https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

Observed evidences of shallow groundwater resources threatened by multi-decadal re-greening practices in the Sahel

Yacouba Nouhou Chaweye[1*], Guillaume Favreau[2], Amaury Dehecq[2], Marie Boucher[2], Boukari Issoufou Ousmane[1], Rabilou Abdou Mahaman[1], Yahaya Nazoumou[1]

[1] Department of Geology, Faculty of Sciences and Techniques, University Abdou Moumouni, 10662 Niamey, Niger.

[2] Univ. Grenoble-Alpes, IRD, CNRS, INRAE, Grenoble INP, IGE, 38000 Grenoble, France.

Correspondence: Yacouba Nouhou Chaweye (chaweye1993@gmail.com)

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

Abstract. Re-greening initiatives in drylands in response to desertification processes represent a key contributing policy for mitigating climate change impacts, restoring biodiversity, and sustainable land management. However, their long-term impact on surface or groundwater resources are rarely assessed and remains poorly documented at a global scale. This study examines how pioneering (1970s-1990s) re-greening and soil and water control (SWC) efforts have affected both surface water drainage and groundwater dynamics within a transboundary watershed of ~3,000 km^2 in the central Sahel, West Africa. Using original field data, water table surveys (1960s-2020s) and a series of historical aerial photographs (1950s-1970s) supplemented with high resolution satellite imagery (1980s-2020s), trends in land use, land cover and hydrological changes were reconstructed. First, a marked decrease (1.6 fold) in the drainage network density was delineated in the upstream part of the basin in response to the development of SWC agricultural techniques, that resulted in lower hortonian runoff through gullies to the downstream river valley. Since groundwater recharge was shown to be mostly indirect through the river network, lower runoff entailed lower groundwater recharge. Second, dense reforestation schemes by non-indigenous phreatophyte trees (*Azadirachta indica)* took place through the main valley to control aeolian erosion processes, inadvertently increasing evapotranspiration discharge fluxes from the initially shallow (< 8 m below ground level) water table. Both of these processes (lower aquifer recharge, higher groundwater uptake by trees) contributed to a long-term plurimetric (3 to 6 m) drop in the piezometric levels, reducing storage or even causing a near dry-up of the alluvial aquifer. Overall, these results highlight a Sahelian trade-off that is relevant for SDG 15 and the flagship African Great Green Wall initiative: while re-greening and SWC practices may improve land conditions, they may also threaten locally fragile groundwater resources.

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

1 Introduction

The Sahel, the semi-arid region of West Africa, experienced a multidecadal-long drought period from the early 1970s through the mid-1990s, that represented one of the most severe climatic signal since the mid-20th century at a global scale (Spinoni et al., 2014; Doblas-Reyes et al., 2021). For the past seven decades (1950s-2020s), the mostly rural population increased sixfold, with demographic growth rates in the range of 2 to 4% yr^{-1} (UNPP, 2024). The observed eco-hydrological changes have been significant and persistent (e.g. Gardelle et al., 2010; De Fleury et al., 2023), causing numerous sustainability challenges on socio-ecosystems (Reenberg et al., 2013; Elie, 2024). Changes in land-use practices adopted in response to desertification processes have had positive or negative impacts in terms of resilience or land productivity in the post-drought period (Reij et al., 2005; Brandt et al., 2014; Hiernaux et al., 2016), with locally evidences of shifting environmental conditions (Gal et al., 2017; Peugeot et al., 2026; Le Roux et al., 2026). For the same period, measured regional climate change effects have shown steadily rising air temperatures (Moron et al., 2016) and rainfall intensities (Chagnaud et al., 2022), both of these trends having increased vulnerability in rain-fed crop production (Mohamed et al., 2025). Consequently, competition for safe access or control of water resources has already impacted regional mitigation strategies and development pathways (Eboreime et al., 2025; Omokpariola et al., 2025).

Landscape re-greening at plot or slope scales through soil and water conservation (SWC) techniques have proved their efficiency for water erosion controls (Wolka et al., 2018; Zouré et al., 2019), enhancing soil water content and limiting or reversing land degradation processes (D'Odorico et al., 2013). At watershed scales, regreening through tree plantations combined with SWC techniques have been successful in limiting gullies development and controlling runoff to river channels or lakes (Valentin et al., 2005; Frankl et al., 2011). At

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

regional or sub-continental scales, re-greening strategies through natural forest conservation or reforestation programs have been shown to significantly reduce wind erosion fluxes and increase long-term soil carbon sequestration (Turner et al., 2023). However successful for land biomass productivity, there is a growing consensus that massive reforestation schemes may alter the water cycle, from enhanced evapotranspiration fluxes from forested areas (An et al., 2025; Ruijsch et al., 2026) and subsequent downwind precipitation transfers, hence modifying regional water availability patterns (Friedlingstein et al., 2019; Yan et al., 2025). Great Green Wall schemes are considered to possibly contribute to reduced runoff and/or lowering of the water table (Turner et al., 2023), with cases shown in semiarid northern China (Zheng et al., 2012; Kuang et al., 2024).

In the Sahel region, the earliest re-greening and land conservation efforts started in the 1960s in the central plateaus of Burkina-Faso and Niger (Vlaar, 1992). These efforts intensified through the early 1980s in response to perceived land degradation, with strategies successfully mobilizing traditional SWC techniques (Critchley et al., 1994; Reij et al., 2005; Tarchiani et al., 2008). In south-central Niger, land management on sandy slopes to limit runoff were considered to reduce seasonal peak river flow at the catchment scale (FAO, 1995). In large valleys, re-greening strategies for windbreak purposes implemented in the 1970s resulted in effective control of aeolian erosion fluxes, using native and non-native tree species (FAO, 1995; Smith et al., 1998). Deep-rooted trees planted in dense arrays for windbreak were shown to tap shallow groundwaters (Smith et al., 1997); however, no dedicated survey was ever scheduled to infer their long-term impact on aquifer dynamics.

In this work, we determine, by combining a series of aerial photographs, satellite images, and hydrological surveys, the fine-scale dynamics in surface and groundwater resources that have occurred in response to multi-decadal regreening practices in the Sahel region. The study was carried out over a ~3,000 km^2 watershed of the high central plateaus of the Niger River

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

basin, one of the two main locations in West Africa where near-continuous re-greening and SWC programs have been performed since the early 1960s (Di Vecchia et al., 2007). This watershed is conveniently located within the limits of the Pan-African Great Green Wall initiative (Figure 1a), the flagship Pan-African land restoration program initiated in 2007 that aims to achieve land degradation neutrality through the whole Sahel region (UNCCD, 2020; Mechiche-Alami et al., 2022; Zhi et al., 2025). Using the same approach but in a reversed trend in the land use/land cover dynamics, this research comes in echo to the emblematic Sahelian paradox case study evidenced in southwest Niger, where unabated land clearing has led to a long-term increase in groundwater resources (Leblanc et al., 2008; Favreau et al., 2009). Overall, our work underscores the need to define criteria embedded in their context to evaluate nature-based solutions in terms of time-lags and potential trade-offs between re-greening, SWC practices, and water resources availability in response to dryland management strategies.

2 Data and Methods

2.1 Study area

The study area is a ~3,000 km^2 watershed of southern Niger (hereafter called the Maggia River watershed, MRW) that belongs to the much larger Niger river basin network and expands to the south to Nigeria (Figure 1b). Its main geomorphological and geological features are as follows: Upstream, the MRW is made up of a lateritic oligocene (Chardon et al., 2016) ferruginous plateaus (~70 % of the basin, ~ 600 m a.m.s.l.) incised by steep narrow valleys (thalweg slopes of ~ 5 to 7 ‰). Downstream, the sandy to clayey alluvial plain (~30 % of the MRW, 250 to 270 m a.m.s.l., smooth slopes of ~ 0.5 ‰) is made up of a few meters of quaternary sandy to clayey sedimentary layers (Sauvel, 1966; Figure 2). The semi-arid climate

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

is characterized by average monthly temperatures ranging from 23°C in January to 34°C in May, a potential evapotranspiration near 2280 mm.yr^{-1}, and a short rainy season from June through September that cumulates annually 530 mm of rainfall (1950-2020 period, Birni N'Konni synoptic station, (ORSTOM, 1966, 1990; and DMN, pers. com). The shallow Maggia river (maximum water level amplitude of ~ 2.5 m at peak flow) used to flow from July through September, with specific flow rates that decreased from upstream to downstream (Lefèvre, 1962). Flow rates recorded at the Tsernaoua station (Figure 1b) were in the range of 3 to 179 Mm^3 year^{-1} for the 1954-1986 period (Brunet-Moret et al., 1986; ABN, pers.com.). Sparser, discontinuous discharge flow surveys at hydrological stations in the downstream part of the basin followed the construction of two main dams (1977, 1981) of respectively 12 and 30 Mm^3 built upstream of the main regional urban area (Birni N'Konni, ~150,000 inhab. in 2012, shown in Figure 1b).

The dense, rural population (~100 inhab.km^{-2}) had increased ~5-fold since the early 1960s (INS, 2012). Most of the local economy is dominated by rain-fed agriculture and livestock cattle herding, with small-scale private land plots upstream and a large-scale ~ 2500 ha state-funded irrigation scheme downstream, exploited since the early 1980s (Figure 1b). Soils are classified as rich hydromorphic vertisols in the valley and are classified as lithosols or regosols on the plateaus (SOGETHA, 1964). The natural vegetation distribution is mainly a function of topography and soil types; plateaus are covered by sparse trees and shrubs, typical of a patterned woody vegetation (e.g. Trichon et al., 2018). The valley bottoms were long covered by a dense biodiverse forest, that partly reflected on the local geology and topography (SOGETHA, 1964). Intense land clearing and subsequent reforestation programs (FAO, 1995) have greatly modified the native vegetation former biome, with now more widespread drought-dominant species (Acacia sp., Balanites aegyptiaca; e.g. Wourro et al., 2026). The partial

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

recovery of the tree cover and of the herbaceous cover since in post-drought period was confirmed at a regional scale by remote sensing analyses (e.g. Dardel et al., 2014).

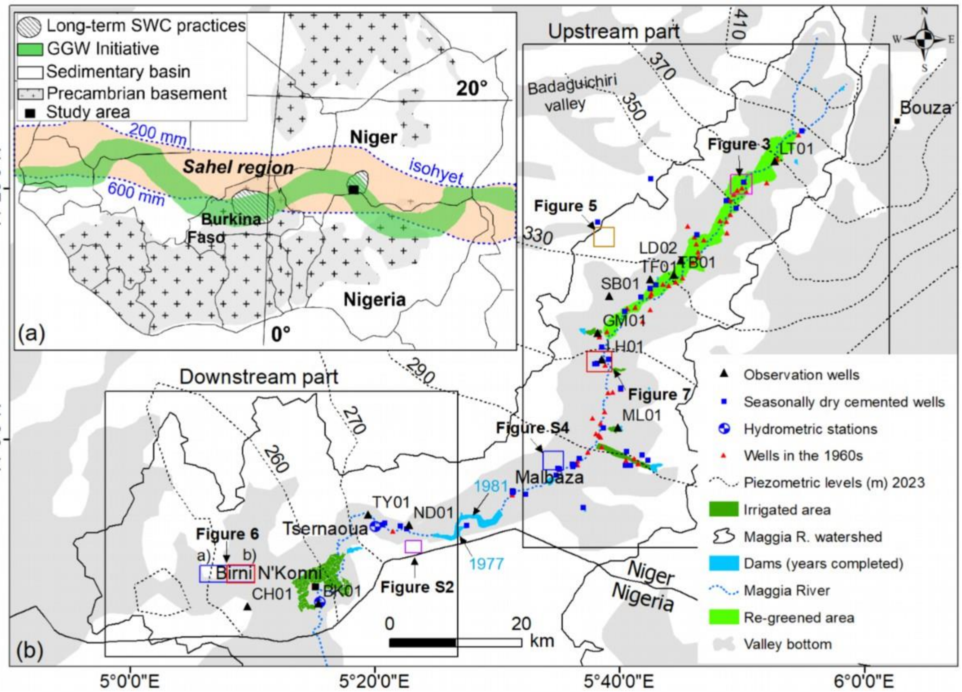

Figure 1. Location and main hydrological characteristics of the study area. Rectangles and figure numbers locate and indicate specific study sites cited in the text. Small inset : Location of study area in West Africa ; The green band pattern through the Sahel region indicates the Great Green Wall (GGW) location as reported from Mugelé (2018). Long-term soil and water conservation practices in central Burkina-Faso and southern Niger are shown as reported in Vlaar (1992).

The unconfined aquifer is made up of a quaternary alluvium outcropping along the main valley river course, that lies over upper cretaceous clays and sands in the upstream part of the MRW, paleocene marls and limestones at mid-slope, and oligocene sandstones downstream (Figure 2). The piezometric map shows a NE-SW hydraulic gradient that decreases with ground elevation,

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

with groundwater fluxes mostly internal to the MRW (Figure 1b). Groundwater recharge of the sandy-clayey quaternary alluvium had been observed by seasonal piezometric fluctuations over one or two years (Sauvel, 1966; Greigert, 1967); the shallow water table, locally outcropping within the main valley (SOGETHA, 1964), was shown to be recharged by seasonal flood infiltration on river banks. Aquifers characteristics estimated by direct pumping experiments (specific yield; Sauvel, 1966) or near-surface geophysics (effective porosity; Chaweye et al., 2026) indicate rather low aquifer hydraulic properties, with values of a few percent in specific yield (0.3 - 2.0 %) or in effective porosity (5-10 %) and of ~1.10^{-4} m^2 s^{-1} in transmissivity in the upstream section of the catchment. Significantly higher values (4 to 37 % for effective porosity and ~2.10^{-3} m^2 s^{-1} for transmissivity values) were recorded in the downstream part of the MRW (Chaweye et al., 2026).

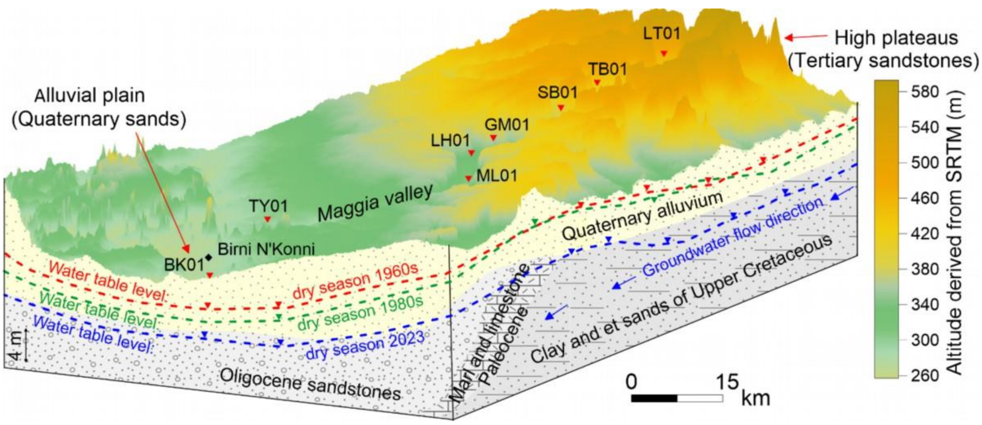

Figure 2. Block diagram illustrating the main landscape, hydrological, and geological units in the study area. Observation wells are shown in triangles (location within the watershed as shown in Figure 1b). The topography is derived from the 30 m resolution SRTM DEM

2.2 Aerial photography and satellite images

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

The pluri-decadal dataset of high-resolution images considered in this study is made up of images obtained from different sources. Older remote sensing archives, such as those of the National Geographic Institutes of France (IGN) and Niger (IGNN), declassified US intelligence data of Hexagon, and more high-resolution recent satellites such as SPOT-5 and -6 images (Table 1). The panchromatic aerial photographs at a scale of 1:50,000 (1956), 1:20,000 (1966), and 1:60,000 (1975) used in this study were obtained from the IGN and IGNN to produce the georectified digital mosaic for each year. In more detail, the 62 photos of 1956 covered the entire study area; They were acquired in strips as part of the global coverage mission known as AOF 1955/56. The altitude of the flights was around 6,500 m above the ground. The cameras, referenced A19 and A20, had a focal length of 125 mm and a format of 180×180 mm. Fewer aerial photographs were available for the year 1966, and it was only possible to cover a part of the upstream section (23%) using 11 aerial photographs. The images were acquired with a format of 180×180 mm as part of the AO 754/100-IR mission. Sixteen images from the Hexagon KH-9 satellite were also obtained from the US Geological Survey (USGS). The satellite Hexagon KH-9 (mission 1218), whose characteristics are shown in Table 1, was equipped with two panoramic rotating cameras with a focal length of 152.4 cm (60 inches) that took images at a ground resolution of 0.6-1.2 m (Ghuffar et al., 2023). Auxiliary data, including the topographic map of the region at a scale of 1:200,000, the digital elevation model at a ground resolution of 30 m (Shuttle Radar Topography Mission SRTM DEM, downloaded from the following site: https://dwtkns.com/srtm30m/), and two SPOT images from December 2002, two from March 2014, two from November 2014, and one image from October 2022 in panchromatic mode, were used to complete the time series. SPOT images were taken at an almost vertical angle (-1.48°) and ordered with level 2A pre-processing in a transverse UTM projection. They were radiometrically corrected with a ground resolution of 2.5 m and a ground coverage of 60×60 km each.

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

Table 1. Characteristics of images used in this study.

Satellite/Mission	Acquisition date	Flight altitude / ground (km)	Ground resolution (m)	No of photos/ Bands	Source
AOF 1955/1956	Feb. 1956	6.5	1.28	67	IGN
AOF 1955/1956	Feb. 1956	6.5	1.28	25	IGNN
AO 754/100-IR	Nov. 1966	7.5	1.06	11	IGNN
75 NIG 40/600	Mar. 1975	5.28	1.32	7	IGN
Hexagon KH-9	Oct. 1983	163-224	0.6 -1.2	16	USGS
SPOT 5 (Upstream)	Dec. 2002	825	2.5	2	CNES
SPOT 5 (Upstream)	Nov. 2014	825	2.5	2	CNES
SPOT 5 (Downstream)	Mar. 2014	825	2.5	2	CNES
SPOT 6 (Upstream)	Oct. 2022	694	1.68	1	CNES

IGN National Geographic Institute of France https://www.ign.fr, IGNN National Geographic Institute of Niger, USGS United State Geological Survey https://www.usgs.gov/, CNES National Center of Spatial Studies https://cnes.fr/

Aerial photographs were scanned using an Expression 12000 XL Pro, a professional A3 graphics scanner at 1200 dots per inch (pixel size of 21 micron). A standard protocol was implemented when scanning the plates. The scanner mechanism was initially checked for possible artifacts (Mugglestone and Renshaw, 1998; Leblanc et al., 2008). A sheet of white photographic paper was scanned, and the resulting grayscale image was subjected to spectral analysis. The analysis detected no significant distortion, systematic striation, or dot striation. The images were then scanned by adjusting the autofocus, i.e., adjusting the focus by a few millimeters in height, and then digitized using Epson Scan 2 software. The scanned photos were converted into digitized images with grayscale values ranging from 0 to 255 (8-bit grayscale) with a ground resolution of 1.28 m, 1.08 m, and 1.32 m, respectively, for years 1956, 1966, and 1975. The Hexagon images were scanned using a Leica DSW700 flatbed photogrammetric

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

scanner at 3,600 dots per inch (7 micron). Before scanning, the device was geometrically calibrated to an accuracy better than 1 µm, to eliminate the distortions imposed by it and scan the images in panchromatic mode (Surazakov and Aizen, 2010). Due to its large size, which does not fit in a standard photogrammetric scanner, each film was scanned in multiple pieces with about 1 cm overlap.

2.3 Image processing

As all raw images lack positional data and orthorectification, aerial photographs and declassified images were manually georeferenced under the "Georeferencer" plugin of the QGIS software using a 3rd polynomial transformation. The 1983 mosaic was first georeferenced using Google Earth® and the already orthorectified 2014 SPOT images as references. For each image, between 20 and 50 homogeneously distributed large Potential Ground Control Points (GCPs) were acquired. The GCPs are distributed between the intersections of roads, tracks, rivers, irrigation canals, large century-old trees, building corners, and the edges of rock outcrops. The 1975, 1966, and 1956 mosaics were subsequently rectified and co-registered, respectively, on the 1983 mosaic. Due to environmental and infrastructural changes (e.g. shifting of riverbeds, trails, and river intersection points, the disappearance of some trees) that have occurred in the area, GCPs were limited to large century trees and rock outcrop edges when the 1956, 1966, and 1975 mosaics were rectified. During georectification, each raw image was co-registered with each neighboring image to create a complete mosaic for each year. All images were projected in the WGS84 (EPSG code 4326) Coordinate Reference System (CRS) to obtain data in latitude and longitude. The accuracy of each image was assessed using a SPOT image overlay. The characteristics of all images used to produce the mosaics are shown in Table 1. The ground resolutions of these images range from 2.5 m for SPOT to 0.6 m for Hexagon KH-9 images. These resolutions are more than sufficient to detect hydrological changes and

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

land use (gullies or drainage networks of the MRW are usually of between 5 to 10 meters in width). All digitized images were converted to an optimum of 2.5 m to produce a time series of equal geometric resolution, covering 66 years (1956 to 2022).

The images scanned were of good quality, virtually scratch-free and dirt-free, with very low radiometric noise. The images used from 1983, 1975, and 1966 were taken on a single day and with the same camera, so radiometric changes within the mosaic were considered as minimal. Each image contains a black, unexposed image edge that needs to be removed before creating the mosaic. Automatic thresholding (Otsu, 1979) was performed for the 1983 images, to identify the top and bottom edges. For the 1956, 1966, and 1975 datasets, the images were cropped to a fixed distance of 500 pixels from the image edge on the four sides to remove the unexposed part of the film. After pre-processing, it was possible to detect changes in image junction areas. Fieldwork and visual inspection of the images allowed us to divide the area into two parts: one with strong soil and water conservation practices (upstream part) and a second without such measures (downstream part). The drainage network was manually digitized over an area of 1,727 km^2 in the upstream part and 930 km^2 in the downstream part. Changes in the drainage network were assessed by comparing gully lengths and connectivity in the upstream and downstream parts. Changes in vegetation were assessed using two classification methods: an unsupervised classification method (ISODATA) and an object-based classification method (COO). The accuracy of the two automatic classification methods was assessed by comparing them with the manual classification method (for more information, refer to the supplement, S1).

2.4 Field inquiries for remote sensing data analysis

Field surveys lasting a total of three months, spread across April 2021, July 2021, August 2022, June 2023, December 2023, and September 2024, were conducted to verify and validate the features detected by aerial photography and satellite imagery. During the survey, several sites

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

of interest previously selected from aerial photography and satellite images for comparative analyses were visited. These sites included previously densely forested valley bottoms, ponds, land developed using re-greening and SWC practices, and major drainage networks. These sites were selected not only based on the observed changes but also when these changes were representative of a larger area. They were delineated using a hand-held GPS with an accuracy of ± 3 m on the site. Field visits provided information on land cover/land use, changes in the drainage network, and perceived changes in water resources. Interviews with local farmers often provided valuable information and clarification on events and changes observed in the landscape over multi-decadal periods. Complementary data, including areas developed with re-greening, SWC practices, and dams built since the 1960s, were also obtained from the Rural Engineering Directions of Birni N'Konni, Malbaza, and Bouza departments (*Pers. Com.* 2022).

2.5 River and groundwater levels surveys

Hydrological and hydrogeological data described in various technical reports have been used to reconstruct the water balance variability through time and space. Daily, monthly, and annual discharge records from 1954 to 1982 of the Maggia River at the Tsernaoua or Birni N'Konni hydrometric stations were found in Bricquet (1983) and in Brunet-Moret et al. (1986). These stations were set up close to the Maggia River, downstream of the SWC development (Figure 1b). High-quality, old groundwater data from several wells were found in technical reports (Boeckh, 1965; Sauvel, 1966; Greigert, 1967). Water table levels were measured in a series of 5 observation wells installed in some forthcoming reforestation site, and 7 wells downstream of forthcoming re-greening and SWC practices sites (Figure 1b and Fig. S3). Hence, these groundwater levels were surveyed well before the intervention of large-scale projects of re-greening and SWC practices. Some sparser measurements were carried out as early as the early 1980s, thanks to the support of numerous national and international programs (SOGREAH,

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

1982; IWACO, 1990; KFW, 1991). Regular measurements were also performed in the 1990s and 2000s by the Ministry of Hydraulic and Sanitation of Niger (MHE, 1999; Pers. Com.). Additional surveys started in 2021 as part of this study, from July 2021 through October 2024, in order to extend the piezometric chronicles to recent years.

Fieldwork and interviews with local populations enable to locate and register the exact position of wells surveyed in the past, allowing to successfully connect older measurements with more recent ones (e.g. Leduc et al., 2001). During this survey, information on the characteristics of the wells (their age and the chronology of their creation in each village) was provided by the local population, and their Identity Number were recorded, enabling them to be formally identified. In some reports, information on the characteristics of wells and their approximate location had already been provided, allowing them to be directly localized. Data from traditional wells that may have been affected by landslides or silting were excluded from the analysis, as well as for cemented wells that had undergone changes in their characteristics (e.g. changes in the elevation of the rim ; Favreau et al., 2000). Measurements from cemented wells or piezometers located relatively close to the river (< 2000 m) were considered and used for long-term trend estimates. These data indicate i) the pattern of surface-ground water relationships through piezometric mapping (Figure 1b), ii) natural seasonal variations in the water table using a few short piezometric chronicles (Sauvel, 1966) of wells located within the alluvial plain or at short distances from the river (Figure 1b), and iii) the long-term trend in water table levels.

3 Results

3.1 Quantifying land clearance and re-greening practices

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

The woody vegetation (dry season observed, low herbaceous cover) changes on the various landscape units of the study area were computed from 1956 to 2014 (supplement, S2). The most noticeable land-cover change throughout the whole MRW has taken place on the plateaus. The woody vegetation on the plateaus has become sparser (30 % in 1956 to 2 % in 2014). On the valley slopes, the natural vegetation land cover had fallen from 20 % in 1956 to 18 % in 1966. Most clearing took place in the 1980s (Table S1 and Table S2). At that time (year 1983), 65 % of the vegetation had been cleared to open up new farmland. In sharp contrast to the plateau and slope areas, an increase in woody vegetation, albeit in a linear, man-made pattern, was shown to occur in valley bottoms (Figure 3). The perennial vegetation cover, which was only 14 % in 1956, had risen to 40 % in 2002.

Field surveys and interviews confirmed land use changes observed in aerial and satellite imagery. By the early 1950s, valley bottoms with sandy-clay soils suitable for agriculture (Gavaud and Boulet, 1967) were already cleared for cropping. In the 1980s, development projects helped restore woody cover in valleys, most notably for windbreak purposes using a single, non-indigenous tree species (*Azadirachta indica*). Due to land degradation and limited farmland available, plateaus were increasingly converted to crop fields and cleared for firewood, leading to their near-full clearance by the mid-2010s. Despite noticeable reforestation efforts, field interviews confirmed that the vegetation cover on the plateaus had not yet fully recovered to its previous extent.

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

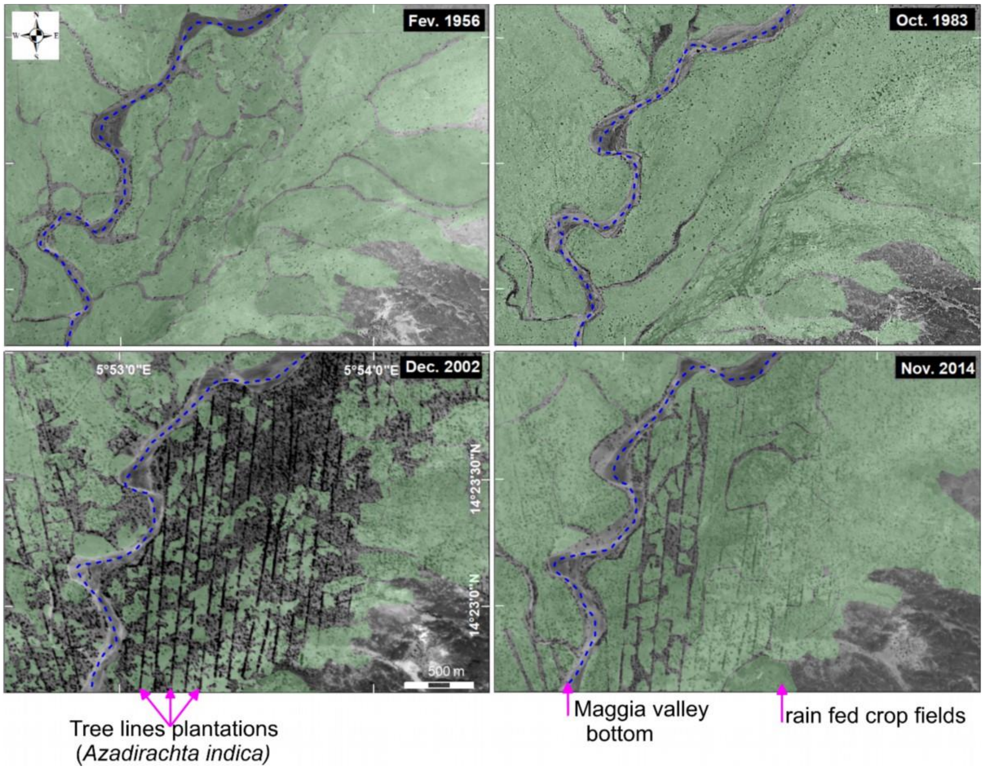

Figure 3. Example of change in land cover in a valley bottom. Tree lines for control of wind erosion were mostly planted during the 1980s-1990s (location shown in Figure 1b). Rainfed crop fields are mapped in green color using object-based classification. The thalweg (Maggia River course) is shown in dotted blue.

Changes in land use are also perceptible in the different landscape units in the downstream part of the MRW, where SWC practices or regreening did not occur before the mid-2010s. Most valley bottoms appear as dark, densely wooded areas on aerial photographs in 1956 ; by 2014, some of these areas had already been completely cleared for agricultural purposes (Figure 6a and Table S2). During this period, the land required for agriculture increased considerably, so that vast areas of natural bush were cleared. By this time, 72 % of the valley bottom vegetation had been lost. What was once dense vegetation is now completely cleared and represents a form

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

of barren land with no vegetation, locally replaced by new ponds. Clearing on the plateaus and slopes is also obvious and has been more noticeable since the 1950s (Figure 6a and Table S2). It resulted in a rapid increase in the number and extent of cultivated fields from the 1950s onwards.

Field surveys and interviews with groups of farmers enabled us to describe the chronology of the observed changes. For most villagers, most of the less densely forested plateaus had already been cleared by the early 1950s. The decline in soil fertility on the plateaus due to runoff and the need to cultivate new fields subsequently led to the expansion of clearing on the sandy slopes. Densely wooded valley bottoms were flooded by runoff from the plateaus, asphyxiating the dense woody vegetation. Peripheral areas with less dense vegetation were cleared to expand crop fields. Most of the area is now made up of numerous cultivated fields, with a few mostly recent ponds on the slopes and valley bottoms (Figure 6a and b).

3.2 Increase and decrease in the density of the drainage system

Analysis of aerial photographs, Hexagon, and SPOT images showed that the drainage network experienced spectacular changes during the 1956-2014 period. These changes were analyzed jointly with accurate mapping and computation of the areas concerned by SWC works on slopes where the drainage system is delineated (Fig. S3). The first major change was the increase in the drainage network in the upstream part between 1956 and 1983. Gullies drastically increased in number and length from 1956 to 1983, from 998 to 4830 and 1440 to 3534 km, respectively (Figure 4, Table S3 and Table S4), resulting in a more than 2.4-fold increase in drainage density. From 1983 onwards, gullies decreased in density, from 2.05 km km^{-2} in 1983 to 1.25 km km^{-2} in 2014, resulting in a more than 1.6-fold decrease in drainage density.

Changes in gully connectivity were analyzed using the Shreve (1966) order (SO) of the final collector in the upstream part of the MRW (Figure 5). Results showed significant shifts

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

in the drainage network; from 1956 to 1983, the mean SO rose from 0.70 to 1.45, reflecting increased connectivity and a 98 % rise in the average drainage length. From 1983 to 2014, gully lengths decreased, reducing connectivity by ~1.8-fold (mean SO dropped to 0.78). Maximum SO increased from 13 (1956) to 23 (1983), then fell to 17 (2014). Between 1983 and 2014, average drainage lengths decreased by 66 % (1983–2002) and 33 % (2002–2014). Most changes affected lower-order gullies (Figure 5), often linked to stone bund lines, which slowed runoff velocities, promoted local sedimentation, and caused some gullies to disappear. Field observations and interviews confirmed that stone bund lines, widely used upstream, were the main cause of gully disappearance.

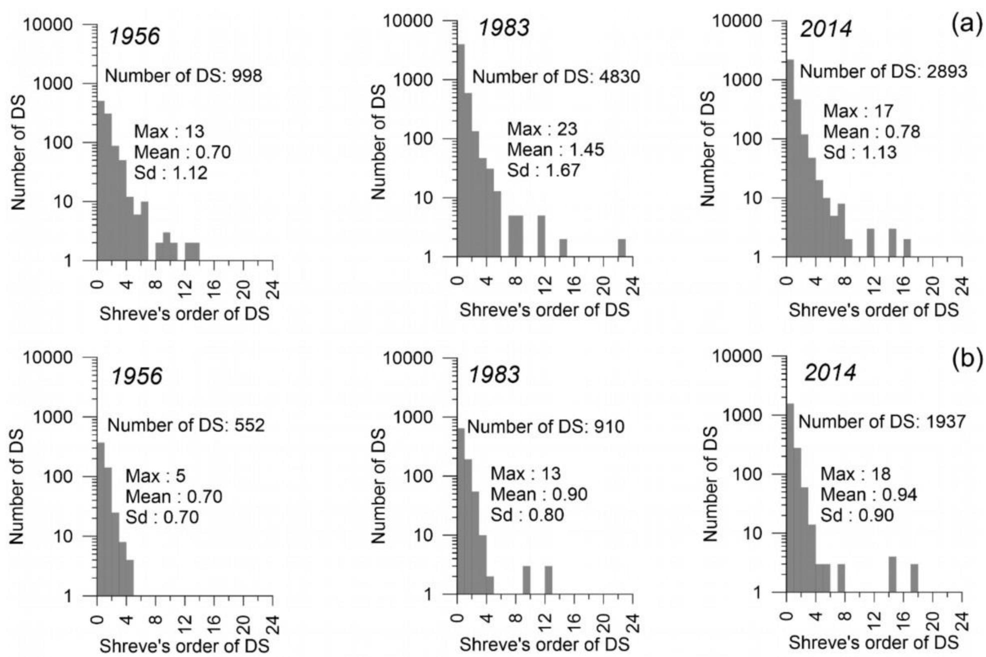

Figure 4. Histograms showing the distribution of drainage systems (DS) according to their Shreve's order (SO) in 1956, 1983, and 2014: (a) upstream part; (b) downstream part.

Other hydrological changes identified were, firstly, the appearance of new ponds through the landscape between 1956 and 1983, and subsequently, their disappearance between 1983 and

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

2014. Field surveys and interviews confirmed that the appearance of new ponds between the 1950s and 1980s and their disappearance afterward was a widespread phenomenon in the upstream part of the basin, locally considered as a result of more, and then lower, runoff on sandy slopes (Figure 5).

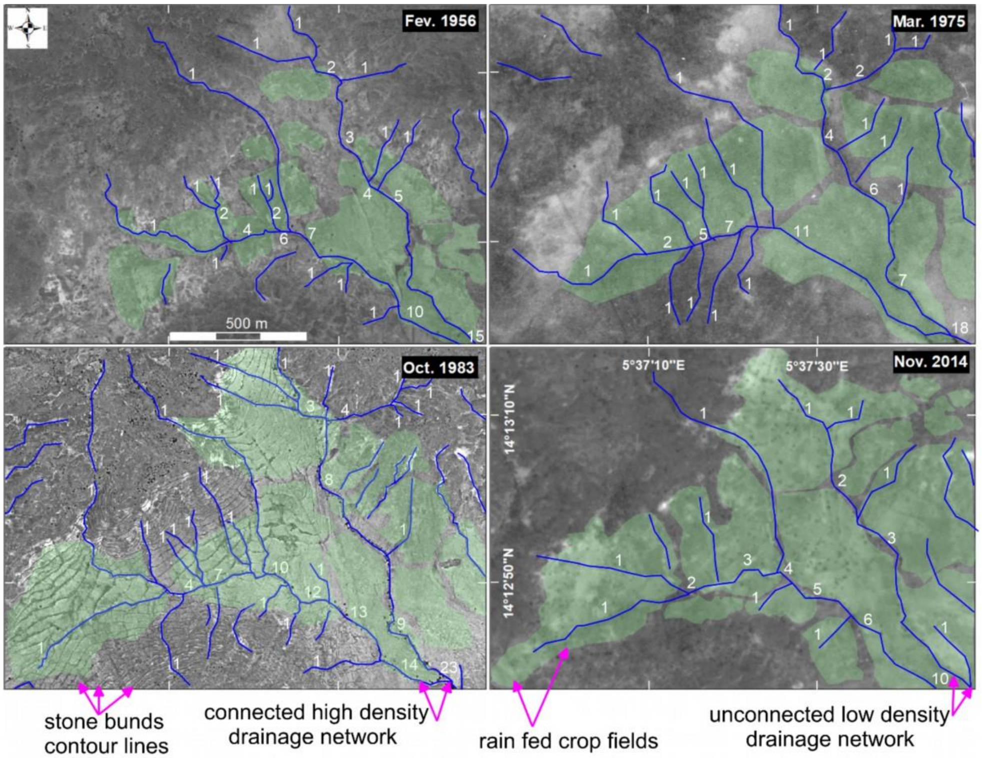

Figure 5. Example showing the long-term impact of stone bunds lines on surface runoff observed for the period 1956-2014. The delineated gullies are shown in blue. Rain-fed crop fields are mapped in green color using object-based image classification (location within the watershed as shown in Figure 1b).

In the downstream part of the basin, the drainage network expanded significantly. The number of drainage systems rose from 552 in 1956 to 910 in 1983 and 1,937 in 2014 (Figure 4b). Average gully length increased from 0.73 km (1956) to 0.94 km (2014), contributing to a 2.8-

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

fold rise in drainage density. Despite this growth, most gullies remained low in Shreve Order (SO), with average SO of 0.70, 0.90, and 0.94 in 1956, 1983, and 2014, respectively. However, the maximum SO increased from 5 to 18 over the same period, indicating the emergence of larger, more connected drainage networks. The increase in drainage connectivity is also evident in the average length of all drainage systems, which increased by over 34 % from 1956 to 2014. Observed change in the drainage network occurred for some sandy spreading areas, a frequent mid-slope hydrological feature in most of the central Sahel (D'Herbès and Valentin, 1997; Massuel et al., 2006). This long-term dynamic is interpreted as a result of increased runoff capacity and sediment transport at slope-scale (Figure 6b).

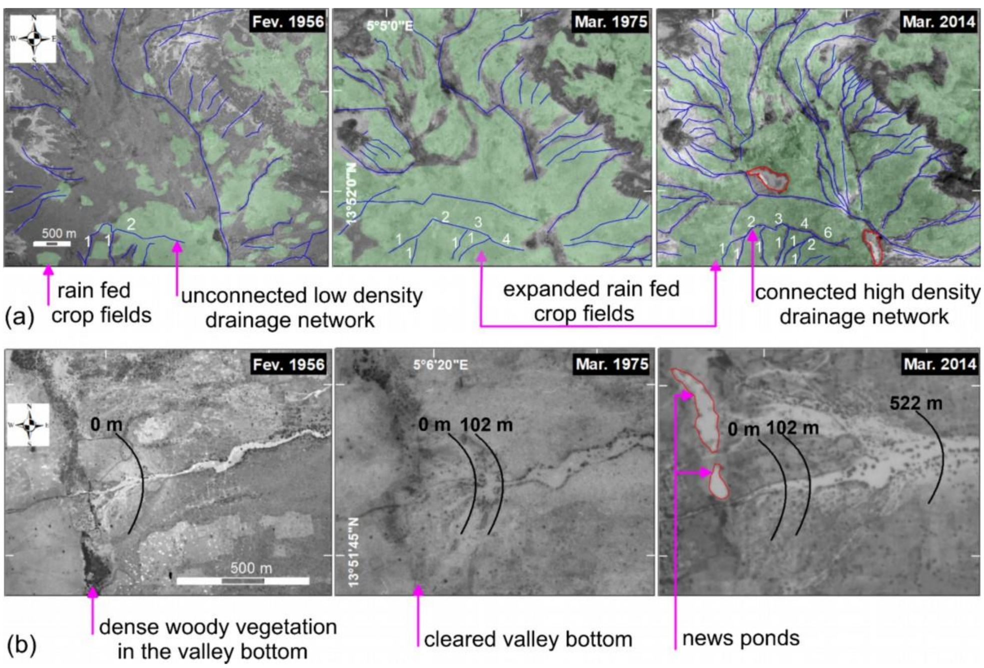

Figure 6. (a) Example of land clearance and expansion of rain-fed crop fields, evolution of drainage network, and ponds formation, and (b) the upward shift of an alluvial fan for the period 1956-2014 in the downstream part of the basin. Rain-fed crop fields are mapped in green color using object-based image classification, and the drainage network is shown in dotted blue lines. The head of the alluvial fan is marked in a black arc at the zero position. The changing position

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

of the head of the alluvial fan is shown again in black arc to the left for each year of the reference arc of 1956. New ponds that appeared between 1983 and 2014 are delineated in red on the 2014 image (location within the watershed as shown in Figure 1b)

3.3 Groundwater resources dynamics

3.3.1 Focused recharge from surface waters to the unconfined aquifer

Surface water - groundwater exchanges were inferred from the piezometric map (end of the dry season, first half of June 2023) at the watershed scale (Figure 1b). Groundwater flows from northeast to southwest with decreasing hydraulic gradients, from 4‰ to 0.4 ‰, reflecting an overall increase in the aquifer thickness and transmissivity to the south (Chaweye et al., 2026). Changes through time (1960s-2020s) in river water – groundwater relationships are shown for a piezometer located close to the main river course (Figure 7). The intermittent, seasonal, and reactive characteristics of the MRW can be seen from the highly variable fluctuations of the computed daily flows, involving large individual peaks reported for a few days, which are followed by longer periods of low or no flux through the dry season. For this site, there is a consistent good match between the timing of rainfall events, river flows, and recharge that peaks by the end of the rainy season, then followed by a long water table recessing discharge period (Figure 7a). Through the 1960s to the early 1980s, the water table was mostly connected to the river and fed by river floods, resulting in a visible succession of ponds along the river by the end of the rainy season and through the dry season (SOGETHA, 1964; Figure 7a and c). For recent years, measurements carried out in the same piezometer (Figure 7b) showed seasonal fluctuations during the rainy season; however, the water table had dropped by a few meters and was no longer outcropping by the end of the rainy season (Figure 7e).

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

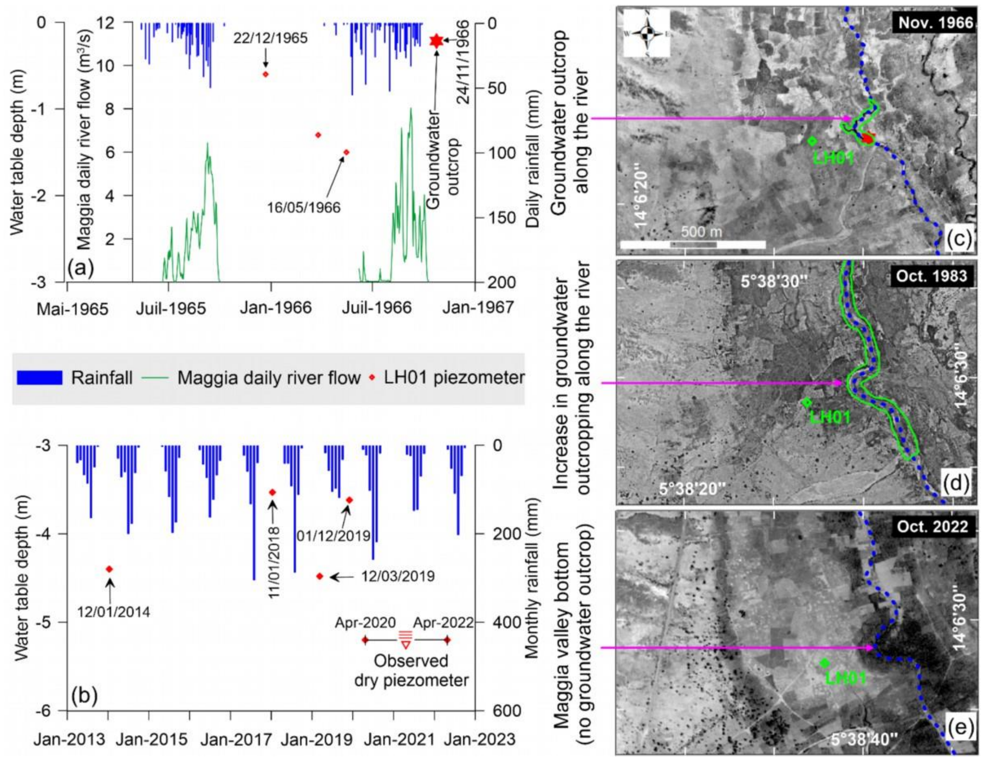

Figure 7. (a) Daily River flow and daily rainfall records (downstream stations, Birni N'Konni, location in Figure 1b) and water table fluctuations measured in piezometer LH01 at ~ 40 m from the River (upstream part of the watershed, location shown in Figure 1b) through the years 1965-1966; (b) Monthly rainfall records (same rainfall station as in Figure 7a and deeper measured water table depths (same piezometer) through the years 2013-2019; (c) Groundwater outcropping along the River in Nov. 1966 (inferred water table depth reported in Figure 7a; (d) Expanded groundwater outcropping along the River in Oct. 1983 (no piezometric data available); (e) Decrease in groundwater level for the past decades, as shown by no more groundwater outcropping in the valley in Oct. 2022. Hydrometric data technical reports are cited within the text.

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

3.3.2 A pluri-decadal fall in the water table

The groundwater level chronicles over the 1960s-2020s (Figure 8a) or over the 1980s-2020s (Figure 8b) indicate a steady downward trend in water table depths. Current groundwater levels are the lowest recorded since the 1960s, regardless of the position within the valley and/or the initial depth of the water table. Wells are located within or close to the main valley of the Maggia River (Figure 1b and Fig. S1) and showed piezometric fluctuations during the rainy season when data were available (1960s or 2020 surveys). In the upstream part of the MRW, extreme ranges for drops in the water table range within -3.0 (LH01) to -6.0 m (GM01) for the 1965-2019 or 1965-2022 periods, respectively, with overall rates of decline in the range of ~ 5 to 11 cm yr^{-1}. In the downstream part of the MRW, available groundwater surveys indicate a narrow range of -4.4 m (BK01) to -4.8 m (TY01) and therefore no significant difference in the drop rate for the 1960s to the 2020s (~ 8 cm yr^{-1}). Whereas some records indicate a steady decline for the whole period (e.g. TY01, located downstream), others indicate an accelerated drop for the more recent decades (eg. GM01, located upstream), or even a decelerated rate in the decline (e.g. TB01, located upstream). Groundwater surveys for the 1980s-2020s (Figure 8b) in the upstream part display rates of decline in the range of -3.0 m (LD02) to - 4.3 m (ML01), that correspond respectively to rates of decline in the range of ~ 6 to 9 cm yr^{-1}. Very similar rates of decline can be computed for the same period for chronicles located in the downstream part of the MRW for deeper wells (CH01, ND01), with estimated rates in the range of ~ 11 cm yr^{-1}. Overall, the limited dataset does not allow to draw accurate information based on the internal variability of each chronicle. The relatively narrow range of the computed rates of water table drops (from ~ 5 to 11 cm yr^{-1}) suggests a consistent pattern of a steady decrease in groundwater levels through the whole MRW.

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

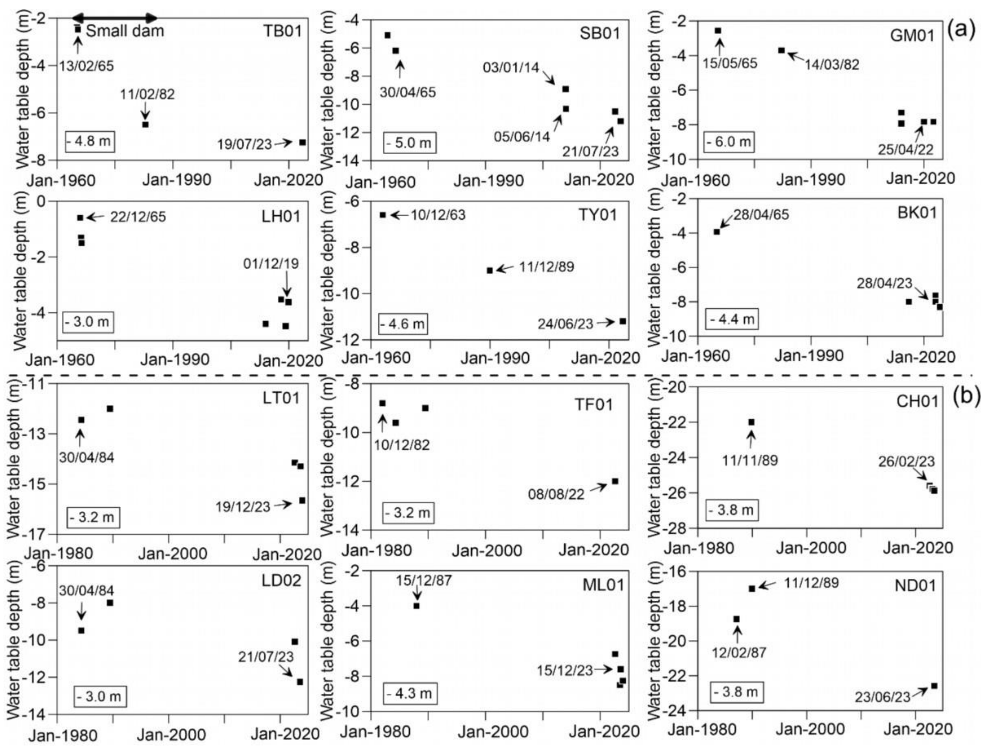

Figure 8. Examples of pluri-decadal drops in groundwater levels: (a) 1960s-2020s, (b) 1980s-2020s for shallow wells or piezometer (LH01) close to the Maggia River (locations shown in Figure 1b and/or reported in Figure 2). Most wells are not in use anymore and record static water levels (except TY01, used for domestic purposes). Wells CH01 and ND01 are deeper and tap, respectively, the Oligocene and Cretaceous aquifers locally fed by the quaternary alluvium. Technical reports and origin of water table data cited within the text.

4 Discussion

4.1 Contrasted trends in response to land management practices

The large diversity in SWC control practices through the MRW (stone bund lines, contour ridges, half-moon or small dams; Fig. S3) and their complex timings of implementation prevent

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

any estimate of their relative impact on runoff production reduction to the valley and at the basin scale. A relative estimate of their combined efficiency can be made by comparing the upstream and downstream parts of the MRW, of similar characteristics but showing different pathways in land management strategies. Two main periods for trends in land use/land cover can be considered, as a function of the available images in both parts of the MRW (Table 1). First, from the 1950s to the early 1980s (computed data 1956-1983), the whole MRW experienced a dramatic loss in the perennial vegetation cover in all parts of the landscape, from plateaus (-75 %) to slopes (-65 %) to valleys (-26 %) (Figure 9a and d). This loss was interpreted, based on intermediate images (1956-1975, Figure 6a) and field surveys, as mostly the result of the extension of crop fields to meet the widespread demand in cultivated areas. Lower natural woody and herbaceous land cover led to an increase in hortonian runoff and drastic changes in the drainage network (Figure 6b). Evidences are reported in both the upstream and downstream parts, with metrics of drainage density showing rising values (from 0.5 to 2.0 km^{-1} and +80 %, respectively, (Figure 9b and e) and by the increase in the connectivity of the drainage network (Shreve's Order increased from 0.70 to 1.45 and from 0.70 to 0.90 between 1956 and 1983, respectively, Figure 4a).

By the early 1980s and onward (1983-2022, images shown), the upstream and downstream parts of the MRW followed distinct pathways. In the upstream part, SWC practices (mostly stone bund lines, Figure 9c), or small dams; Fig. S3) were increasing in density on slopes (example shown in Fig. S3, 1975-1983 period) and largely resulted in a lowering of the connectivity of the drainage network, with no or limited change in the cultivated cropland surface areas. Limiting runoff resulted in less soil loss and higher infiltration at plot scale, and hence, lower runoff to the main outlets and therefore lowered river water discharge fluxes. The drainage density lowered by ~1.6 fold, and the SO lowered to 0.78 (mean value, Figure 4a). No such SWC practices were observed in the downstream part of the MRW were trends did not

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

shift for the same period, and showed increasing drainage density values (up to 1.5 km^{-1}, Figure 9e), increasing connectivity (Figure 4b, SO of 0.94 in 2014). This resulted in hydrological changes in the landscape as shown by mid-slope migrations in alluvial fans positions (Figure 6b) and/or creation of new surface water ponding (Figure 6a). These changes appear very much similar to those previously reported in semiarid SW Niger in response to long-term land clearing (Massuel et al., 2006; Leblanc et al., 2008).

Another change in pathways between the two sub-basins occurred through the development of i) large and small irrigation schemes and ii) regreening strategies by non-indigenous tree plantations through valleys. By the early 1980s, two main dams were completed (in 1977 and 1981) and enabled irrigation schemes to expand in the downstream part, increasing water availability for crop production during the onset of the dry season (Figure 1 and Figure 9f). A side effect has been that the natural flooding of the plain during extreme rainy years was suppressed, hence contributing to an imbalance in this part of the aquifer, and hence, lowering trends in the water table (Figure 2). In the upstream part of the basin, much smaller dams were built and could have contributed to locally lowering the water table (e.g. small TB dam, 1967-1983, Figure 8a). However, the main land cover change occurred through massive reforestation schemes through the MRW valley, with an estimated 850 km in tree lines of regreening (*Azadirachta indica)* occurring between the end of the 1970s – early 1980s to the mid-2000 (Figure 1b and Figure 9a). Reforestation occurred in a dense array of 400 trees ha^{-1}, that remained visible through the 2000-2010s (Figure 3). These large-scale regreening programs to protect and restore degraded land and prevent aeolian erosion processes represent the main cause of the observed increase in perennial vegetation density through the valley.

These divergent pathways in a single watershed can be used as a comparative pair of examples to better constrain the main causes of the observed changes. Factors, such as less abundant precipitation, particularly during the Sahelian drought period (~1971-1990; Figure

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

9f), may have been considered as possible causes of the decrease in the drainage network during the 1983-2002 period. Between 1971 and 1990, average annual rainfall fell from 557 mm to 485 mm, while drainage density fell from 2.05 to 1.62 km^{-1} between 1983 and 2002. However, if the observed changes in the drainage network in the upstream part were a consequence of the pluri-decadal drought period, the very same impact should have been observed on the downstream part of the MRW, which did not occur (Figure 9e and f). The reduction in runoff in response to re-greening and SWC development appears to be the single possible explanation for the observed change in drainage density and its consequences in runoff production or indirect groundwater recharge reduction on the long-term.

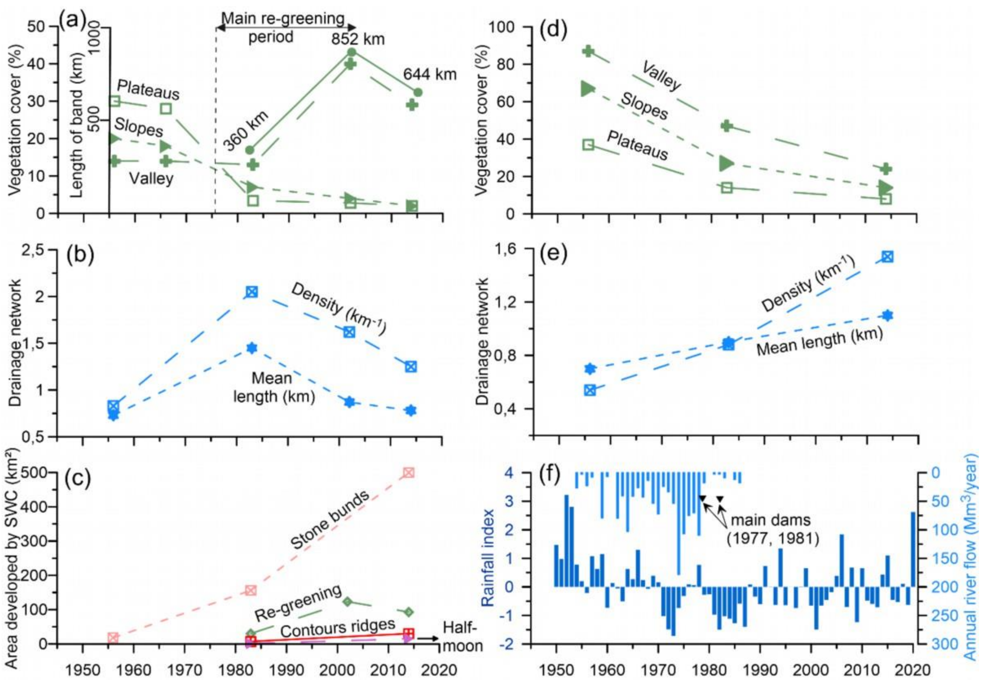

Figure 9. Synthetic view of pluri-decadal (1950s-2020s) observed land use/land cover and hydrological changes in the upstream (a, b, c) and downstream (d, e, f) parts of the Maggia River watershed. (a) and (d): Changes in the dry-season perennial vegetation cover estimated by remote sensing analysis; (b) and (e): Changes in the drainage network as computed by remote sensing analysis; (c) Computed changes in the different techniques used for soil and water

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

conservation practices on degraded soil surfaces; (e) Annual rainfall and annual river flow measured in the downstream part of the watershed (Birni N'Konni station, location shown in Figure 1b).

4.2 Trade-off between re-greening, SWC and groundwater resources

A comparison of the observed changes in LULC, drainage network, and groundwater levels over a pluri-decennial period (1956-2022 for HR images; 1965-2023 for water table level data) offers a unique insight into the relationships between re-greening and SWC practices and water resources of the MRW. In the Sahel, as in most parts of dryland regions, a significant part of groundwater recharge is indirectly fed by river or lakes (e.g. Fan, 2015; Rau et al., 2026), so the groundwater system most often acts as an integrator of hydrological changes that may result from climate and/or LULC changes (Favreau et al., 2009; Kuang et al., 2024). Piezometric data through the MRW show a long-term decrease in groundwater levels, noticeable since the mid-1980s (Figure 8). This decrease reflects a disturbance in the hydrological balance, the origin of which remains to be explained and deciphered as a function of observed hydrological trends. Rainfall data indicate that over the main Sahelian drought period (1971-1990), annual rainfall was 30 % below the 1950-2020 average (Figure 9f). These below-average rainfall conditions may have contributed to reduce runoff; for instance, in a similar landscape context in SW Niger, reduced rainfall of ~25 % was estimated by distributed surface water modeling to lower runoff by half over a ~2 km^2 watershed (Favreau et al., 2009). The mean annual baseflow of the Maggia River measured in the downstream part of the basin dropped from 179 to 9 Mm^3 (minus 95 %) between 1974 and 1983, while the mean annual rainfall amounts were respectively of 289 and 386 mm (30 % higher).

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

Another explanation lies in the timing of the damming of the river (years 1977 and 1981; Figure 9f). The reduction in river flow in the downstream part of the MRW, and most notably of flood events by dams with initial combined volumetric capacity (42 Mm^3), lies within the range of average annual river flow (3 to 179 Mm^3) and is probably a large contributing factor to the lowered groundwater recharge and long-term disequilibrium shown in the unconfined aquifer (Figure 2 and Figure 8b).

In addition, numerous groundwater pumping wells (estimated density ~80 wells km^{-2} in 2023) through the large (~2500 ha; Figure 1b, downstream part) irrigation scheme were reported and could have significantly contributed to the long-term drop in the water table levels. At a global scale, excess in pumping for irrigation represents a significant parameter for fluxes to be considered for explaining the long-term lowering of the water table in drylands (Kuang et al., 2024). A rapid estimate based on numerical solutions for estimating drawdowns and using sub-surface geophysics-derived hydraulic aquifer parameters (Chaweye et al., 2026) indicates that, considering a five-month irrigation (November through April) period on the long-term (40 years) and typical irrigation demand of water-demanding cropping (*Allium cepa*, *Solanum lycopersicum*, *Moringa oleifera*) using groundwaters (~1000 m^3 ha^{-1} $week^{-1}$), the resulting long-term drawdown would be of the order of 1 to 2 meters compared to non-pumping conditions. This would have resulted in an estimated drawdown of ~ 0.02 to ~ 0.05 m yr^{-1}, a rate consistent, albeit on the lower range, with the observations for wells located within or near the irrigated scheme (Figure 1b and Figure 8).

In the upstream part of the MRW, another more subtle explanation for increased withdrawal lies in large-scale regreening and SWC developments that occurred through the landscape (Figure 1b; upstream part). During the 1975-2005 decades, more than 17,000 ha were developed using re-greening and SWC practices. These developments considerably reduced the flow rate, albeit in an unknown proportion, downstream and, consequently, indirect recharge

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

through gullies and stream beds to the unconfined aquifer (Figure 7). This explanation comes in echo, whereas in inverse trend, to the processes evidenced in SW Niger, where increased recharge was shown to occur in response to increased focused recharge through gullies and ponds (Favreau et al., 2009). Through the MRW upstream part, the observed decline in groundwater level coincided (Figure 8b), but most certainly preceded (Figure 8a) a decrease in the drainage network, and an increase in developed areas with SWC practices (Figure 9a and c). During interviews, the impact of stone bund lines, for example, the disappearance of gullies, was readily understood (with an estimated short time-lag of 2 to 5 years, depending on the size of the gully).

Re-greening strategies to counter aeolian erosion processes were developed within the MRW, using *Azadirachta indica* phreatophytes species (Smith et al., 1997). Through estimates by HR images analyses, 93 km^2 for the whole period could be delineated as re-greened areas (Figure 1b) and represents a likely significant discharge component for the aquifer balance of the quaternary alluvium. Early studies recognized the potential impact of this species on the aquifer balance and showed, by combining stable water isotope techniques and the heat-pulse technique for sap-flow measurements, that most of the deeper underground/groundwater dependence occurred through the dry season (Brenner et al., 1991; Smith et al., 1997). Using estimates from field studies performed within the MRW (water table depth 6 to 8 m, tree density of ~ 400 units ha^{-1}), transpiration fluxes were estimated at 2.8 mm day^{-1} « per unit projected crown area » for the end of the crop (rainy) season (Smith et al., 1998). Considering this value a conservative estimate, and given the known parameters of the unconfined aquifer (Sauvel, 1966; Chaweye et al., 2026), this would represent about 6 m of total drawdown for the whole data period (1983-2023), i.e ~15 cm yr^{-1}. This rate is slightly higher, although consistent with observations of drawdowns observed through the regreened area of the upstream part of the MRW. Although some recharge is shown to occur (Figure 7b), the long-term drop in the water

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

table has not yet reached an equilibrium and threatens the already low groundwater reserves of the unconfined aquifer in this part of the aquifer, as shown by the large number (~25) of seasonally dry wells in this part of the MRW (Figure 1b).

4.3 Representativity at a regional and global scales

SWC efforts in the Sahel regions, including the flagship Pan-African GGW initiative (e.g. Turner et al., 2023), are yet to estimate the long-term impact of reforestation initiatives on groundwater resources. However, the need to reconcile groundwater uses and land development is increasingly recognized for better evaluating mitigation strategies and nature-based solutions (Griscom et al., 2017; Bastin et al., 2019; Douville et al., 2022). To the best of our knowledge, no research or long-term survey has yet estimated the impact of reforestation in the Sahel region. At a global scale, studies on groundwater changes following large-scale reforestation remain equally scarce. Examples of changes in the surface water/groundwater balance observed through piezometric surveys and evaluated as a consequence of afforestation include i) reported long-term decreases in groundwater-fed river flows (Le Maitre et al., 1999) or ii) multi-decadal drops in the shallow water table in response to reforestation in the Mediterranean climate of SW Australia (Bari and Schofield, 1992). At much larger scales, the Three Norths Shelterbelt Program (TNSP) in northern China is globally recognized as an emblematic program having helped in emphasizing the impact of reforestation on the groundwater balance (Turner et al., 2023; Kuang et al., 2024). Large-scale reforestation programs have made a significant contribution to global re-greening, although more specific studies help to better define the long-term impact of afforestation on groundwater resources.

In Northern Victoria, Heuperman (1999) recorded a decrease in groundwater levels of 2 to 4 m beneath a mature forest of ~ 40 trees.ha^{-1}, where the water table was at ~10 m depth. Similar hydraulic gradient reversal effects were observed at irrigation sites with varying tree

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

spacings (Heuperman, 1999). Approximately four years after plantation, higher tree density (3-meter spacing) began to lower groundwater levels, and two years later, similar results were observed for trees spaced 7.3 meters apart. Results from six experimental sites in SW Australia showed that the magnitude of the drop in the water table increased with the proportion of reforested area, with drops ranging from 0.6 m to 3 m between 1979 and 1986 (Bell et al., 1990). In humid subtropical Brazil, Mattos et al. (2019) recorded a decrease of 1 to 3 m between 2004 and 2016 in an *eucalyptus* stand with a density of 1,334 trees ha^{-1}. The most comprehensive quantitative study directly addressing reforestation and groundwater levels is that of Zheng et al. (2012) in cold, semiarid Northeast China. Using groundwater level data, they demonstrate that the ~ 5 m drop in groundwater level between 1954 and 2009 was indirectly due to water consumption by *Sylvestris var. mongolica* tree plantations type, exceeding aquifer recharge rate. In temperate, humid region of Argentina, Jobbágy and Jackson (2004) reported the impact of reforestation by *Eucalyptus sp*. on groundwater dynamics, showing by piezometric surveys, increased evapotranspiration fluxes below afforested plots.

This study represents a pioneering effort to quantify the impacts of reforestation on groundwater resources in the Sahel. Our research has shown that tree plantations in semiarid regions consume significant amounts of groundwater, which may exceed aquifers' recharge rates. At a global scale, more long-term studies are obviously needed to better assess the magnitude of the impact of reforestation on groundwater, particularly in Africa, where groundwater data are often scarce (MacDonald et al., 2012; Cuthbert et al., 2019) and require a more integrated perspective in global fluxes and ecosystem sustainability (Rohde et al., 2024; Saccò et al., 2024).

5 Conclusion and perspectives

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

This study offers a detailed, fine-scale insight into the environmental and hydrological changes that have occurred over a six-decades time period in response to re-greening strategies developed in the Sahel region. To the best of our knowledge, this represents the longest combined reconstructed chronicles of land cover, surface water, and groundwater levels in drylands of sub-Saharan Africa. Hence, it enables to evaluate, and exemplify, the impact and trade-off of nature-based re-greening strategies, at an integrated time-scale that matches closely the multi-decadal continental (African Union, 2020) or global sustainable development goals (GSDGR, 2023).

Main conclusions are as follows:

- Soil and water conservation practices were shown to successfully reverse trends of increasing runoff, resulting in a lowering of erosion, gullies density and indirect recharge fluxes to the unconfined aquifer. The Sahelian paradox was demonstrated by remote sensing and on the long term, for the first time to the best of our knowledge, to be a reversible process.
- Reforestation by non-indigenous phreatophytes trees was shown to have a direct impact on the groundwater balance of the aquifer. Discharge rates could translate in observed 5 to 10 cm yr^{-1} in lowering of the water table, resulting in a 3 to 6 m drop in the water table since the early 1980s. Recent observations did not allow to observe any stabilization in the drawdown. This represents the first observed evidence of a negative long-term impact of reforestation schemes on groundwater resources in the Sahel region.
- The time-lag between SWC practices or reforestation and their impact on the groundwater balance is much longer (few decades) than on surface waters (few years, metrics computable by HR remote sensing). Nature-based solutions need to be evaluated

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

on the long-term when dealing with groundwater resources, particularly in sensitive, complex or fragile dryland ecosystems.

These results have important implications as they show a trade-off between land restoration management and groundwater resources, often the most vital component of the economy in drylands for domestic, irrigation, pastoralism, renewable energy, or mining or industrial water uses. They come in support of conclusions that the water component represents an overlooked limit that needs to be more accurately evaluated in development strategies, as well as mitigating climate change impacts (Douville et al., 2022).

Author contributions. YNC and GF conceived the manuscript idea**.** YNC acquired, and treated the data, and wrote the first draft of the manuscript. AD contributed to the treatment of historical images, reviewed and edited the methodology. GF contributed to writing and editing the manuscript. BIO and RAM contributed to field surveys. All authors discussed the results and contributed to writing the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. This study was carried out as part of a doctoral thesis co-funded by the Ministry of Research and Innovation (MESRI) of the Niger Republic and the French National Research Institute for Sustainable Development (IRD). We express our gratitude to the Ministries of Hydraulics and Sanitation, Rural Engineering, and the Department of Rural Engineering of Birni N'Konni, Malbaza, and Bouza for providing various types of data on water resources and SWC practices. The Ministry of Hydraulics and the private BERIA consulting

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

organization greatly helped in providing access to their archives. The authors acknowledge the use of SPOT data distributed by DINAMIS (https://catalogue-dinamis.data-terra.org/).

References

African Union: Framework for Irrigation Development and Agricultural Water Management in Africa, https://www.fsnnetwork.org/sites/defa ult/files/2021-08/38632-doc-english.pdf, 2020.

An, Q., Liu, L., Staal, A., Yang, K., Cheng, Y., Liu, J., and Huang, G.: Land Cover Changes Redistribute China's Water Resources Through Atmospheric Moisture Recycling, Earth's Futur., 13, https://doi.org/10.1029/2024EF005565, 2025.

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

Bastin, J. F., Finegold, Y., Garcia, C., Mollicone, D., Rezende, M., Routh, D., Zohner, C. M., and Crowther, T. W.: The global tree restoration potential, Science (80-.), 364, 76–79, https://doi.org/10.1126/science.aax0848, 2019.

Bell, R. W., Schofield, N. J., Loh, I. C., and Bari, M. A.: Groundwater response to reforestation in the Darling Range of Western Australia, J. Hydrol., 115, 297–317, https://doi.org/10.1016/0022-1694(90)90211-F, 1990.

Boeckh, E.: Contribution à l'étude hydrogéologique de la zone sédentaire de la République du Niger. Ministère des Travaux publics et des Mines de la République du Niger. Rapport technique BRGM / BFBH, DAK65. Dakar, Sénégal, 1965.

Brandt, M., Romankiewicz, C., Spiekermann, R., and Samimi, C.: Environmental change in time series - An interdisciplinary study in the Sahel of Mali and Senegal, J. Arid Environ., 105, 52–63, https://doi.org/10.1016/j.jaridenv.2014.02.019, 2014.

Brenner, A. J., Jarvis, P. G., and Vandenbeldt, R. J.: Transpiration from a neem windbreak in the Sahel, in: IAHS-AISH Publication, 375–385, 1991.

Bricquet, J. P.: Mémoire de fin d'études en hydrologie: Niamey ORSTOM. multigr. + annexes. Mém. Fin d'Études : Hydrol., ORSTOM : Paris. 1983/08. 26 pp., 1983.

Brunet-Moret, Y., Chaperon, P., Lamagat, J., and Molinier, M.: Monographie hydrologique du fleuve Niger, 2, 8. 3. éd.. Paris (FRA) : ORSTOM, 1986, 402 + 510 p.. (Monographies Hydrologiques (FRA)), 8. ISBN 2-7099-0790-9; 2-7099-0791-7, 1986.

Chagnaud, G., Panthou, G., Vischel, T., and Lebel, T.: A synthetic view of rainfall intensification in the West African Sahel, Environ. Res. Lett., 17, 44005, https://doi.org/10.1088/1748-9326/ac4a9c, 2022.

Chardon, D., Grimaud, J. L., Rouby, D., Beauvais, A., and Christophoul, F.: Stabilization of large drainage basins over geological time scales: Cenozoic West Africa, hot spot swell growth, and the Niger River, Geochemistry, Geophys. Geosystems, 17, 1164–1181, https://doi.org/10.1002/2015GC006169, 2016.

Chaweye, Y. N., Boucher, M., Favreau, G., Ousmane, B. I., Mahaman, R. A., Legchenko, A., and Nazoumou, Y.: Fine-scale mapping of aquifer limits and relationships in the upper plateaus of the Iullemmeden basin, Niger, J. African Earth Sci., 237, https://doi.org/10.1016/j.jafrearsci.2026.106068, 2026.

Critchley, W. R. S., Reij, C., and Willcocks, T. J.: Indigenous soil and water conservation: A review of the state of knowledge and prospects for building on traditions, L. Degrad. Dev., 5, 293–314, https://doi.org/10.1002/ldr.3400050406, 1994.

Cuthbert, M. O., Taylor, R. G., Favreau, G., Todd, M. C., Shamsudduha, M., Villholth, K. G., MacDonald, A. M., Scanlon, B. R., Kotchoni, D. O. V., Vouillamoz, J. M., Lawson, F. M. A., Adjomayi, P. A., Kashaigili, J., Seddon, D., Sorensen, J. P. R., Ebrahim, G. Y., Owor, M., Nyenje, P. M., Nazoumou, Y., Goni, I., Ousmane, B. I., Sibanda, T., Ascott, M. J., Macdonald, D. M. J., Agyekum, W., Koussoubé, Y., Wanke, H., Kim, H., Wada, Y., Lo, M. H., Oki, T., and Kukuric, N.: Observed controls on resilience of groundwater to climate variability in sub-Saharan Africa, Nature, 572, 230–234, https://doi.org/10.1038/s41586-019-1441-7, 2019.

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

D'Odorico, P., Bhattachan, A., Davis, K. F., Ravi, S., and Runyan, C. W.: Global desertification: Drivers and feedbacks, Adv. Water Resour., 51, 326–344, https://doi.org/10.1016/j.advwatres.2012.01.013, 2013.

Dardel, C., Kergoat, L., Hiernaux, P., Grippa, M., Mougin, E., Ciais, P., and Nguyen, C. C.: Rain-use-efficiency: What it tells us about the conflicting Sahel greening and sahelian paradox, Remote Sens., 6, 3446–3474, https://doi.org/10.3390/rs6043446, 2014.

De Fleury, M., Kergoat, L., and Grippa, M.: Hydrological regime of Sahelian small waterbodies from combined Sentinel-2 MSI and Sentinel-3 Synthetic Aperture Radar Altimeter data, Hydrol. Earth Syst. Sci., 27, 2189–2204, https://doi.org/10.5194/hess-27-2189-2023, 2023.

Di Vecchia, A., Pini, G., Sorani, F., & Tarchiani, V.: Keita, Niger: the impact on environment and livelihood of 20 years fight against desertification. Centro Città del Terzo Mondo

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

Politechnico di Torino, Turin, Italy. Working Paper, 2007, no 26, p. 19, 19 pp., 2007.

Doblas-Reyes, F. J,. A. A. Sörensson, M. Almazroui, A. Dosio, W. J. Gutowski, R. Haarsma, R. Hamdi, B. Hewitson, W-T. Kwon, B. L. Lamptey, D. Maraun, T. S. Stephenson, I. Takayabu, L. Terray, A. Turner and Z. Zuo.: Linking Global to Regional Climate Change. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1363–1512, https://doi.org/10.1017/9781009157896.012, 2021.

Douville, H., Allan, R. P., Arias, P. A., Betts, R. A., Caretta, M. A., Cherchi, A., Mukherji, A., Raghavan, K., and Renwick, J.: Water remains a blind spot in climate change policies, PLOS Water, https://doi.org/10.1371/journal.pwat.0000058, 2022.

Eboreime, E., Anjorin, O., Obi-Jeff, C., Ojo, T. M., and Hertelendy, A.: From drought to displacement: Assessing the impacts of climate change on conflict and forced migration in West Africa's Sahel Region, J. Clim. Chang. Heal., 23, https://doi.org/10.1016/j.joclim.2025.100448, 2025.

Elie, M.: Toward a complex socio-environmental understanding of drought: The contribution of the social sciences and humanities, Wiley Interdiscip. Rev. Clim. Chang, https://doi.org/10.1002/wcc.907, 2024.

Fan, Y.: Groundwater in the Earth's critical zone: Relevance to large-scale patterns and processes, Water Resour. Res., 51, 3052–3069, https://doi.org/10.1002/2015WR017037, 2015.

FAO: The Keita Integrated Rural Development Project. FAO, Rome, Italy, pp. 39, Rome, Italy, 1995.

Favreau, G., Leduc, C., and Marlin, C.: Représentativité de l'échantillonnage géochimique et hydrodynamique en nappe libre de milieu semi-aride, J. African Earth Sci., 31, 669–678, https://doi.org/10.1016/S0899-5362(00)80014-7, 2000.

Favreau, G., Cappelaere, B., Massuel, S., Leblanc, M., Boucher, M., Boulain, N., and Leduc, C.: Land clearing, climate variability, and water resources increase in semiarid southwest Niger: A review, Water Resour. Res., 45, W00A16, https://doi.org/10.1029/2007WR006785, 2009.

Frankl, A., Nyssen, J., De Dapper, M., Haile, M., Billi, P., Munro, R. N., Deckers, J., and Poesen, J.: Linking long-term gully and river channel dynamics to environmental change using repeat photography (Northern Ethiopia), Geomorphology, 129, 238–251, https://doi.org/10.1016/j.geomorph.2011.02.018, 2011.

Friedlingstein, P., Allen, M., Canadell, J. G., Peters, G. P., and Seneviratne, S. I.: Comment on "The global tree restoration potential," Science (Vol. 366, Issue 6463, p. 8060). American Association for the Advancement of Science, https://doi.org/10.1126/science.aay8060, 2019.

Gal, L., Grippa, M., Hiernaux, P., Pons, L., and Kergoat, L.: The paradoxical evolution of runoff in the pastoral Sahel: Analysis of the hydrological changes over the Agoufou watershed (Mali) using the KINEROS-2 model, Hydrol. Earth Syst. Sci., 21, 4591–4613, https://doi.org/10.5194/hess-21-4591-2017, 2017.

Gardelle, J., Hiernaux, P., Kergoat, L., and Grippa, M.: Less rain, more water in ponds: A remote sensing study of the dynamics of surface waters from 1950 to present in pastoral Sahel (Gourma region, Mali), Hydrol. Earth Syst. Sci., 14, 309–324, https://doi.org/10.5194/hess-14-309-2010, 2010.

Gavaud, M., Boulet, R.: Carte pédologique de reconnaissance de la République du Niger 1:500000, Feuille Niamey. Paris: Éditions ORSTOM, 1967.

Ghuffar, S., King, O., Guillet, G., Rupnik, E., and Bolch, T.: Brief communication: Glacier mapping and change estimation using very high-resolution declassified Hexagon KH-9 panoramic stereo imagery (1971-1984), Cryosphere, 17, 1299–1306, https://doi.org/10.5194/tc-17-1299-2023, 2023.

Greigert, J.: Atlas hydrogéologique de l'Ader Doutchi. Rapport BRGM 68 ABI 004 NIA, 208 pp., 1967.

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., Schlesinger, W. H., Shoch, D., Siikamäki, J. V, Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R. T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M. R., Herrero, M., Kiesecker, J., Landis, E., Laestadius, L., Leavitt, S. M., Minnemeyer, S., Polasky, S., Potapov, P., Putz, F. E., Sanderman, J., Silvius, M., Wollenberg, E., and Fargione, J.: Natural climate solutions, Proc. Natl. Acad. Sci. U. S. A., 114, 11645–11650, https://doi.org/10.1073/pnas.1710465114, 2017.

GSDGR: Times of crisis, times of change: Science for accelerating transformations to sustainable development (United Nations, New York, 2023). https://sdgs.un.org, 2023.

Heuperman, A.: Hydraulic gradient reversal by trees in shallow water table areas and repercussions for the sustainability of tree-growing systems, Agric. Water Manag., 39, 153–167, https://doi.org/10.1016/S0378-3774(98)00076-6, 1999.

Hiernaux, P., Dardel, C., Kergoat, L., and Mougin, E.: Desertification, Adaptation and Resilience in the Sahel: Lessons from Long Term Monitoring of Agro-ecosystems, 147–178, https://doi.org/10.1007/978-3-642-16014-1_6, 2016.

INS: Recensement Général de la population et de l'habitation, 2012. (NER-INS-RGPH--2012-V1.0). https://anado.ins.ne/index.php., 374 pp., 2012.

IWACO: Création d'un réseau piézométrique national. Réconnaissance des sites présélectionnés. Ouagadougou, Burkina Faso, 24 pp., 1990.

Jobbágy, E. G. and Jackson, R. B.: Groundwater use and salinization with grassland afforestation, Glob. Chang. Biol., 10, 1299–1312, https://doi.org/10.1111/j.1365-2486.2004.00806.x, 2004.

KFW: Implantation des puits cimentés par prospection géoélectrique dans l'Ader-Doutchi, Rapport d'étude, 2ème Partie., 1991.

Kuang, X., Liu, J., Scanlon, B. R., Jiao, J. J., Jasechko, S., Lancia, M., Biskaborn, B. K., Wada, Y., Li, H., Zeng, Z., Guo, Z., Yao, Y., Gleeson, T., Nicot, J. P., Luo, X., Zou, Y., and Zheng, C.: The changing nature of groundwater in the global water cycle, Science (80-.), https://doi.org/10.1126/science.adf0630, 2024.

Le Roux, E., Wendling, V., Panthou, G., Dubas, O., Vandervaere, J.-P., Hector, B., Favreau, G., Cohard, J.-M., Pierre, C., Descroix, L., Mougin, E., Grippa, M., Kergoat, L., Demarty, J., Rouche, N., Etchanchu, J., and Peugeot, C.: Hydrological regime shifts in Sahelian watersheds: an investigation with a simple dynamical model driven by annual precipitation, Hydrol. Earth Syst. Sci., 30, 929–944, https://doi.org/10.5194/HESS-30-929-2026, 2026.

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

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

Lefèvre, R.: Inventaire des études hydrologiques et hydrogéologiques exécutées dans les zones sahéliennes et désertiques de la République du Niger. Paris (FRA) : ORSTOM, 1993, 6 pp, 1962.

MacDonald, A. M., Bonsor, H. C., Dochartaigh, B. É. Ó., and Taylor, R. G.: Quantitative maps of groundwater resources in Africa, Environ. Res. Lett, https://doi.org/10.1088/1748-9326/7/2/024009, 2012.

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

Massuel, S., Favreau, G., Descloitres, M., Le Troquer, Y., Albouy, Y., and Cappelaere, B.: Deep infiltration through a sandy alluvial fan in semiarid Niger inferred from electrical

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

conductivity survey, vadose zone chemistry and hydrological modelling, Catena, 67, 105–118, https://doi.org/10.1016/j.catena.2006.02.009, 2006.

Mattos, T. S., de Oliveira, P. T. S., Lucas, M. C., and Wendland, E.: Groundwater recharge decrease replacing pasture by Eucalyptus plantation, Water (Switzerland), 11, https://doi.org/10.3390/w11061213, 2019.

Mechiche-Alami, A., O'Byrne, D., Tengberg, A., and Olsson, L.: Evaluating the scaling potential of sustainable land management projects in the Sahelian Great Green Wall countries, Environ. Res. Lett., 17, 084016, https://doi.org/10.1088/1748-9326/ac8111, 2022.

MHE: Synthèse des données piézométriques et proposition d'un réseau minimum de surveillance des aquifères sensibles. Rapport Programme Hydraulique Niger-Suisse. Mandat de gestion n° 140/PNS/CN, 1999.

Mohamed, A. M. L., Seyni, S., Mkuhlani, S., Chemura, A., Faye, B., Kadir, S. A., Gadedjisso-Tossou, A., and Auwalu, B. M.: Impact of climate change on millet yield under different fertilization levels in three agroecological zones of Niger Republic, PLoS One, 20, https://doi.org/10.1371/journal.pone.0333963, 2025.

Moron, V., Oueslati, B., Pohl, B., Rome, S., and Janicot, S.: Trends of mean temperatures and warm extremes in northern tropical Africa (1961-2014) from observed and PPCA-reconstructed time series, J. Geophys. Res., 121, 5298–5319, https://doi.org/10.1002/2015JD024303, 2016.

Mugelé, R.: The great green wall in Sahel: From global to local ambitions, Bull. d'Association Geogr. Fr., 95, 187–202, https://doi.org/10.4000/bagf.3084, 2018.

Mugglestone, M. A. and Renshaw, E.: Detection of geological lineations on aerial photographs using two-dimensional spectral analysis, Comput. Geosci., 24, 771–784, https://doi.org/10.1016/S0098-3004(98)00065-X, 1998.

Omokpariola, D. O., Agbanu-Kumordzi, C., Samuel, T., Kiswii, L., Moses, G. S., and Adelegan, A. M.: Climate change, crop yield, and food security in Sub-Saharan Africa, Discov. Sustain, https://doi.org/10.1007/s43621-025-01580-4, 2025.

ORSTOM: République du Niger : précipitations journalières de l'origine des stations à 1965. Ouagadougou (BKF) : CIEH ; Paris (FRA) : ORSTOM, 505 pp,1966.

ORSTOM: Précipitations journalières de 1966 à 1980 : République du Niger. Montpellier (FRA) : ORSTOM, 1990, 366 pp, 1990.

Otsu, N.: A threshold selection method from gray-level histograms, IEEE Trans. Syst. Man Cybern., 9, 62–66, 1979.

Peugeot, C., Wendling, V., Le Roux, E., Panthou, G., Hector, B., Rouché, N., Crespin-Boucaud, A., Favreau, G., Dobi, B., Cohard, J.-M., Demarty, J., Descroix, L., Etchanchu, J., Grippa, M., Hiernaux, P., Warzagan, A. I., Kergoat, L., Abdou, M. M., Mougin, E., Pierre, C., Rajot, J.-L., Vandervaere, J.-P., Vischel, T., and Lebel, T.: Evidence of hydrological regime shifts associated with a major decades-long drought in West Africa, nature.com, https://doi.org/10.1038/s41467-026-72648-6, 2026.

Rau, G. C., Bastías Espejo, J., Acworth, I., Andersen, M. S., Irvine, D. J., Bernardi, T., and Cuthbert, M. O.: Temporally clustered streamflow events control focused groundwater recharge in drylands, Environ. Res. Lett., 21, 34014, https://doi.org/10.1088/1748-9326/ae3e01, 2026.

Reenberg, A., Maman, I., and Oksen, P.: Twenty years of land use and livelihood changes in SE-Niger: Obsolete and short-sighted adaptation to climatic and demographic pressures?, J. Arid Environ., 94, 47–58, https://doi.org/10.1016/j.jaridenv.2013.03.002, 2013.

Reij, C., Tappan, G., and Belemvire, A.: Changing land management practices and vegetation on the Central Plateau of Burkina Faso (1968-2002), in: Journal of Arid Environments, 642–659, https://doi.org/10.1016/j.jaridenv.2005.03.010, 2005.

Rohde, M. M., Albano, C. M., Huggins, X., Klausmeyer, K. R., Morton, C., Sharman, A., Zaveri, E., Saito, L., Freed, Z., Howard, J. K., Job, N., Richter, H., Toderich, K., Rodella, A. S., Gleeson, T., Huntington, J., Chandanpurkar, H. A., Purdy, A. J., Famiglietti, J. S., Singer, M. B., Roberts, D. A., Caylor, K., and Stella, J. C.: Groundwater-dependent ecosystem map exposes global dryland protection needs, Nature, 632, 101–107, https://doi.org/10.1038/s41586-024-07702-8, 2024.

Ruijsch, J., Teuling, A. J., Taylor, C. M., Steeneveld, G. J., and Hutjes, R. W. A.: Clustered Land Restoration Projects Increase Cloud Formation in West African Drylands, J. Geophys. Res. Atmos., 131, https://doi.org/10.1029/2025JD044393, 2026.

Saccò, M., Mammola, S., Altermatt, F., Alther, R., Bolpagni, R., Brancelj, A., Brankovits, D., Fišer, C., Gerovasileiou, V., Griebler, C., Guareschi, S., Hose, G. C., Korbel, K., Lictevout, E., Malard, F., Martínez, A., Niemiller, M. L., Robertson, A., Tanalgo, K. C., Bichuette, M. E., Borko, Š., Brad, T., Campbell, M. A., Cardoso, P., Celico, F., Cooper, S. J. B., Culver, D., Di Lorenzo, T., Galassi, D. M. P., Guzik, M. T., Hartland, A., Humphreys, W. F., Ferreira, R. L., Lunghi, E., Nizzoli, D., Perina, G., Raghavan, R., Richards, Z., Reboleira, A. S. P. S., Rohde, M. M., Fernández, D. S., Schmidt, S. I., van der Heyde, M., Weaver, L., White, N. E., Zagmajster, M., Hogg, I., Ruhi, A., Gagnon, M. M., Allentoft, M. E., and Reinecke, R.: Groundwater is a hidden global keystone ecosystem, Glob. Chang. Biol, https://doi.org/10.1111/gcb.17066, 1 January 2024.

Sauvel, C.: Hydrogéologie de la haute Maggia. Rapport de fin de campagne 1964-1965. BRGM 66 NIA, 96p, Annexes 2, ND31-24., 96 pp, 1966.

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

Shreve, R. L.: Statistical Law of Stream Numbers, J. Geol., 74, 17–37, https://doi.org/10.1086/627137, 1966.

Smith, D. M., Jarvis, P. G., and Odongo, J. C. W.: Sources of water used by trees and millet in Sahelian windbreak systems, J. Hydrol., 198, 140–153, https://doi.org/10.1016/S0022-1694(96)03311-2, 1997.

Smith, D. M., Jarvis, P. G., and Odongo, J. C. W.: Management of windbreaks in the Sahel: The strategic implications of tree water use, Agrofor. Syst., 40, 83–96, https://doi.org/10.1023/A:1005962813999, 1998.

SOGETHA: Aménagement de l'Ader Doutchi-Maggia : Études pédologiques de détail. Bassins versants expérimentaux. Rapport d'étude, 3e partie, 114pp, 1964.

SOGREAH: Projet de réhabilitation des aménagements hydro-agricoles au Niger. Étude de la nappe alluviale de l'Ader-Doutchi. Rapport d'étude, Grenoble, France. 32.0786.R4., OECD Publishing, https://doi.org/10.1787/601276CD-EN, 1982.

Spinoni, J., Naumann, G., Carrao, H., Barbosa, P., and Vogt, J.: World drought frequency, duration, and severity for 1951-2010, Int. J. Climatol., 34, 2792–2804, https://doi.org/10.1002/joc.3875, 2014.

Surazakov, A. and Aizen, V.: Positional accuracy evaluation of declassified hexagon KH-9 mapping camera imagery, Photogramm. Eng. Remote Sensing, 76, 603–608, https://doi.org/10.14358/PERS.76.5.603, 2010.

Tarchiani, V., Di Vecchia, A., Genesio, L., and Sorani, F.: Monitoring Drylands Ecosystem Dynamics for Sustainable Development Policies: The Keita Experience, in: The Future of Drylands, Springer Netherlands, 395–407, https://doi.org/10.1007/978-1-4020-6970-3_38, 2008.

Trichon, V., Hiernaux, P., Walcker, R., and Mougin, E.: The persistent decline of patterned woody vegetation: The tiger bush in the context of the regional Sahel greening trend, Glob. Chang. Biol., 24, 2633–2648, https://doi.org/10.1111/gcb.14059, 2018.

Turner, M. D., Davis, D. K., Yeh, E. T., Hiernaux, P., Loizeaux, E. R., Fornof, E. M., Rice, A. M., and Suiter, A. K.: Great Green Walls: Hype, Myth, and Science, Annu. Rev. Environ. Resour, https://doi.org/10.1146/annurev-environ-112321-111102, 13 November 2023.

UNCCD: The Great Green Wall Implementation Status and Way Ahead to 2030, 2020–2021, 2020.

UNPP: World Population Prospects 2024: Summary of Results (UN DESA/POP/2024/TR/NO. 9). New York: United Nations, 2024.

Valentin, C., Poesen, J., and Li, Y.: Gully erosion: Impacts, factors and control, in: Catena,

https://doi.org/10.5194/egusphere-2026-4118
Preprint. Discussion started: 14 July 2026

132–153, https://doi.org/10.1016/j.catena.2005.06.001, 2005.

Vlaar, J. C. J.: Les techniques de conservation des eaux et des sols dans les pays du Sahel. Rapport d'une étude effectuée dans le cadre de la collaboration entre le Comité Interafricain d'Études Hydrauliques (C1EH), Ouagadougou, Burkina Faso, et l'Université Agronomique Wageningen : Université agronomique, 113 p, 1992.

Wolka, K., Mulder, J., and Biazin, B.: Effects of soil and water conservation techniques on crop yield, runoff and soil loss in Sub-Saharan Africa: A review, Water Manag, https://doi.org/10.1016/j.agwat.2018.05.016, 2018.

Wourro, F., Akodewou, A., Kassi N'dja, J., and Hérault, B.: Re-greening the Sahel? Evaluating tree cover restoration strategies in Niger, J. Arid Environ., 232, https://doi.org/10.1016/j.jaridenv.2025.105484, 2026.

Yan, H., Guo, K., and Guan, M.: Enhanced Urban Flood Hazard Assessment by Stochastic Event Catalog, Water Resour. Res., 61, https://doi.org/10.1029/2025WR040459, 2025.

Zheng, X., Zhu, J. J., Yan, Q. L., and Song, L. N.: Effects of land use changes on the groundwater table and the decline of Pinus sylvestris var. mongolica plantations in southern Horqin Sandy Land, Northeast China, Agric. Water Manag., 109, 94–106, https://doi.org/10.1016/j.agwat.2012.02.010, 2012.

Zhi, Y., Li, X., Shen, T., Metternicht, G., Grainger, A., Pan, Y., Lu, Q., and Kabo-Bah, A. T.: Land productivity declines in the GGW while human contributions to restoration far outweighing degradation, Sci. Rep., 15, https://doi.org/10.1038/s41598-025-18963-2, 2025.

Zouré, C., Queloz, P., Koïta, M., Niang, D., Fowé, T., Yonaba, R., Consuegra, D., Yacouba, H., and Karambiri, H.: Modelling the water balance on farming practices at plot scale: Case study of Tougou watershed in Northern Burkina Faso, Catena, 173, 59–70, https://doi.org/10.1016/j.catena.2018.10.002, 2019.