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Abstract

The west African semiarid belt of the Sahel, south of the Sahara desert is one of the most sensitive places in the world to climatic and land cover changes. For the second half of the XXth century, lasting droughts and one of the world's highest population growth have resulted in major land cover change that can be quantified using aerial photographs. This paper examines land cover and hydrological changes over a 500 km^2 study area in the Sahelian environment of southwest Niger using a time series of normalised mosaics of aerial photographs dating back from 1950, field inquiries, and updated groundwater data. The study area was chosen (i) for its rural environment representative of the rain-fed agriculture belt of the Sahel and (ii) to encompass the main hydrological study sites investigated in this region for the past two decades (Hapex Sahel and AMMA experiments, 1990s – 2000s).

For the 1950 - 1992 period, all of the landscape units were significantly cleared, mostly to extend the agriculture surface area. Compared with 1950, tree cover on the plateaux had decreased by 28% in 1975 and 59% in 1992, while a decrease of 6% in 1975 and 42% in 1992 is detected in the valley bottoms; by 1975 and 1992, land clearance had affected respectively 23% and 87% of the sandy slopes. These results attest an accelerated loss in the perennial savannah vegetation that could not be recovered on short term. For the same period, aerial photographs show a 157% increase of the drainage density with the development of large drainage systems and new ponds. These geomorphological changes highlight a long-term increase in surface runoff production. In this endoreic environment, groundwater data display a widespread, steady rise of the water table that continues to present (2005); the mean rise of 4 m since the early 1960 (+15% in aquifer reserves). These trends for surface runoff and groundwater indicate that for this part of the Sahel, land clearance had a stronger effect on the terrestrial water balance than the monsoonal rainfall deficit. In terms of dynamics, the hydrological answer to land clearance appears as non-linear, with a stronger impact on the drainage network of a given land clearance percentage for the 1975-1992 period, compared to the earlier period (1950-1975) of the survey. For groundwater recharge, more sensitive to large drainage systems, this has resulted in a significant time-lag in the water table rise, of at least 30 years compared to the onset of the new land clearance dynamics.

This study is one of the best semiarid examples of combined analysis of land cover, surface water and ground water change on a long-term perspective. As the rate of land clearance increased for the past century in semiarid Africa, its main hydrological effects may not yet be fully perceptible and our results are therefore of broad interest for accurately simulating the respective impacts of climate and environmental changes on the terrestrial part of the water cycle.

Key words

Remote sensing, aerial photographs, drainage network, groundwater, land cover, semiarid area.

1. Introduction

The semiarid belt of the Sahel in Africa, south of the Sahara desert, is one of the most sensitive places in the world to small environmental changes (Scheffer et al., 2001). During the Holocene, gradual climatic changes have caused abrupt shifts in the hydrological balance, as shown by the rapidly moving vegetation distribution (Foley et al., 2003), changing aquifer recharge rates (Zuppi and Sacchi, 2004) and dramatic fluctuations in lake area (Hoelzmann et al., 2000; Leblanc et al., 2006).

For the past few decades, this region has experienced both (i) a lasting drought, which started at the end of the 1960s and culminated in the 1980s with a rainfall deficit of 25-40% compared to the 1930-60s (Hunt, 2000; L'Hôte et al., 2002) and (ii) one of the world's highest demographic growth, from about 1.5% yr^{-1} in the 1950s to about 3% yr^{-1} in the 1990s, that has resulted in a three fold increase of the population for the second part of the XXth century (Raynaut, 2001; UNPP, 2005). This strong demographic growth has been supported by an increase in the surface area of rain-fed cultivated lands at the expense of the natural wooded savannah (Ringrose and Matheson, 1992; Raynaut, 2001). For the same period, the main basic source of energy throughout the whole Sahel has remained firewood (FAO, 2003; Bugaje, 2006).

Several field-based and remote sensing studies from various parts of the Sahel showed that these climatic and demographic changes have resulted in a severe degradation of the natural vegetation, mostly noticeable on the perennial tree cover (e.g. Vetaas, 1993; Diouf and Lambin, 2001; Rasmussen et al., 2001). Several studies have also reported significant changes in the hydrological balance. Regionally, both lower evapotranspiration fluxes (McGuffie et al., 1995; Taylor et al., 2002) and lower river discharges to the Atlantic ocean (Mahe and Olivry, 1999) are observed. At a smaller scale, contradictory changes compared to rainfall fluctuations have been described, with both decreases or increases in river flows (Mahe et al., 2000; Mahe et al., 2005), and falling or rising water table elevations (Biroue and Schneider, 1993; Leduc et al., 2001). However, most of these studies have investigated the change in climate, land use and hydrology independently and within different regions of the Sahel. This has resulted in a complex picture of time frames and shifts in the hydrological balance in response to land use and climate change.

Remote sensing is a valuable tool for monitoring rapid environmental changes. At a regional scale, satellite data, such as Landsat MSS or NOAA-AVHRR, have been widely used for mapping changes in the vegetation density and/or rainfall use efficiency (e.g., Ringrose and Matheson, 1992; Hein and de Ridder, 2006). Some of these satellite data sets are available since the early 1980s (1972 for Landsat data), with a coarse spatial resolution ranging from about 10^2 to 10^6 m^2. Aerial photographs, at scales down to 1/50 000 and dating back to the 1950s for most parts of the Sahel, allows reconstruction of changes at a much higher spatial resolution (few m^2) and over a longer period. However, the main restriction to the extensive use of aerial photograph is that they require a fastidious, time-consuming data pre-processing (Couteron, 2002). As a consequence, the information they contain has been seldom used, although a few attempts proved to be successful in accurately mapping land cover changes (Tengberg, 1995; Hiernaux and Gerard, 1999; Couteron, 2002). For the practical reasons aforementioned, these studies often considered areas of a few km^2 and the changes between two dates.

Using a time series of aerial photographs together with updated long-term water surveys and field enquiries, the aim of this paper is to characterize and quantify the dynamics of land and water changes that have occurred in a representative 500 km^2 area of the central Sahel. This analysis is performed in southwest Niger, where a wealth of hydrological studies conducted over the past 15 years provide the finest appraisal of the eco-hydrological processes in semiarid West Africa (e.g., D'Herbes and Valentin, 1997; Galle et al., 1999; Martin-Rosales and Leduc, 2003; Massuel et al., 2006). In this region, the best integrator of hydrological change is the water table because (i) it acts as the final outlet for surface water runoff and (ii) groundwater data dates back to the 1960s and documents the spectacular changes in the hydrological budget that have occurred (Leduc et al., 2001; Favreau et al., 2002). On a long term, multi-decennial perspective, the relationships between land use, land cover and drainage network changes are discussed in terms of time lag, non linear processes and direct or indirect impacts leading to the observed changes in surface water and groundwater resources. Finally, this study provides key criterion for semiarid areas at a global scale for a diagnosis in water resources changes, based on a determination of hydrological processes and land cover changes as observed by remote sensing.

2. Study area and background

The study area is located in the Sahelian environment of southwest Niger, at a mean distance of 60 km east of Niamey (Fig. 1). The rural population, mainly living on rain-fed cropping, is spread over numerous villages with few hundreds of inhabitants. Increase in population for the second half of the XXth century was shown to be representative of West Africa (i.e., near +1.5% yr^{-1} in the 1950s, increasing to 3 % yr^{-1} in the 1980-1990s) but with locally higher rates for some decades (e.g., up to 7.5% for few cantons during the 1977-1988 period; Loireau, 1998); the resulting population density was approximately 30 inhab.km^{-2} according to the last 2001 census.

The climate is semiarid, with a potential evapotranspiration near 2500 mm yr^{-1} and a yearly mean rainfall of 567 mm (1908-2003; Niamey Airport, pers. com.). The Sahelian rainfall deficit observed for the 1970-1990s is ~25 % compared to the 1950-60s; this deficit results mainly from a decrease in the mean number of rainfall events per year, whereas the mean rainfall amount per event and the rainfall intensity remained unchanged (Balme et al., 2006). At the seasonal scale, 90% of the annual rainfall, mostly of convective origin, occurs during June to September. The usually short rainfall events falling on crusted soils results in Hortonian runoff that rapidly (within 1-3 h) concentrates in temporary ponds, natural outlets of endoreic catchments of a few square kilometres. In this environment, all hydrological data indicate that most of the groundwater recharge is indirect and occurs by deep infiltration below ponds and gullies (Desconnets et al., 1997; Martin-Rosales and Leduc, 2003; Massuel et al., 2006).

The unconfined aquifer is part of the Continental Terminal formation (Tertiary), which is made up of loosely cemented clays, silts and sands. The Continental Terminal outcrops over a surface area of 150,000 km^2 in Niger and extends further in West Africa (Lang et al., 1990). The landscape reflects the succession of former wetter and drier climatic conditions. The upper surface, locally covered by aeolian sands, represents the remains of a nearly horizontal laterite plateau (27 % of the area) cut by many sandy valleys (“kori” and “dallols”, Fig. 1) of highly variable size, formed during more humid periods of the Quaternary (Fig. 2). The differences in altitude never exceeds 100 metres, for slopes of the order of 1 to 2 %. To the southwest of the study area, the Niger River flows directly over the Precambrian basement and acts as a regional groundwater discharge area (Fig. 1). The water table elevation exhibits a classical pattern for large semiarid aquifers: a continuous, smooth surface (hydraulic gradients <1‰) with high piezometric fluctuations of up to a few metres observed near ponds or large gullies during the rainy season (Desconnets et al., 1997; Favreau et al., 2002). Depending on the topography, the depth to the water table varies between 75 m below the laterite plateaux to less than 5 m below the sandy valleys, for a mean water table depth of 50 m (2003 data). Surprisingly, recent investigations have revealed a long-term rise in the groundwater levels, with an average increase of 4 m since the early 1960s (Leduc et al., 2001). The explanation is that, following land clearance, increased runoff accumulates in temporary endoreic ponds, always in a perched position compared to the water table. As surface waters in ponds mostly infiltrates to the water table, increased runoff has resulted in an increase in groundwater recharge, estimated to be about tenfold since the 1950s (Favreau et al., 2002). For the same period, groundwater extraction remained lower than 1 mm yr^{-1} and mostly dedicated to domestic use and livestock watering (Favreau, 2000).

The natural vegetation was a wooded savannah (dominant species: *Acacia sp., Balanites aegyptiaca, Prosopis sp.*) but under increasing land clearance most of the sandy slopes are now covered by a patchwork of fallow (*Guiera senegalensis* dominated) and rain-fed millet fields (Loireau, 1998). As elsewhere in the Sahel, a typically semiarid banded vegetation pattern of “tiger bush” (*Combretum micranthum, Guiera senegalensis, Boscia sp.* dominated) covers most of the laterite plateaux (Galle et al., 1999). In the more clayey valley bottoms, the original bushy vegetation (*Piliostigma reticulatum, Bauhinia rufescens, Acacia sp.*) has now almost disappeared for cultivation of some specific water-demanding domestic crops (cassava, groundnut or sorghum).

3. Data and methods

A combination of various data sets was used to describe land cover and hydrological changes for the past decades: (i) time-series of aerial photographs, supplemented by some ancillary GIS data (digital elevation model (DEM), SPOT-derived land cover map), (ii) field reconnaissance inquiries and (iii) water level surveys, both for ground water and surface water. The study area was chosen to encompass the main hydrological study sites investigated in southwestern Niger during the Hapex Sahel experiment (Desconnets et al., 1997; Leduc et al., 1997). The location is at a significant distance (> 50 km) from Niamey,Niger’s capital, and therefore urban artefacts (locally described in Orr, 1995 for wood harvesting) are minimized in determining the land clearance dynamics.

3.1. Aerial photographs and associated digitized images

Panchromatic aerial photographs were obtained from the National Geographic Institutes of France (IGN) and Niger (IGNN) and used to construct radiometrically corrected and georectified digital mosaics at four dates (1950, 1960, 1975 and 1992), producing a time series covering forty-two years. The photograph characteristics varied between years; the details of the photographs used to construct the mosaics are given in Table 1. The area covered includes a main study zone of 380 km^2, and a second smaller zone of 120 km^2 (Fig. 1). The two study areas were entirely covered using 28 aerial photographs for 1950, 17 for 1975 and 10 for 1992. For 1960, fewer aerial photographs were available and it was only possible to cover the southern study area using 4 aerial photographs. Ancillary data included a few microlight aircraft panchromatic photographs for one more recent years (1998), a 1991 digital topographic map of the region at a scale of 1/200 000, a set of topographic maps at a scale of 1/50 000 and a land cover map at a scale of 1/50 000 derived from a October 1992 SPOT image (D'Herbes and Valentin, 1997). The DEM used (Massuel, 2005) was specifically produced for the study area with square mesh of 40 × 40 m^2, using a methodology described in Elizondo et al. (2002).

Aerial photographs were scanned with a Microtek Scanmaker 9600XL flatbed scanner at 1200 dots per inch (dpi). The scanner was checked for faults using a plain sheet of white paper (Mugglestone and Renshaw, 1998). The analysis of the resulting test scan did not show significant distortion, systematic striation or dots. Aerial photographs were scanned and converted into digitized images with grey-level values in the range 0-255 (8 bit grey scale). Scanned (or digitized) photographs are hereafter referred to as digitized images. At 1200 dpi the ground resolutions of the digitized images for 1950, 1960, 1975 and 1992 are approximately of 1.05 m, 1.08 m, 1.32 m and 1.27 m, respectively. These ground resolutions are sufficient to detect the land cover and hydrological changes in the study area. For instance, the average size of the temporary ponds is 26,000 m^2 and the smallest ponds are about 500 m^2, and the average width of the gullies varies from ~1 m in the upstream to 5 m in the downstream parts of the basins (Massuel, 2005). On the plateaux, the tiger bush vegetation is a few metres in height and displays an average canopy radius of 1.3 to 5.4 m depending on the tree species (Galle et al., 1999); the perennial tree cover on sandy slopes presents similar characteristics (Loireau, 1998).

All digitized images were converted to an optimal 1.5 m ground resolution, allowing the detection of most ground features while maintaining workable file sizes. Some information required for the conversion to orthophotos (camera reports) was not available; consequently, the images were rectified to map coordinates using a third order polynomial transformation and Delaunay triangulation. Relief displacement was not measured but was considered to be negligible due to the flat topography of the study area. A hybrid approach to georectification was adopted, involving both image to image rectification, and image to map georectification (Jensen, 1996). Each raw image was initially co-registered to each neighbouring image to produce a perfect mosaic for each year. The 1992 mosaic was then georectified to the topographic map, and subsequently the 1950, 1960, and 1975 mosaics were co-registered to the 1992 mosaic. Potential Ground Control Points (GCPs) when rectifying image to image could include anything as small as a single tree or a termites' nest. Alternatively, when rectifying image to map these features cannot be used as GCPs, as they are not found on the topographic map; therefore, GCPs are restricted to road or river intersections. Most of these GCPs could not be found on the three earliest mosaics due to varying photograph quality and the environmental and infrastructure changes that have occurred in the study area. There is also much less difference in scale between image dates than between any image and the small-scale topographic map. Therefore a greater number of common and more accurate GCPs are possible when rectifying image to image, rather than image to map. For this reason, only the 1992 mosaic was georectified to the 1991 topographic map and later used as a reference for the co-registration of the other mosaics. Projection and datum for all data sets used and produced was NUTM 31, Clarke 1880.

The images for each mosaic were obtained on a single day (or two days for 1975) and with the same camera; therefore, the radiometric variability within a mosaic was minimal except for some corner shadowing in each image that were clipped. This small variability between images in a mosaic was corrected by using histogram matching. Histogram matching modifies the histogram of one image so that it matches the histogram of a reference image, the result being a more uniform level of brightness between the two images making the seam between the two almost imperceptible. Each image in a mosaic was histogram matched to the image subjectively deemed to be least affected by the aforementioned differences. This was done after mosaicking as this defined the actual aerial extent of each image that used and resulted in edge clipping of most images to remove the corner shadows.

Relative radiometric normalisation was used to correct for inter-mosaic radiometric variability (Schott et al, 1988; Lunetta and Elvidge, 1999). This variability was more substantial due to the data being non-anniversary dates and possible differences in photographic equipment used between years. The 1992 mosaic was chosen as the reference to which each of the other mosaics were normalised. Correlating pixel values of pseudo-invariant targets present in both the mosaic being normalised and the reference scene developed a regression equation. The regression equation predicts what any given pixel value would be if the image was acquired in the same circumstances as the 1992 mosaic. Six targets were found for each of the 1950, 1960, and 1975 mosaics. Targets of varying brightness were chosen to obtain as accurate regression line as possible. Pseudo-invariant targets included bright and dark bare soil, both on the plateaux and valley bottoms (Séguis and Puech, 1997). Each mosaic was normalised to the 1992 mosaic by applying the appropriate regression equation to each pixel.

After image pre-processing, change detection was possible in overlapping areas of the mosaics. For each of the mosaics, the extent of the drainage network was digitized manually. Edge detection filters and histogram stretch were used for visual enhancement. The available digital elevation model and topographic maps were used to cross-check this mapping, and reject linear features that did not follow the slope of the terrain. Changes in the drainage network were assessed by comparing the lengths and connectivity of the drainage network for the whole study area.

The plateaux and the valley bottoms (Fig. 2) have limited land cover types: perennial trees, bare soil, grass and water. Perennial trees always represent the darkest pixels of the digitized images in these areas. A simple threshold technique (DN<140) on the normalized mosaics allows the detection of perennial trees. Changes in the perennial tree cover were estimated for the plateaux and the valley bottom landscape units by applying this threshold technique to all the normalized mosaics. More land cover types exist on the cultivated sandy slopes, and spectral limitations of the panchromatic images made it more difficult to derive meaningful information on deforestation in these areas. Land clearing on the sandy slopes will be discussed using the field-based surveys presented in several previous, smaller scale studies (Loireau, 1998; Seguis et al., 2004).

3.2. Field inquiries

A few days of field inquiries, both for (i) ground truth validation of aerial photographs detected units and (ii) changes in the landscape as perceived by its inhabitants were performed between 1996 and 2003 (Favreau, 2000; Massuel, 2005; Fig. 1). Field inquiries consisted of portable GPS delineation of current ponds, densely wooded valley bottoms, banded vegetation pattern on plateaux and main drainage networks on the sandy slope. These ground truth data were completed with semi-structured interviews of the village leaders and/or groups of farmers about their perception of changes in the landscape over the past decades.

3.3. Surface and ground water surveys

This paper expands on hydrological and hydrogeological data sets that have been described elsewhere (e.g., Desconnets et al., 1997; Leduc et al., 2001; Martin-Rosales and Leduc, 2003). During the early 1990s, within the framework of the international Hapex-Sahel experiment, the hydrodynamics of a few natural ponds were monitored at twice-daily or three-hourly intervals (Fig. 1). These surveys provided estimates on the indirect recharge rates through the pond systems (Desconnets et al., 1997). In addition, the water table fluctuations were surveyed at about one hundred wells or boreholes at a quarterly to bimonthly frequency (Leduc et al., 1997). For the study area, this represents an average of 150 measurements for each of the 45 observation wells (Fig. 1). Most of these hydrodynamic surveys have continued to the present, as part of the international African Monsoon Multidisciplinary Analysis project (2005-2009, *http://medias.obs-mip.fr/amma*). They provide a detailed perspective on the hydrological balance variability since the early 1990s. High quality groundwater data from the 1940s to 1960s were obtained in old reports and included in the piezometric time series (Favreau, 2000; Leduc et al., 2001). In this paper, groundwater chronicles are updated with new data, comprising between 50 to 100 % of additional measurements performed over 1999-2005, for a resulting time series over the 1963-2005 period.

4. Results

4.1 Land cover and land use change

Using aerial photographs, the most striking change in land cover is observed on the laterite plateaux, where deforestation is obvious for the whole period (Fig. 3). In the northern area, the woody vegetation covered 65% of the plateaux in 1950, 47% in 1975 and only 27% in 1992 (this last figure is consistent with the 25% in tree cover estimated by Galle et al. (1999) for the same year on a 0.3 km^2 area, near Banizoumbou; Fig. 1). In the southern area, a similar trend is observed, with a small decrease of 7% noticed between 1950 and 1960 (Table 2). Over the whole study area, the resulting decrease is of 38% in tree cover for the 1950-1992 period. A similar decrease of 38% in tree cover was obtained for the 1950 - 1995 period by Hiernaux and Gerard (1999) on a 9 km^2 plateau area near Kodey (Fig. 1).

Land clearance on sandy slopes is visually at least as important as on the plateaus, though less easily quantifiable when relying solely on aerial photographs. Where field inquiries were conducted to constrain the interpretation, the rapid increase in both the number and extent of the millet fields was obvious (Fig. 4); land use change on the slopes appears more important for the 1975-1992 period (17 years) than for the previous 1950-1975 period (25 years). For the 2 km^2 Wankama catchement, the natural savannah cover decreased of 20% in surface area between 1950 and 1975, and of 32% between 1975 and 1992 (Seguis et al., 2004). According to Loireau's estimates on a surface area of about 630 km^2 (Fig. 1) more than two thirds of the land cleared on sandy slopes occurred during 1975 -1992, with only 11% of the natural vegetation cover remaining in 1992 (Table 2).

Changes in land cover are also noticeable for the ecologically significant valley bottom landscape unit. Most of these areas (64%) appear as black, densely wooded areas on aerial photographs (Fig. 2 and 5). In 1975, some of these areas were already completely cleared for cultivation (e.g. Fig. 5) but most of the clearance occurred between 1975 and 1992, by then 42% of the valley bottom canopy had disappeared (Table 2).

Field inquiries and interviews largely confirmed the land use change dynamics as observed from aerial photographs. Most of the inhabitants have described the following succession of events: by the end of the 1960s, the need to cultivate new fields for millet crop have led to the expansion of land clearance, mostly on sandy slopes or in clayey valley bottoms. As recognized by the villagers, this resulted in a complete clearance from the hillslopes to the foot of the plateaux by the mid-1990s. Plateaux are traditionally used to supply firewood and are widely recognized as less densely wooded than before. In some villages where the neighbouring plateaux are covered by aeolian sands, millet fields have expanded at the expense of the natural tree cover.

4.2. Surface water change

Our analysis of the time series of aerial photographs, validated by field inquiries, shows that the drainage network and pond systems have been subject to dramatic changes over the past decades. The first major change is the spectacular development of the drainage network over the whole study area (Fig. 6). Gullies continuously increased in number and length from 1950 to 1975 and 1992, resulting in more than a 2.5 fold increase in the drainage density (Table 3). For a more systematic description of the change, the connectivity of the gullies was quantified by determining the Shreve's (1966) Number (SN) of the final collector (The Shreve's number is a relevant parameter for quantifying the connectivity of the drainage network; Maidment, 1993). Fig. 7 shows the histograms for the distribution of the drainage systems according to their Shreve order in 1950, 1975 and 1992 for the whole study area. Although, most gullies remained with a small Shreve order during the whole period (mean SN of 1.3, 1.4 and 2.1 in 1950, 1975 and 1992 respectively), a striking feature is this apparition of some large drainage systems. The number of drainage system with a Shreve order >3 was only 17 in 1950, 30 in 1975 but 83 in 1992. The maximum Shreve order for a drainage system in the study area was 8 in 1950, 11 in 1975 and 47 in 1992. A detailed example of the development of a large drainage system for the 1950-1992 period is displayed in Fig. 8. Visually, an increase in the length of the gullies is already obvious between 1950 (SN = 2) and 1960 (SN = 3); however, the SN is rising more significantly between 1960 and 1975 (SN = 10) and 1992 (SN = 19).

A second, more subtle change in the drainage network occurred for mid-slope fan areas, a hydrological feature which is common on sandy slopes (D'Herbes and Valentin, 1997). In response to increased runoff, a general upslope shift of the fan position was noticed. On the example reported in Fig 9, the head of the alluvial fan shifted by 140 m between 1950 and 1992, and a further 80 m between 1992 and 2005; this has resulted in a much larger sandy fan. Because alluvial fans have been shown to infiltrate most of the run-on water to the water table (Massuel et al., 2006), such a change has significant implications for groundwater recharge.

A third significant observation is that most of the hill slope ponds (Fig. 2) are of recent origin. In most places, the ponds appeared after a complete land clearance of the valley bottoms to cultivate millet fields (Fig. 5); in other places, some ponds appeared even when the valley bottom remained densely vegetated (e.g. for 1992, Fig. 2). Field inquiries and interviews confirmed that the appearance of new ponds has been a widespread phenomenon. Additionally, villagers spontaneously recognized that if ponds of the “Kori” type had always existed, they are now receiving much more surface runoff than before. Using the 40×40 m DEM produced for the area to delineate watersheds, the 09/1992 photograph mosaic for the pond census and field trip surveys as validation, hill slope ponds were shown to be in a ratio of 2/1 compared to Kori ponds (Massuel, 2005). Moreover, water level monitoring showed that most (> 85%) of the incoming surface water to the ponds rapidly infiltrates to the water table (e.g. Kafina, Fig. 4c; Favreau, 2000). This result challenges preliminary surveys which suggested that Kori ponds were the dominant type and the most significant for groundwater recharge (Desconnets et al., 1997). Because most of the Hillslope ponds are of recent origin (Fig. 4c) this result is of importance for explaining the present distribution of groundwater recharge.

4.3. Groundwater change

Groundwater records obtained from a hundred sites in southwestern Niger have shown a continuous rise of the water table since the early 1990s (Leduc et al., 1997). This trend has also been observed over the longer-term since the 1950-60s (Leduc et al., 2001; Favreau et al., 2002). More recent data (1999-2005), presented here, confirm that the trend continues up to now, the current groundwater levels are the highest ever recorded (Fig. 9). For the study area, the rise in the water table started by the middle of the 1980s, independently of the position in the landscape and whatever the depth to the water table (Fig. 10). A synthetic, time series of water table elevation is therefore considered for discussing the groundwater changes that have occurred over the past 4 decades. The mean increase in levels since the early 1960s is now estimated to be close to 4 m (Fig. 11).

5. Discussion

5.1. Origin and dynamics of the changes

The comparison of the land use / land cover, surface water drainage and groundwater levels changes offers a unique insight of the environmental and hydrological processes in play in the Sahel in response to climate variability and rapid land clearance.

The perennial vegetation cover displays a general contraction since the 1950s, with relatively little change for the 1950 - (1960) - 1975 period, and a much more rapid degradation between 1975 and 1992. For sandy slopes and valley bottoms, our results showed that cultivation of new millet fields in response to an increasing demographic pressure was the main cause of the diminution of the natural vegetation. For tiger bush on the plateaux, this cause could also be important at a local scale (Hiernaux and Gerard, 1999); at a larger scale, both the influence of the climate variability (Couteron, 2002) or of external and local demand for firewood

(Spath and Francis, 1994) need to be considered. The significant decrease in the tiger bush vegetation cover for the relatively humid 1950 and 1960 decades (Fig. 11A), on the same rate as for the 1950-1975 period and of similar intensity as for sandy slopes (Fig. 11B) indicate that the climatic factor is probably not the single factor in play. According to Spath and Francis (1994), the firewood demand for Niamey was estimated to be of the order of 200 000 tons yr^{-1} for the early 1990s, most of the firewood coming then from a few tens of km from the city. The lack of significant increase in the contraction rate of tiger bush on plateaux for the 1975-1992 period confirms that the external demand for firewood is unlikely to be the dominant factor for tiger bush shrinkage; moreover, personal observations suggest that the plateaux of the study area have become a main source for urban firewood only by the end of the 1990s.

An estimate of the respective impacts of wood harvesting and rainfall variability on the plateaus' perennial vegetation is made possible by considering the empiric relationship between the mean rainfall amount (averaged over 15 years) and the interband:band ratios built from about 10 sites with tiger bush in southwestern Niger (Valentin and D'Herbes, 1999; Equation 1):

$$y = 4.13\ e^{(-0.0026x)} \qquad (1)$$

where "y" stands for the interband:band ratio (adimensional) and "x" is the annual rainfall (in mm) averaged over the 15 years preceding the considered year. Between 1950 and 1975, the computed decrease from 65% to 47% in tree cover corresponds to a change in the mean annual rainfall from 556 to 583 mm (Niamey, airport, averaged for the 15 years preceding 1950 or 1975); this implies that for this period, all of the tiger bush shrinkage would have been due to human influence. Between 1975 and 1992, the wooded cover decreased from 47% down to 27%, for a decrease in the mean annual rainfall from 583 mm down to 496 mm. For this period, according to Equation 1, the decrease in the tiger bush cover should not have exceeded 4%; the climate variability could therefore be accounted for about 20% of the tiger bush shrinkage, the remaining (80%) being due to human influence (estimating the respective impacts of wood harvesting or land clearance for cultivation would need a more specific study).

In western Africa, runoff production was shown to depend heavily on soil surface properties (Casenave and Valentin, 1992). In southwestern Niger, the general decrease in vegetation cover has modified the hydraulic properties of the top cm of the soil and has led to an increase in Hortonian runoff collected in numerous gullies and ponds (Valentin et al., 2004). This has resulted in changes in the drainage network that appear among the most rapid and most convincing ever described for the Sahel. Enhanced runoff has resulted in an increase in both the number and in the length of the gullies, therefore increasing the drainage density (Fig. 11C). Within the limits of the study area, at the scale of a 2 km^2 watershed, Seguis et al. (2004) estimated by hydrological modelling that change in land cover had multiplied the mean annual runoff coefficient by a factor close to three for the 1950-1992 period (Wankama, Fig. 1). Although the number of new ponds created for the past decade in response ton increased runoff remains difficult to estimate (aerial photographs were taken during the dry season), it is clear from our field inquiries that their number has dramatically increased for the past decades. Our results indicate that the main outbreak occurred between 1975 and 1992, when the drainage network became more and more connected, as shown by the abrupt increase in the mean length of each drainage system (Fig. 11C) and the occurrence of drainage systems with larger Shreve's number (Fig. 7). This non-linear process rapidly increased the volume of surface water reaching the ponds and/or created new ponds (e.g., Fig. 5). When compared to land cover dynamics, this period corresponds to a change in natural vegetation cover (compared to the 1950) higher than 23-28%, by when the natural vegetation cover was < 65% of the total surface area (Table 1). A similar conclusion was obtained by hydrological modelling at a larger scale for the Chad and Niger basins, where a threshold effect for the hydrological response to land clearance is suggested when the deforestation percentage is higher than 50% (Li et al., 2007). Although additional studies would be needed to make these figures more precise, the existence of a threshold effect in the hydrological answer to land clearance in semiarid west Africa is obviously a key factor to take into account when simulating future changes in the hydrological budget.

In Niger southwest, the unconfined sedimentary aquifer act as a collector of surface water infiltrated through the drainage system and represents the best integrator of hydrological changes (Leduc et al., 2001). The long-term water table rise (Fig. 11D) implies a significant increase in recharge, as groundwater withdrawal has remained low during this period (< 1 mm yr^{-1}, no irrigation). Change in the groundwater balance mainly started for the 1980s, i.e. for a period exhibiting the lowest rainfall records (Fig. 11A). Groundwater recharge appears therefore much more related to change in the land cover (Fig. 11B) than to climate variability. By crossing various hydrogeological methods, Favreau et al. (2002) estimated that groundwater recharge increased by about tenfold for the 1950s-1990s period. Our analysis shows that most of this increase in recharge occurred for the 1980s and 1990s (Fig. 11C). When compared to land use change, the time-lag between the presumed onset in the new land clearance dynamics (~1950; Loireau, 1998; Leduc et al., 2001) and the beginning of a measurable water table rise (1980) would be of about 30 years (Fig. 11B). A non-linear relationship is also obvious when comparing the groundwater response to land use change; for instance, whereas 24% of the observed land clearance occurred for the 1950-1975 period (Table 2), less than 10% of the change in groundwater reserves is estimated to having occurred for this period (Fig. 10; Fig. 11C). When compared to the changes in the hydrological network, the timing of the water table appears logically much more consistent, as shown by the close timing between groundwater and the increase in the mean length per drainage network (Fig. 11B). The very short time lag in the groundwater response to surface water changes is explained by the indirect recharge processes in play in the area: groundwater recharge occurs mainly by rapid infiltration down to the water table (in a few days or a few weeks) of surface water accumulated in ponds or main gullies (Desconnets et al., 1997; Martin Rosales and Leduc, 2003). Elsewhere in other semiarid areas, aquifers fed mostly by direct recharge (slow motion of infiltrated waters through the deep unsaturated zone) display a time-lag in the aquifer response which is a function of the depth to the water table; this results in time lags of the order of 10 to hundreds of years, as shown for instance in southwestern USA (Scanlon et al., 2005). In our study site, the new groundwater equilibrium was still not yet reached by the mid-2000s (Fig. 11D). Considering the very small natural discharge from the aquifer (mean depth to the water table of about 50 m in 2003; hydraulic gradients < 1‰) a new equilibrium will probably take decades to being reached, as long as the main environmental conditions (e.g. weak pumping, no irrigation, soil crusting) remain equal.

5.2 Representativity

For semiarid west Africa, changes in land use, surface runoff or groundwater recharge have been mostly described separately, and the representativity of the processes described for southwestern Niger are somehow difficult to estimate due to the lack of studies encompassing the hydrological cycle from soil surface down to the aquifer. At a global scale for semiarid regions, studies on changes in groundwater recharge following land use or land cover changes remain equally scarce (Scanlon et al., 2006).

The massive deforestation following the increase in human pressure that occurred for the past decades is a widely recognized phenomenon in Africa (FAO, 2003). For the Sahel region, the recent small increase in rainfall since the early 1990s (Fig. 11A) has enhanced the biomass productivity of the annual vegetation, as shown by large-scale remote sensing analysis (Hein and De Ridder, 2006); however, the perennial vegetation cover has been durably affected by the steady need for new lands, as shown by several studies having used remote sensing along with field surveys and interviews (e.g., Reenberg et al., 1998; Mortimore et al., 2005). Our study, combining these methods over a relatively large area (500 km^2) and quantifying land clearance as a function of the landscape units, brings results with significance at the whole Sahelian scale. Elsewhere in semiarid Africa, similar trends in land use and land cover changes have been described for different regions but with various timings, some areas being cleared much earlier in the XX[th] century (Guyer et al., 2007). At a global scale, the recent encroachment of croplands observed in Niger southwest appears among the most recent described in the semiarid tropics (Lambin et al., 2003). Therefore, although similar changes are likely to have occurred in other semiarid regions, only the most recent ones can be fully surveyed by remote sensing.

The observed increase in the drainage density of gullies, the upslope shift in alluvial fans and the increase in the number of endoreic ponds have been explained by an increase in Hortonian runoff following soil crusting and land clearance (Leduc et al., 2001; Seguis et al., 2004). In the southern part of the Sahel, a few studies have also described increasing runoff following deforestation for the second half of the XX[th] century, for watersheds ranging from a few km^2 up to 20 000 km^2 (Mahé et al., 2005). For more arid parts of the Sahel, land clearance may however have resulted for the past decades in dune revitalisation, as shown for instance at various scales in northern Burkina faso (Tengberg, 1995; Rasmussen et al., 2001). In this drier, more sandy environment, a complex pattern of surface water redistribution may occur, with infiltration occurring both in gullies and in the active parts of the dunes (Ribolzi et al., 2006). As shown by various examples at a global scale for semiarid areas, a given change in land use may therefore lead to different hydrological answers even for slight differences in the initial environmental conditions.

Increases in groundwater recharge following a change in land use has yet been rarely shown in West Africa. The difficulty is determining changes in groundwater recharge result mostly from water levels surveys that are rarely of sufficient accuracy to be conclusive. However, Barber and Dousse (1965) in north Nigeria (Lake Chad basin) reported water table rises up to 20 m for the 1930-1960s, as a consequence of land clearance that increased surface runoff and increase in river flow that, in turn, increased recharge through the river banks. In southern Senegal, Charreau and Fauck (1970) reported a plurimetric water table rise in twenty years following land clearance for cultivation. Elsewhere, long-term drops in water table levels were concurrently reported, as for instance in the central lake Chad basin (Biroué and Schneider, 1993). However, whereas a rising water table is directly conclusive for attesting an increase in recharge (as long as pumping from the aquifer increased) a decrease in the water table can conceal an opposite change, if pumping to the aquifer offsets higher recharge rates. More conclusive results may be expected from unsaturated zone profiles, as shown for instance in southeastern Australia (Allison et al., 1990) or southwestern USA (Scanlon et al., 2005) where groundwater recharge was shown to have increased at least by tenfold as a consequence of a change in land use. In northern Senegal, changes in solute contents of the vadose zone were positively correlated with changing environmental conditions back to the end of the XIXth century (Edmunds et al., 1993). For semiarid areas, going back to the past may imply to combine land use change estimates with unsaturated zone profiles. At a global scale, more studies are obviously needed to better assess the magnitude of the impact of land clearance on groundwater recharge.

6. Conclusion

One of the World's largest population growths since the middle of the 20th Century in southwest Niger was accompanied by major changes in land cover and water resources.

Between 1950 and 1992, 81% of the 500 km^2 study area has been cleared to open new areas for agriculture and supply firewood (59% of the plateaux, 42 % of the valley bottoms, and 89% of the sandy slopes based on Loireau's (1998) estimates. Land clearance has resulted in a modification of the soil properties and infiltration capacity (Seguis et al., 2004). A strong, indirect impact of land clearance is observed on the water resources. Between 1950 and 1992, aerial photographs show a ~2.5 fold increase of the drainage density with the development of large drainage systems and new ponds. Updated groundwater data also indicate that the rise of the water table continues, with a mean groundwater level rise since early 1960 of ~4m.

Continued increase in runoff and groundwater recharge indicates that the indirect impact of land clearance on water resources has been stronger than that of the droughts. The long-lasting impact of land clearance on water resources has been observed in other semiarid, non irrigated areas, where more than 100 yrs after land clearing groundwater levels are still rising (Allison et al., 1990; Scanlon et al., 2005). Change in land cover in semiarid areas may not be always linked with changes in the drainage pattern: for instance, in the USA and S Australia, changes in land use have induced a drastic change in groundwater recharge, without any modification of the surface water drainage network (Allison et al., 1990; Scanlon et al., 2005) Attention: in the Murray Basin: Groundwater is now lowering in the small groundwater fow systems (but still rising in the large regional ones). Conversely, changes in land use may change surface water flow, without any obvious impact on groundwater dynamics (Mahe et al., 2005). Results from all these semiarid regions and southwest Niger show that the response of water resources to land clearance is complex. Direct impact of land clearance on transpiration and soil infiltration capacity mostly vary according to the vegetation and soil type. This in turn determines the shift in the hydrological balance and the partition between increased surface runoff, direct and indirect [Marc dit: être plus précis] groundwater recharge. Therefore, best land management in regards to land clearing cannot be based on a single parameter but must include a global assessment of long-term socio-economical, environmental and hydrological implications.

Although this paper deals exclusively with the terrestrial part of the hydrological cycle, the results obtained have also an atmospheric significance in terms of possible time-lags for retroaction on the climate. Finally, because land clearance is often more accurately quantifiable than changes in sub-surface water resources, this study provides key criterion for semiarid areas at a global scale for a diagnosis in water resources changes, based on a determination of hydrological processes and land cover changes as observed by remote sensing.

Change in land cover in semiarid areas may not be always linked with changes in the drainage pattern : for instance, in the USA and S Australia, changes in land use have induced a drastic change in groundwater recharge, without any modification of the surface water drainage network (Allison et al., 1990 ; Scanlon et al., 2005). Conversely, changes in land use may change surface water flow, without any obvious impact on groundwater dynamics (Mahe et al., 2005).

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FIGURE CAPTIONS

Fig. 1. Location and main hydrological features of the study area in South West Niger, central Sahel. Letters within the limits of the study area localize specific study sites quoted in the text (B: Banizoumbou, G: Gassan Kournié, K: Kafina, W: Wankama).

Fig. 2. Block-diagram showing the main landscape and hydrological units of the study area (aerial photograph from November 1992).

Fig. 3. Example of deforestation on the plateaus as observed on aerial photographs between 1950, 1975 and 1992.

Fig. 4. Example of land clearance and increase of the drainage density on the hillslopes as observed on aerial photographs between 1950, 1975 and 1992.

Fig. 5. Example of deforestation and apparition of ponds in the valley bottoms as observed on aerial photographs between 1950, 1975 and 1992.

Fig. 6. Drainage network density increase between 1950, 1975 and 1992 over the study area.

Fig. 7: Histograms showing for the study area the distribution of the drainage systems according to their Shreve order in 1950, 1975 and 1992.

Fig. 8. Example of the development of a large drainage system. The figure shows an increase in drainage network density and connectivity as delineated between 1950, 1960, 1975 and 1992. Note the increase of the Shreve (1966) stream order function for the main channel (increasing from 2 to 3, 10 and 19 for each observed year).

Fig. 9. Example of a marked upslope shift of an alluvial fan for the 1950-2005 period. This change results from changing conditions in the longitudinal equilibrium of the drainage network.

Fig. 10. Examples of long-term changes in the water tables levels (1963-2005). A: Wankama, near a kori pond; B: Gassan Kournié, near a hillslope pond (located in Fig. 1). Although different in amplitude, both rises indicate an increase in groundwater recharge beginning during the 1980s.

Fig. 11. Simultaneous changes over the study area in rainfall (A) land cover (B), drainage network (C) and mean groundwater level (D) for the 1950-1992 period (A: rainfall index computed for 1908-2003; C: groundwater levels computed for 1963-2003). The comparison highlights that most of the changes occurred for the 1975-1992 period, with lasting effects on the groundwater dynamics.

TABLES

flight mission	date	acquisition time	flight altitude / soil (m)	photo. size (cm)	Scale	no. photo.	source
AOF 1950	06/11/1950	08h15–15h15	6250	18.0 × 18.0	1:50,000	28	1
AO 60-61	20/12/1960	09h30–13h40	6500	18.0 × 18.0	1:51,000	4	2
75 NIG 40/600	21–22/03/1975	08h35–14h57	5280	22.5 × 22.5	1:62,500	17	2
IGNN - JICA	01/11/1992	10h05–14h00	5750	22.5 × 22.5	1:60,000	10	2
IRD 98	16/08/1998	10h30	2200	10.1 × 15.2	1:16,200	2	3

1: IGN (France); 2: IGNN (Niger); 3: IRD (Niger)

Table 1. Details of the panchromatic aerial photographs used for the study

Date	tree cover			change / 1950		
	plateaux[a]	***slopes***[b]	***ponds***[c]	***plateaux***[a]	***slopes***[b]	***ponds***[c]
1950	65%	84%	64%	-	-	-
1960	-	-	-	- 7%[d]	-	-
1975	47%	65%	60%	-28%	-23%	-6%
1992	27%	11%	37%	-59%	-87%	-42%

[a] total surface area of 137 km^2. [b] field based estimates of Loireau (1998) over ~ 430 km^2 of sandy slopes (cf. Fig. 1). [c]: 91 valley bottoms, for a total surface area of 2.3 km^2. [d]: computed for the plateaux (61 km^2) of the southern area.

Table 2. Computed deforestation for the study area, 1950-1992.

Date	total drainage length (km)	mean length (km) / drainage system	drainage density (km^{-1})	change / 1950
1950	298	0,61	0.60	-
1960	-	*0,61*[a]	-	*+ 20 %*[a]
1975	421	0,61	0.84	+ 40 %
1992	770	0,94	1.54	+ 157 %

[a]: computed for the 120 km^2 southern area

Table 3. Computed drainage network changes for the study area, 1950-1992.

FIGURES

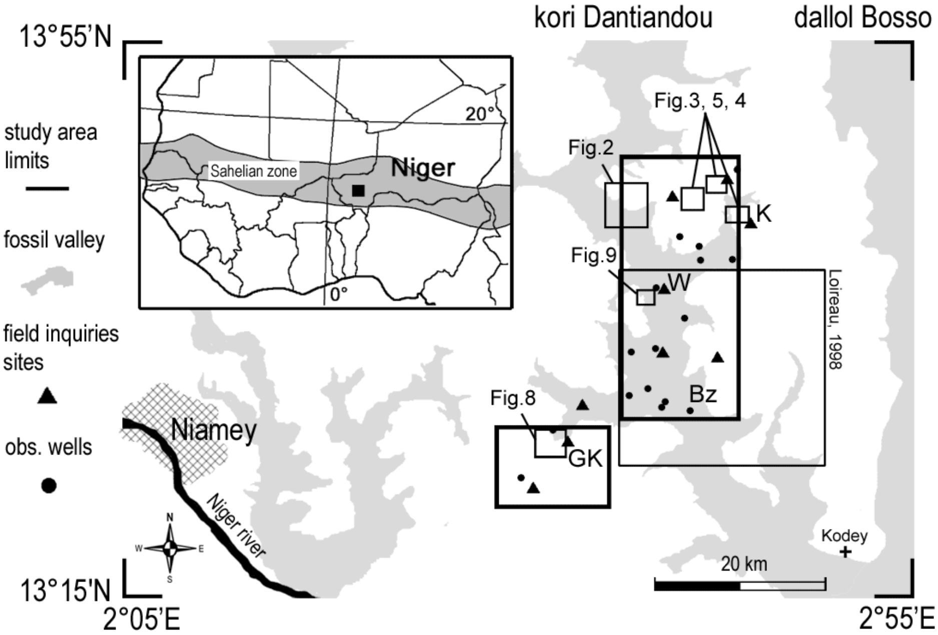


Figure 1

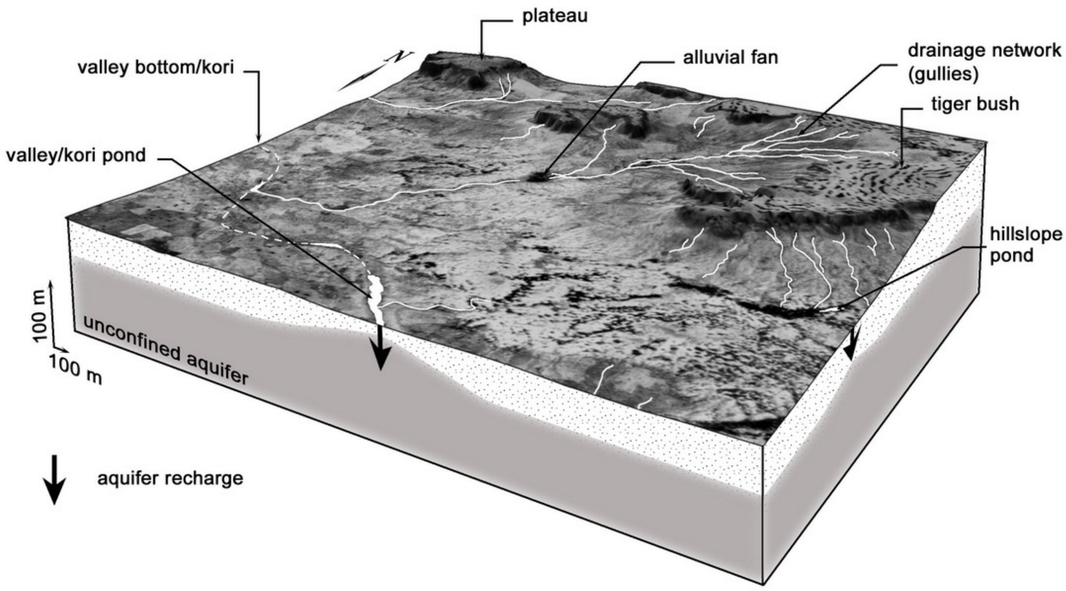

plateau
valley bottom/kori
alluvial fan
drainage network
(gullies)
tiger bush
valley/kori pond
hillslope
pond
100 m
100 m
unconfined aquifer
aquifer recharge

Figure 2

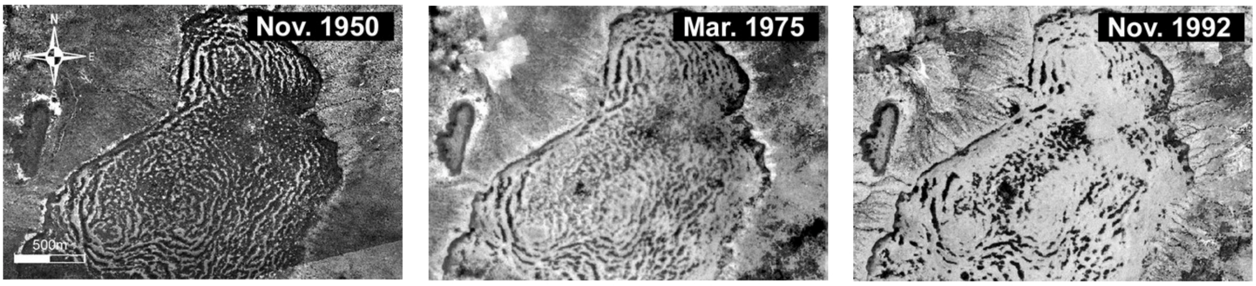


Figure 3

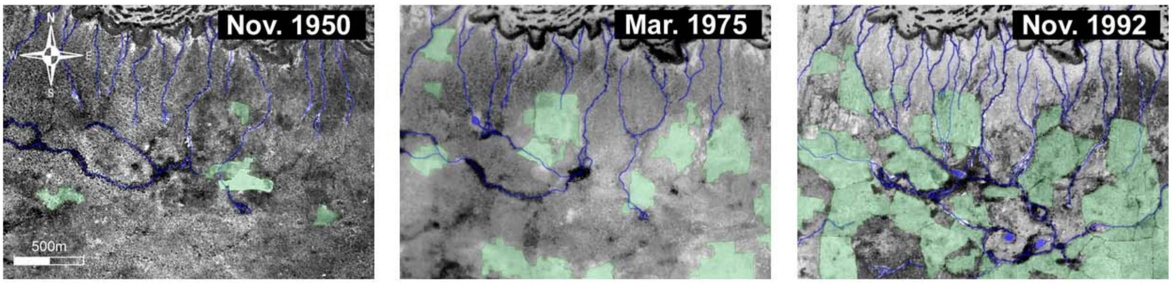


Figure 4

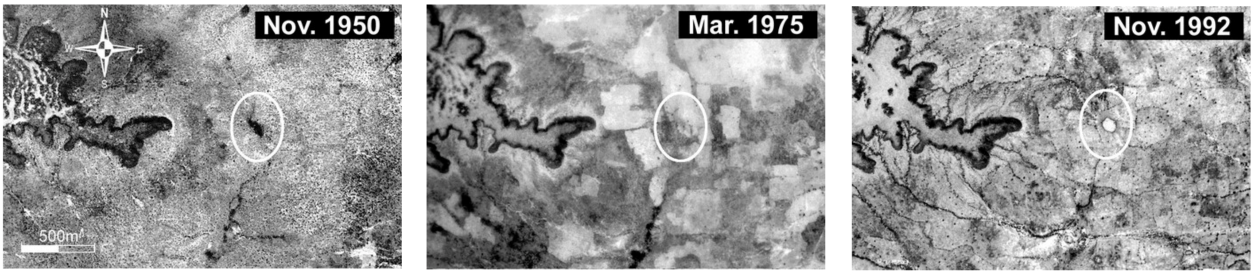


Figure 5

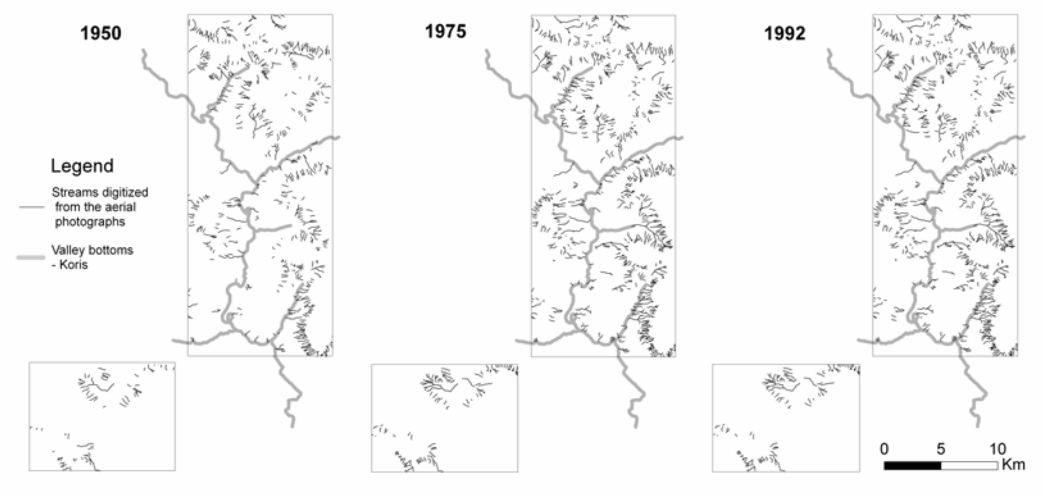

1950
1975
1992
Legend
Streams digitized from the aerial photographs
Valley bottoms - Koris
0
5
10
Km

Figure 6

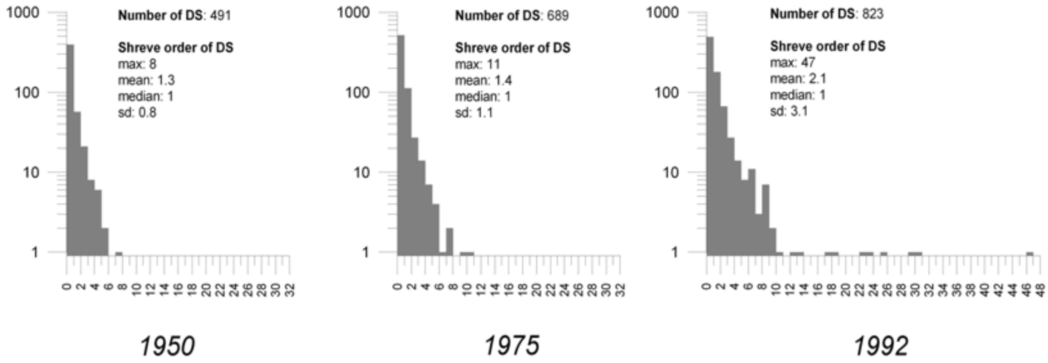

Number of DS: 491
Shreve order of DS
max: 8
mean: 1.3
median: 1
sd: 0.8
1950
Number of DS: 689
Shreve order of DS
max: 11
mean: 1.4
median: 1
sd: 1.1
1975
Number of DS: 823
Shreve order of DS
max: 47
mean: 2.1
median: 1
sd: 3.1
1992

Figure 7

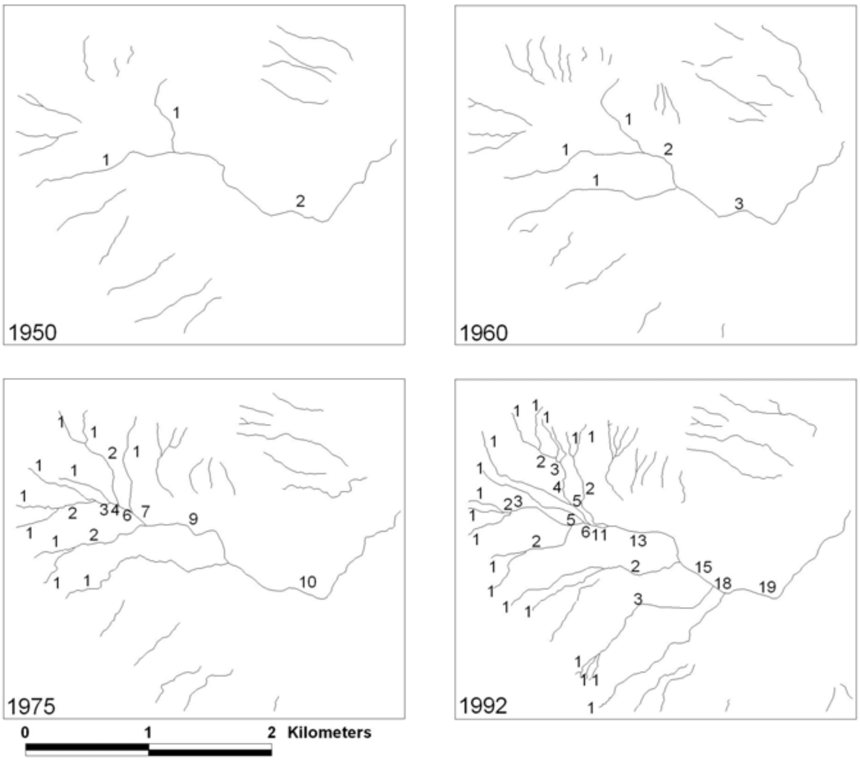


Figure 8

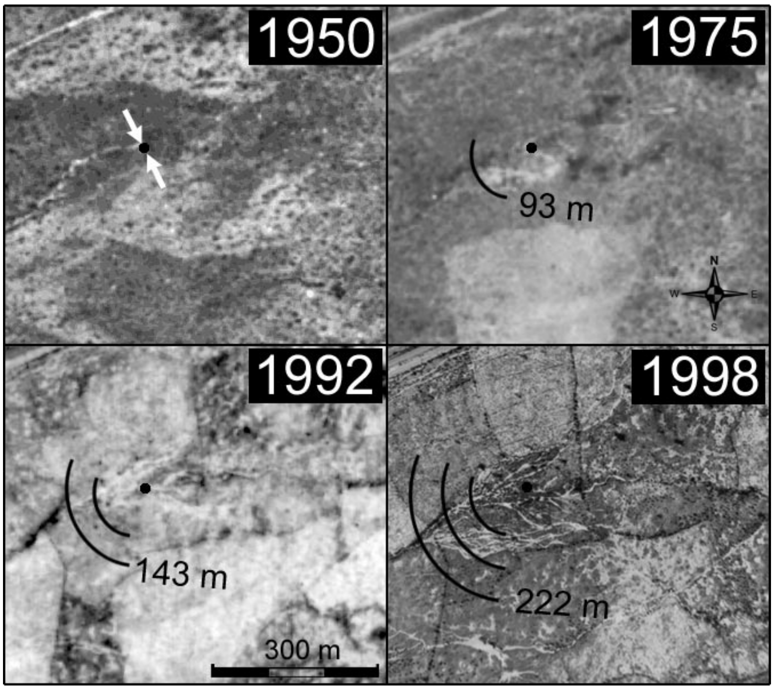


Figure 9

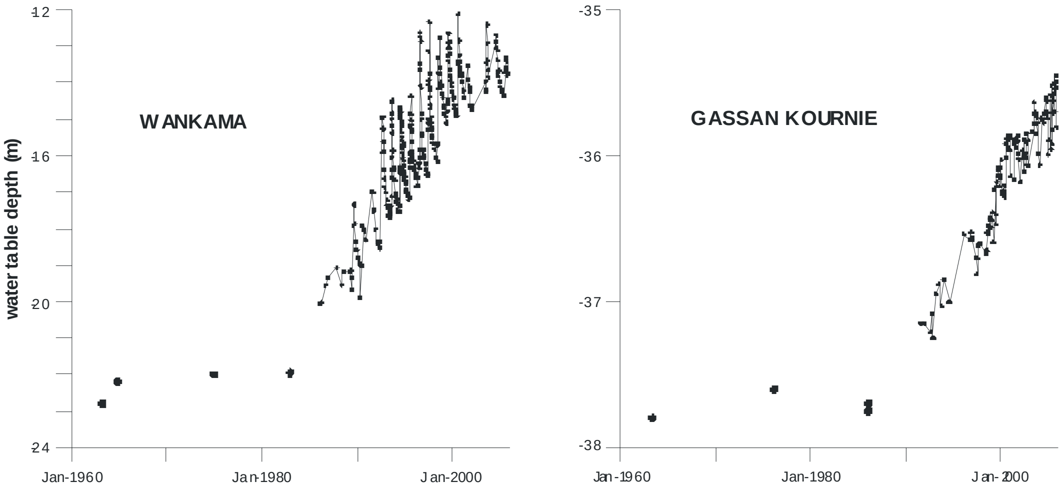
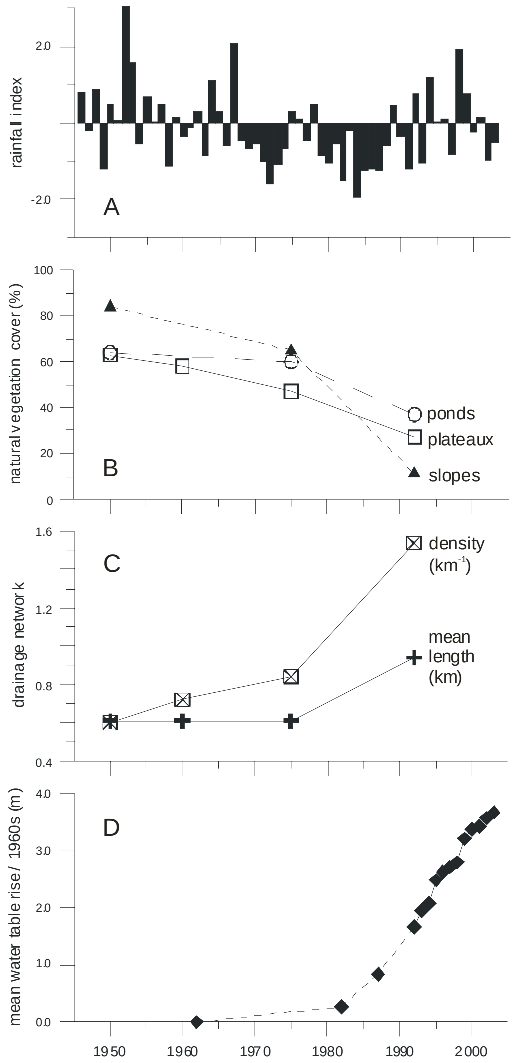

water table depth (m)
WANKAMA
-12
-16
-20
-24
Jan-1960
Jan-1980
Jan-2000
GASSAN KOURNIE
-35
-36
-37
-38
Jan-1960
Jan-1980
Jan-2000

Figure 10



rainfall index
2.0
-2.0
A
natural vegetation cover (%)
100
80
60
40
20
0
B
ponds
plateaux
slopes
drainage network
1.6
1.2
0.8
0.4
C
density (km-1)
mean length (km)
mean water table rise / 1960s (m)
4.0
3.0
2.0
1.0
0.0
D
1950
1960
1970
1980
1990
2000

Figure 11