M. W. Hughes (1990), Land clearance and river salinisation in the western Murray Basin, Australia, *J. Hydrol.*, *119*, 1–20, doi:10.1016/0022-1694(90)90030-2.

Balme, M., T. Lebel, and A. Amani (2006a), Dry years and wet years in the Sahel: Quo vadimus?, *Hydrol. Sci. J.*, *51*, 254–271, doi:10.1623/hysj.51.2.254.

Balme, M., T. Vischel, T. Lebel, C. Peugeot, and S. Galle (2006b), Assessing the water balance in the Sahel: Impact of small scale rainfall variability on runoff. Part 1: Rainfall variability analysis, *J. Hydrol.*, *331*, 336–348, doi:10.1016/j.jhydrol.2006.05.020.

Barber, W., and B. Dousse (1965), Rise in the water-table in parts of Potiskum division, Bornu province. Further observations, *Rec. Geol. Surv. Nigeria*, *9*, 41–57.

Barbiéro, L., and B. Van Vliet-Lanoë (1998), The alkali soils of the middle Niger valley: Origins, formation and present evolution, *Geoderma*, *84*, 323–343, doi:10.1016/S0016-7061(98)00003-2.

Bari, M. A., and N. J. Schofield (1992), Lowering of a shallow, saline water table by extensive eucalypt reforestation, *J. Hydrol.*, *133*, 273–291, doi:10.1016/0022-1694(92)90259-X.

Barnes, C. J., G. Jacobson, and G. D. Smith (1992), The origin of high nitrate ground waters in the Australian arid zone, *J. Hydrol.*, *137*, 181–197, doi:10.1016/0022-1694(92)90055-Z.

Biroue, W. K., and J. L. Schneider (1993), Towards the drying of the water table aquifer in the Chad Sahel?, *C. R. Acad. Sci., Ser. II*, *317*, 89–92.

Boeckh, E. (1965), Contribution à l'étude hydrogéologique de la zone sédentaire de la république du Niger, *Tech. Rep. BRGM/BFBH, DAK65-A20*, Dakar.

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

Bromley, J., W. M. Edmunds, E. Fellman, J. Brouwer, S. R. Gaze, J. Sudlow, and J.-D. Taupin (1997), Estimation of rainfall inputs and direct recharge to the deep unsaturated zone of southern Niger using the chloride profile method, *J. Hydrol.*, *188–189*, 139–154, doi:10.1016/S0022-1694(96)03157-5.

Brunel, J. P., G. R. Walker, J. C. Dighton, and B. Monteny (1997), Use of stable isotopes of water to determine the origin of water used by the vegetation and to partition evapotranspiration. A case study from HAPEX-Sahel, *J. Hydrol.*, *188–189*, 466–481, doi:10.1016/S0022-1694(96)03188-5.

Buerkert, A., and P. Hiernaux (1998), Nutrients in the West African Sudano-Sahelian zone: Losses, transfers and role of external inputs, *Z. Pflanzenernaehr Bodenkd.*, *161*, 365–383.

Canadell, J., R. B. Jackson, J. R. Ehleringer, H. A. Mooney, O. E. Sala, and E. D. Schulze (1996), Maximum rooting depth of vegetation types at the global scale, *Oecologia*, *108*, 583–595, doi:10.1007/BF00329030.

Cappelaere, B., B. E. Vieux, C. Peugeot, A. Maia, and L. Seguis (2003), Hydrologic process simulation of a semiarid, endoreic catchment in Sahelian West Niger, Africa. 2. Model calibration and uncertainty characterization, *J. Hydrol.*, *279*, 244–261, doi:10.1016/S0022-1694(03)00182-3.

Carter, J. D., and W. Barber (1958), The rise in the water-table in parts of Potiskum division, Bornu province, *Rec. Geol. Surv. Nigeria*, *5*, 5–13.

Cartwright, I., T. R. Weaver, D. Stone, and M. Reid (2007), Constraining modern and historical recharge from bore hydrographs, ^{3}H, ^{14}C and chloride concentrations: Application to dual-porosity aquifers in dryland salinity areas, Murray basin, Australia, *J. Hydrol.*, *332*, 69–92, doi:10.1016/j.jhydrol.2006.06.034.

Casenave, A., and C. Valentin (1992), A runoff capability classification system based on surface features criteria in semiarid areas of West Africa, *J. Hydrol.*, *130*, 231–249, doi:10.1016/0022-1694(92)90112-9.

Charreau, C., and R. Fauck (1970), Mise au point sur l'utilisation agricole des sols de la region de Séfa (Casamance), *Agron. Trop. Paris*, *25*, 151–191.

Crosbie, R. S., P. Binning, and J. D. Kalma (2005), A time series approach to inferring groundwater recharge using the water table fluctuation method, *Water Resour. Res.*, *41*, W01008, doi:10.1029/2004WR003077.

D'Herbès, J.-M., and C. Valentin (1997), Land surface conditions of the Niamey region: Ecological and hydrological implications, *J. Hydrol.*, *188–189*, 18–42, doi:10.1016/S0022-1694(96)03153-8.

D'Orgeval, T., and J. Polcher (2008), Impact of precipitation events and land use changes on West African river discharges during the years 1951–2000, *Clim. Dyn.*, *31*, 249–262, doi:10.1007/s00382-007-0350-x.

De Vries, J. J., E. T. Selaolo, and H. E. Beekman (2000), Groundwater recharge in the Kalahari, with reference to paleo-hydrologic conditions, *J. Hydrol.*, *238*, 110–123, doi:10.1016/S0022-1694(00)00325-5.

Deans, J. D., W. M. Edmunds, D. K. Lindley, C. B. Gaye, B. Dreyfus, J. J. Nizinski, M. Neyra, K. Ingleby, and R. C. Munro (2005), Nitrogen in interstitial waters in the Sahel; natural baseline, pollutant or resource?, *Plant Soil*, *271*, 47–62, doi:10.1007/s11104-004-1994-5.

Desconnets, J.-C., J.-D. Taupin, T. Lebel, and C. Leduc (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, doi:10.1016/S0022-1694(96)03158-7.

Edmunds, W. M., W. G. Darling, D. G. Kinniburgh, S. Kotoub, and S. Mahgoub (1992), Sources of recharge in Abu Delaig, Sudan, *J. Hydrol.*, *131*, 1–24, doi:10.1016/0022-1694(92)90211-D.

Elbaz-Poulichet, F., G. Favreau, C. Leduc, and J.-L. Seidel (2002), Major ion chemistry of groundwaters in the Continental Terminal water table of southwestern Niger (Africa), *Appl. Geochem.*, *17*, 1343–1349, doi:10.1016/S0883-2927(02)00024-0.

Elizondo, D., B. Cappelaere, and C. Faure (2002), Automatic versus manual model differentiation to compute sensitivities and solve non-linear inverse problems, *Comput. Geosci.*, *28*, 309–326, doi:10.1016/S0098-3004(01)00048-6.

Eltahir, A. B., and C. Gong (1996), Dynamics of wet and dry years in West Africa, *J. Clim.*, *9*, 1030–1042, doi:10.1175/1520-0442(1996)009<1030:DOWADY>2.0.CO;2.

Engel, V., E. G. Jobbagy, M. Stieglitz, M. Williams, and R. B. Jackson (2005), Hydrological consequences of Eucalyptus afforestation in the Argentine Pampas, *Water Resour. Res.*, *41*, W10409, doi:10.1029/2004WR003761.

Esteves, M., and J.-M. Lapetite (2003), A multi-scale approach of runoff generation in a Sahelian gully catchment: A case study in Niger, *Catena*, *50*, 255–271, doi:10.1016/S0341-8162(02)00136-4.

Favreau, G. (1996), Site-scale modelling of groundwater recharge in southwestern Niger (in French), M.S. thesis, Univ. Paris XI, Orsay, France.

Favreau, G. (2000), Characterization and modelling of a rising water table in the Sahel: Dynamic and geochemistry of the Dantiandou kori natural hollow aquifer (southwest Niger) (in French), Ph.D. thesis, 258 pp., Univ. Paris XI, Orsay, France.

Favreau, G., and C. Leduc (1998), Fluctuations à long terme de la nappe phréatique du Continental Terminal près de Niamey (Niger) entre 1956 et 1997, in *Water Resources Variability in Africa During the XXth Century*, edited by E. Servat et al., *IAHS Publ.*, *252*, 253–258.

Favreau, G., C. Leduc, and C. Marlin (2000), Reliability of geochemical and hydrodynamic sampling in a semi-arid water table, *J. Afr. Earth Sci.*, *31*, 669–678, doi:10.1016/S0899-5362(00)80014-7.

Favreau, G., C. Leduc, C. Marlin, M. Dray, J.-D. Taupin, M. Massault, C. Le Gal La Salle, and M. Babic (2002a), Estimate of recharge of a rising water-table in semi-arid Niger from ^{3}H and ^{14}C modeling, *Ground Water*, *40*, 144–151, doi:10.1111/j.1745-6584.2002.tb02499.x.

Favreau, G., C. Leduc, and P. Schroeter (2002b), Reply to comment on "Long-term rise in a Sahelian water-table: The Continental Terminal in South-West Niger" by Leduc C., Favreau, G., Schroeter, P., 2001. Journal of Hydrology 243, 43–54, *J. Hydrol.*, *255*, 263–265, doi:10.1016/S0022-1694(01)00517-0.

Favreau, G., C. Leduc, J.-L. Seidel, S. D. Ousmane, and A. Mariotti (2003), Land clearance and nitrate-rich groundwater in a Sahelian aquifer, Niger, in *Hydrology of the Mediterranean and Semiarid Regions*, edited by E. Servat et al., *IAHS Publ.*, *278*, 163–167.

Favreau, G., A. Guéro, and J.-L. Seidel (2004a), Comment on "Improving noble gas based paleoclimate reconstruction and groundwater dating using $^{20}Ne/^{22}Ne$ ratios" by F. Peeters et al. (2003) *Geochim. Cosmochim. Acta*, 67, 587–600, *Geochim. Cosmochim. Acta*, *68*, 1433–1435, doi:10.1016/j.gca.2003.07.022.

Favreau, G., J.-L. Seidel, C. Leduc, C. Marlin, and A. Mariotti (2004b), Land clearance as the cause of groundwater nitrate increase in semiarid Niger: Evidence using nitrate isotopes, paper presented International Workshop on the Application of Isotope Techniques in Hydrological and Environmental Studies, U. N. Educ., Sci., and Cult. Organ., Paris, France, 6–10 Sept.

Favreau, G., M. Boucher, J.-M. Vouillamoz, M. Descloitres, S. Massuel, Y. Nazoumou, and A. Legchenko (2007), Apport des sondages TDEM et RMP à une meilleure estimation des paramètres de la modélisation d'un aquifère libre en milieu semi-aride (Niger), paper presented at 6th Colloque Geofcan, Inst. de Rech. Pour le Dev., Bondy, France, 25–26 Sept.

Fontes, J.-C., J. N. Andrews, W. M. Edmunds, A. Guerre, and Y. Travi (1991), Paleorecharge by the Niger River (Mali) deduced from groundwater geochemistry, *Water Resour. Res.*, *27*, 199–214, doi:10.1029/90WR01703.

Freydier, R., B. Dupré, and J.-P. Lacaux (1998), Precipitation chemistry in intertropical Africa, *Atmos. Environ.*, *32*, 749–765, doi:10.1016/S1352-2310(97)00342-7.

Galle, S., M. Ehrmann, and C. Peugeot (1999), Water balance in a banded vegetation pattern. A case study of tiger bush in western Niger, *Catena*, *37*, 197–216, doi:10.1016/S0341-8162(98)90060-1.

Galy Lacaux, C., and A. I. Modi (1998), Precipitation chemistry in the Sahelian savanna of Niger, Africa, *J. Atmos. Chem.*, *30*, 319–343, doi:10.1023/A:1006027730377.

Gates, J. B., J. K. Böhlke, and W. M. Edmunds (2008), Ecohydrological factors affecting nitrate concentrations in a phreatic desert aquifer in northwestern China, *Environ. Sci. Technol.*, *42*, 3531–3537, doi:10.1021/es702478d.

Gaze, S. R., J. Brouwer, L. P. Simmonds, and J. Bromley (1998), Dry season water use patterns under Guiera senegalensis L. shrubs in a tropical savanna, *J. Arid Environ.*, *40*, 53–67, doi:10.1006/jare.1998.0435.

George, R. J., R. A. Nulsen, R. Ferdowsian, and G. P. Raper (1999), Interaction between trees and groundwaters in recharge and discharge areas—A survey of western Australian sites, *Agric. Water Manage.*, *39*, 91–113, doi:10.1016/S0378-3774(98)00073-0.

Girard, P., and C. Hillaire-Marcel (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, doi:10.1016/S0022-1694(96)03318-5.

Goutorbe, J.-P., et al. (1997), An overview of Hapex-Sahel: A study in climate and desertification, *J. Hydrol.*, *188–189*, 4–17, doi:10.1016/S0022-1694(96)03308-2.

Haarsma, R. J., F. M. Selten, S. L. Weber, and M. Kliphuis (2005), Sahel rainfall variability and response to greenhouse warming, *Geophys. Res. Lett.*, *32*, L17702, doi:10.1029/2005GL023232.

Hadjer, K., T. Klein, and M. Schopp (2005), Water consumption embedded in its social context, north-western Benin, *Phys. Chem. Earth*, *30*, 357–364, doi:10.1016/j.pce.2005.06.014.

Healy, R. W., and P. G. Cook (2002), Using groundwater levels to estimate recharge, *Hydrogeol. J.*, *10*, 91–109, doi:10.1007/s10040-001-0178-0.

Heaton, T. H. E. (1984), Sources of the nitrate in phreatic groundwater in the western Kalahari, *J. Hydrol.*, *67*, 249–259, doi:10.1016/0022-1694(84)90244-0.

Heilweil, V. M., T. S. McKinney, M. S. Zhdanov, and D. E. Watt (2007), Controls on the variability of net infiltration to desert sandstone, *Water Resour. Res.*, *43*, W07431, doi:10.1029/2006WR005113.

Held, I. M., T. L. Delworth, J. Lu, K. L. Findell, and T. R. Knutson (2005), Simulation of Sahel drought in the 20th and 21st centuries, *Proc. Natl. Acad. Sci. U. S. A.*, *102*, 17,891–17,896, doi:10.1073/pnas.0509057102.

Hiernaux, P., C. L. Bielders, C. Valentin, A. Bationo, and S. Fernandez-Rivera (1999), Effects of livestock grazing on physical and chemical properties of sandy soils in Sahelian rangelands, *J. Arid Environ.*, *41*, 231–245, doi:10.1006/jare.1998.0475.

Hoogmoed, W. B., and L. Stroosnijder (1984), Crust formation on sandy soils in the Sahel. 1. Rainfall and infiltration, *Soil Tillage Res.*, *4*, 5–23, doi:10.1016/0167-1987(84)90013-8.

Hulme, M., R. Doherty, T. Ngara, M. New, and D. Lister (2001), African climate change: 1900–2100, *Clim. Res.*, *17*, 145–168, doi:10.3354/cr017145.

Igwe, C. A. (2005), Erodibility in relation to water-dispersible clay for some soils of eastern Nigeria, *Land Degrad. Dev.*, *16*, 87–96, doi:10.1002/ldr.647.

Kalma, J. D., and S. W. Franks (2003), Rainfall in arid and semi-arid regions, in *Understanding Water in a Dry Environment: Hydrological Processes in Arid and Semiarid Zones*, *Int. Contrib. Hydrogeol.*, vol. 23, edited by I. Simmers, pp. 15–63, Balkema, Lisse, Netherlands.

Kendall, C., and R. Aravena (2000), Nitrate isotopes in groundwater systems, in *Environmental Tracers in Subsurface Hydrology*, edited by P. G. Cook and A. Herczeg, pp. 261–297, Kluwer Acad, Dordrecht, Netherlands.

Kho, R. M., B. Yacouba, M. Yayé, B. Katkore, A. Moussa, A. Iktam, and A. Mayaki (2001), Separating the effects of trees on crops: The case of *Faidherbia albida* and millet in Niger, *Agrofor. Syst.*, *52*, 219–238, doi:10.1023/A:1011820412140.

Kreitler, C. W., and D. C. Jones (1975), Natural soil nitrate: The cause of the nitrate contamination of groundwater in Runnels County, Texas, *Ground Water*, *13*, 53–62, doi:10.1111/j.1745-6584.1975.tb03065.x.

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

Labbo, R., A. Fouta, I. Jeanne, I. Ousmane, and J.-B. Duchemin (2004), *Anopheles funestus* in Sahel: New evidence from Niger, *Lancet*, *363*(9409), 660, doi:10.1016/S0140.

Lambin, E. F., H. J. Geist, and E. Leperse (2003), Dynamics of land use and cover change in tropical regions, *Annu. Rev. Environ. Resour.*, *28*, 205 – 241, doi:10.1146/annurev.energy.28.050302.105459.

Lang, J., et al. (1990), The Continental Terminal in West Africa, *J. Afr. Earth Sci.*, *10*, 79 – 99, doi:10.1016/0899-5362(90)90048-J.

Leaney, F. W., A. L. Herczeg, and G. R. Walker (2003), Salinization of a fresh palaeo-ground water resource by enhanced recharge, *Ground Water*, *41*, 84 – 92, doi:10.1111/j.1745-6584.2003.tb02571.x.

Le Barbé, L., T. Lebel, and D. Tapsoba (2002), Rainfall variability in West Africa during the years 1950 – 90, *J. Clim.*, *15*, 187 – 202, doi:10.1175/1520-0442(2002)015<0187:RVIWAD>2.0.CO;2.

Lebel, T., J.-D. Taupin, and N. D'Amato (1997), Rainfall monitoring during Hapex-Sahel. 1. General rainfall conditions and climatology, *J. Hydrol.*, *188 – 189*, 74 – 96, doi:10.1016/S0022-1694(96)03155-1.

Leblanc, M., G. Favreau, S. Tweed, C. Leduc, M. Razack, and L. Mofor (2007), Remote sensing for groundwater modelling in large semiarid areas: Lake Chad Basin, Africa, *Hydrogeol. J.*, *15*, 97 – 100, doi:10.1007/s10040-006-0126-0.

Leblanc, M., G. Favreau, S. Massuel, S. Tweed, M. Loireau, and B. Cappelaere (2008), Land clearance and hydrological change in the Sahel: SW Niger, *Global Planet. Change*, *61*, 135 – 150, doi:10.1016/j.gloplacha.2007.08.011.

Leduc, C., and M. Loireau (1997), Fluctuations piézométriques et évolution du couvert végétal en zone sahélienne (sud-ouest du Niger), in *Sustainability of Water Resources Under Increasing Uncertainty*, edited by D. Rosbjerg et al., *IAHS Publ.*, *240*, 193 – 200.

Leduc, C., and J.-D. Taupin (1997), Hydrochimie et recharge de la nappe phréatique du Continental Terminal (Niamey, Niger), in *Hydrochemistry*, edited by N. E. Peters and A. Coudrain-Ribstein, *IAHS Publ.*, vol. 244, pp. 235 – 243.

Leduc, C., J. Bromley, and P. Schroeter (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, doi:10.1016/S0022-1694(96)03156-3.

Leduc, C., G. Favreau, and P. Schroeter (2001), Long-term rise in a Sahelian water table: The Continental Terminal in south-west Niger, *J. Hydrol.*, *243*, 43 – 54, doi:10.1016/S0022-1694(00)00403-0.

Le Gal La Salle, C., C. Marlin, C. Leduc, J.-D. Taupin, M. Massault, and G. Favreau (2001), Renewal rate estimation of groundwater based on radioactive tracers (^{3}H, ^{14}C) in an unconfined aquifer in a semiarid area, Iullemeden Basin, Niger, *J. Hydrol.*, *254*, 145 – 156, doi:10.1016/S0022-1694(01)00491-7.

Legchenko, A., J.-M. Baltassat, A. Bobachev, C. Martin, H. Robain, and J.-M. Vouillamoz (2004), Magnetic resonance sounding applied to aquifer characterization, *Ground Water*, *42*, 363 – 373, doi:10.1111/j.1745-6584.2004.tb02684.x.

Le Maitre, D. C., D. F. Scott, and C. Colvin (1999), A review of information on interactions between vegetation and groundwater, *Water SA*, *25*, 137 – 152.

Lézine, A.-M. (2007), Pollen records, postglacial, Africa, in *Encyclopedia of Quaternary Science*, edited by S. A. Elias, pp. 2681 – 2699, Elsevier, Amsterdam.

Li, K. Y., M. T. Coe, N. Ramankutty, and R. De Jong (2007), Modeling the hydrological impact of land use change in West Africa, *J. Hydrol.*, *337*, 258 – 268, doi:10.1016/j.jhydrol.2007.01.038.

Loireau, M. (1998), Espaces, ressources, usages: Spatialisation des interactions dynamiques entre les systèmes sociaux et les sytèmes écologiques au Sahel nigérien, PhD thesis, 411 pp., Univ. Montpellier III, Montpellier, France.

Lørup, J. K., J. C. Refsgaard, and D. Mazvimavi (1998), Assessing the effect of land use change on catchment runoff by combined use of statistical tests and hydrological modelling: Case studies from Zimbabwe, *J. Hydrol.*, *205*, 147 – 163, doi:10.1016/S0168-1176(97)00311-9.

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

Mahé, G., and J.-C. Olivry (1999), assessment of freshwater yields to the ocean along the intertropical Atlantic coast of Africa (1951 – 1989), *C. R. Acad. Sci., Ser. IIa Sci. Terre Planetes*, *328*, 621 – 626, doi:10.1016/S1251-8050(99)80159-1.

Mahé, G., J.-E. Paturel, E. Servat, D. Conway, and A. Dezetter (2005), The impact of land use change on soil water holding capacity and river flow modelling in the Nakambe river, Burkina-Faso, *J. Hydrol.*, *300*, 33 – 43, doi:10.1016/j.jhydrol.2004.04.028.

Malam Issa, O., L. J. Stal, C. Défarge, A. Couté, and J. Trichet (2001), Nitrogen fixation by microbial crusts from desiccated Sahelian soils (Niger), *Soil Biol. Biochem.*, *33*, 1425 – 1428, doi:10.1016/S0038-0717(01)00046-3.

Martin-Rosales, W., and C. Leduc (2003), Dynamics of emptying of a temporary pond in the Sahel: The case study of Banizoumbou (southwestern Niger), *C. R. Geosci.*, *335*, 461 – 468, doi:10.1016/S1631-0713(03)00059-2.

Massuel, S. (2005), Evolution récente de la ressource en eau consécutive aux changements climatiques et environnementaux du sud-ouest Niger. Modélisation des eaux de surface et souterraines du bassin du kori de Dantiandou sur la période 1992 – 2003, Ph.D. thesis, 220 pp., Univ. Montpellier II, Montpellier, France.

Massuel, S., G. Favreau, M. Descloitres, Y. Le Troquer, Y. Albouy, and B. Cappelaere (2006), Deep infiltration through a sandy alluvial fan in semiarid Niger inferred from electrical conductivity survey, vadose zone chemistry and hydrological modelling, *Catena*, *67*, 105 – 118, doi:10.1016/j.catena.2006.02.009.

McMahon, P. B., and J. K. Böhlke (2006), Regional patterns in the isotope composition of natural and anthropogenic nitrate in groundwater, High Plains, USA, *Environ. Sci. Technol.*, *40*, 2965 – 2970, doi:10.1021/es052229q.

McMahon, P. B., K. F. Dennehy, B. W. Bruce, J. K. Böhlke, R. L. Michel, J. J. Gurdak, and D. B. Hurlbut (2006), Storage and transit time of chemicals in thick unsaturated zones under rangeland and irrigated cropland, High Plains, United States, *Water Resour. Res.*, *42*, W03413, doi:10.1029/2005WR004417.

Mortimore, M., M. Ba, A. Mahamane, R. S. Rostom, and B. Turner (2005), Changing systems and changing landscapes: Measuring and interpreting land use transformation in African drylands, *Geogr. Tidsskr.*, *105*, 45 – 62.

Nicholson, S. E., B. Some, and B. Kone (2000), An analysis of recent rainfall conditions in West Africa, including the rainy seasons of the 1997 El Nino and the 1998 La Nina years, *J. Clim.*, *13*, 2628 – 2640, doi:10.1175/1520-0442(2000)013<2628:AAORRC>2.0.CO;2.

Nickling, W. G., and S. A. Wolfe (1994), The morphology and origin of nabkhas, region of Mopti, Mali, West Africa, *J. Arid Environ.*, *28*, 13 – 30, doi:10.1016/S0140-1963(05)80017-5.

Peeters, F., U. Beyerle, W. Aeschbach-Hertig, J. Holocher, M. S. Brenwald, and R. Kipfer (2003), Improving noble gas based paleoclimate reconstruction and groundwater dating using ^{20}Ne/^{22}Ne ratios, *Geochim. Cosmochim. Acta*, *67*, 587 – 600, doi:10.1016/S0016-7037(02)00969-9.

Peugeot, C., M. Esteves, S. Galle, J.-L. Rajot, and J. P. Vandervaere (1997), Runoff generation processes: Results and analysis of field data collected at the east central supersite of the HAPEX-Sahel experiment, *J. Hydrol.*, *188 – 189*, 179 – 202, doi:10.1016/S0022-1694(96)03159-9.

Peugeot, C., B. Cappelaere, B. E. Vieux, L. Séguis, and A. Maia (2003), Hydrologic process simulation of a semiarid, endoreic catchment in Sahelian West Niger: 1. Model-aided data analysis and screening, *J. Hydrol.*, *279*, 224 – 243, doi:10.1016/S0022-1694(03)00181-1.

Raynaut, C. (2001), Societies and nature in the Sahel: Ecological diversity and social dynamics, *Global Environ. Change*, *11*, 9 – 18, doi:10.1016/S0959-3780(00)00041-8.

Redelsperger, J.-L., C. D. Thorncroft, A. Diedhiou, T. Lebel, D. J. Parker, and J. Polcher (2006), African monsoon multidisciplinary analysis: An international research project and field campaign, *Bull. Am. Meteorol. Soc.*, *87*, 1739 – 1746, doi:10.1175/BAMS-87-12-1739.

Reenberg, A., T. Louring-Nielsen, and K. Rasmussen (1998), Field expansion and reallocation in the Sahel—Land-use pattern dynamics in a fluctuating biophysical and socio-economic environment, *Global Environ. Change*, *8*, 309 – 327, doi:10.1016/S0959-3780(98)00003-X.

Ribolzi, O., M. Hermida, H. Karambiri, J.-P. Delhoume, and L. Thiombiano (2006), Effects of aeolian processes on water infiltration in sandy Sahelian rangeland in Burkina-Faso, *Catena*, *67*, 145 – 154, doi:10.1016/j.catena.2006.03.006.

Rockström, J., and J. Barron (2007), Water productivity in rainfed systems: Overview of challenges and analyses of opportunities in water scarcity prone savannahs, *Irrig. Sci.*, *25*, 299 – 311, doi:10.1007/s00271-007-0062-3.

Rockström, J., J. Barron, J. Brouwer, S. Galle, and A. de Rouw (1999), On farm temporal and spatial variability of soil and water in pearl millet cultivation, *Soil Sci. Soc. Am. J.*, *63*, 1308 – 1319.

Scanlon, B. R., D. G. Levitt, R. C. Reedy, K. E. Keese, and M. J. Sully (2005a), Ecological controls on water-cycle response to climate variability in deserts, *Proc. Natl. Acad. Sci. U. S. A.*, *102*, 6033 – 6038, doi:10.1073/pnas.0408571102.

Scanlon, B. R., R. C. Reedy, D. A. Stonestrom, D. E. Prudic, and K. F. Dennehys (2005b), Impact of land use and land cover change on groundwater recharge and quality in the southwestern US, *Global Change Biol.*, *11*, 1577–1593, doi:10.1111/j.1365-2486.2005.01026.x.

Scanlon, B. R., K. E. Keese, A. L. Flint, L. E. Flint, C. B. Gaye, W. M. Edmunds, and I. Simmers (2006), Global synthesis of groundwater recharge in semiarid and arid regions, *Hydrol. Processes*, *20*, 3335–3370, doi:10.1002/hyp.6335.

Scanlon, B. R., I. Jolly, M. Sophocleous, and L. Zhang (2007), Global impacts of conversions from natural to agricultural ecosystems on water resources: Quantity versus quality, *Water Resour. Res.*, *43*, W03437, doi:10.1029/2006WR005486.

Séguis, L., B. Cappelaere, G. Milesi, C. Peugeot, S. Massuel, and G. Favreau (2004), Simulated impacts of climate change and land-clearing on runoff from a small Sahelian catchment, *Hydrol. Processes*, *18*, 3401–3413, doi:10.1002/hyp.1503.

Siebert, S., P. Doll, J. Hoogeveen, J. M. Faures, K. Frenken, and S. Feick (2005), Development and validation of the global map of irrigation areas, *Hydrol. Earth Syst. Sci.*, *9*, 535–547.

Simmers, I. (1997), Groundwater recharge principles, problems and developments, *Recharge of Phreatic Aquifers in (Semi-) Arid Areas, Int. Assoc. of Hydrogeol.*, vol. 19, edited by I. Simmers, pp. 1–18, Balkema, Rotterdam, Netherlands.

Stonestrom, D. A., D. E. Prudic, R. L. Laczniak, and K. C. Akstin (2004), Tectonic, climatic and land-use controls on groundwater recharge in an arid alluvial basin: Amargosa desert, USA, in *Groundwater Recharge in a Desert Environment: The Southwestern United States*, *Water Sci. Appl.*, vol. 9, edited by J. F. Hogan, F. M. Philipps, and B. Scanlon, pp. 29–47, AGU, Washington, D.C.

Taupin, J.-D., G. Gaultier, G. Favreau, C. Leduc, and C. Marlin (2002), Isotopic variability of Sahelian rainfall at different time steps in Niamey (Niger, 1992–1999), climatic implications, *C. R. Geosci.*, *334*, 43–50, doi:10.1016/S1631-0713(02)01702-9.

Taylor, C. M., E. F. Lambin, N. Stephenne, R. J. Harding, and R. L. H. Essery (2002), The influence of land use change on climate in the Sahel, *J. Clim.*, *15*, 3615–3629, doi:10.1175/1520-0442(2002)015<3615:TIOLUC>2.0.CO;2.

Tengberg, A. (1995), Nebkha dunes as indicators of wind erosion and land degradation in the Sahel zone of Burkina Faso, *J. Arid Environ.*, *30*, 265–282, doi:10.1016/S0140-1963(05)80002-3.

Valentin, C., J.-L. Rajot, and D. Mitja (2004), Responses of soil crusting, runoff and erosion to fallowing in the subhumid and semi-arid regions of West Africa, *Agric. Ecosyst. Environ.*, *104*, 287–302, doi:10.1016/j.agee.2004.01.035.

Valenza, A., J.-C. Grillot, and J. Dazy (2000), Influence of groundwater on the degradation of irrigated soils in a semi-arid region, the inner delta of the Niger River, Mali, *Hydrogeol. J.*, *8*, 417–429, doi:10.1007/PL00010977.

Vandersypen, K., A. C. T. Keita, Y. Coulibaly, D. Raes, and J.-Y. Jamin (2007), Formal and informal decision making on water management at the village level: A case study from the office du Niger irrigation scheme (Mali), *Water Resour. Res.*, *43*, W06419, doi:10.1029/2006WR005132.

Viramontes, D., and L. Descroix (2003), Changes in the surface water hydrologic characteristics of an endoreic basin of northern Mexico from 1970 to 1998, *Hydrol. Processes*, *17*, 1291–1306, doi:10.1002/hyp.1285.

Vouillamoz, J.-M., G. Favreau, S. Massuel, M. Boucher, Y. Nazoumou, and A. Legchenko (2008), Contribution of magnetic resonance sounding to aquifer characterization and recharge estimate in semiarid Niger, *J. Appl. Geophys.*, *64*, 99–108, doi:10.1016/j.jappgeo.2007.12.006.

Warner, T. T. (2004), *Desert Meteorology*, 612 pp., Cambridge Univ. Press, Cambridge, U.K.

Wei, W., L. Chen, B. Fu, Z. Huang, D. Wu, and L. Gui (2007), The effect of land uses and rainfall regimes on runoff and soil erosion in the semi-arid loess hilly area, China, *J. Hydrol.*, *335*, 247–258, doi:10.1016/j.jhydrol.2006.11.016.

Wilcox, B. P. (2007), Does rangeland degradation have implications for global streamflow?, *Hydrol. Processes*, *21*, 2961–2964, doi:10.1002/hyp.6856.

Wood, W. W., and W. E. Sanford (1995), Chemical and isotopic methods for quantifying groundwater recharge in a regional, semiarid environment, *Ground Water*, *33*, 458–468, doi:10.1111/j.1745-6584.1995.tb00302.x.

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