Contrasted land-surface processes along the West African rainfall gradient - Monsoon Multidisciplinary Analysis (AMMA) : an integrated project for understanding of the West African climate system and its human dimension

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Contrasted• land-surface processes along the West African rainfall gradient

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Abstract

We review the main results of land-surface studies obtained in the three sites of the long-term observing system AMMA-CATCH. Runoff in the Sahel enhances the variability of energy partitioning between non-infiltrative areas where sensible heat is dominant and infiltrative areas where soil water availability increases the latent flux. In terms of water resources, an increase in runoff over the past 50 years, already reported for the exoreic Sahel, was revealed in the endoreic Sahel. In the Sudanian domain, the subsurface origin of streamflow could explain its decrease over the same period. Copyright © 2010 Royal Meteorological Society

Keywords: **energy fluxes; runoff; groundwater; Sahel; Sudanian climate; water resources**

1. Introduction

As West Africa is located in the inter-tropical belt, it has a monsoon climate (Lafore *et al*., 2011) and is subject to marked seasonal variability. Drought, with relative deficits in precipitation of 25–50%, was widespread in the Sahel (mean annual rainfall 100–700 mm) during the 1970s and 1980s. Wetter biogeographic zones such as the Sudanian (700–1400 mm) and Guinean belts (>1400 mm) were also affected. Since the 1990s, a return to relatively wetter conditions has been observed in much of West Africa (Lebel and Ali, 2009).

The most populated regions of West Africa lie along the coast and in the cultivated Sahel (400–700 mm rainfall belt). A great part of the Sudanian region is characterised by relatively low population density, which explains the wide extent of forest even today. However, over the past 60 years, forest clearing and the establishment of croplands have considerably expanded in sub-Saharan Africa to meet the demand for food and firewood of the growing population (FAO, 2004). And the duration of fallow in the traditional sustainable crop-long fallow cycle has been drastically shortened since 1970 (Valentin *et al*., 2004).

West Africa presents considerable regional evidence of the impacts of changes, particularly concerning water resources: despite a decrease in rainfall during the 1968–1995 period, streamflow has been increasing in most exoreic Sahelian basins (Mahé and Paturel, 2009) over the last three decades. Conversely, in Sudanian regions, reduced rainfall has led to an even greater relative reduction in discharges (Descroix *et al*., 2009). As a result, the main West African rivers, such as the Niger and the Senegal, have undergone a significant decrease in flow because their discharges are mainly supplied by Sudanian and Guinean tributaries. Groundwater resources have also been affected: for instance since the early 1960s, the level of the aquifer has been continuously rising in endorheic areas of Sahelian West Niger (Favreau *et al*., 2009). As joint studies of water and energy fluxes are rare in West Africa, documenting the land-surface processes that drive the water and energy budgets was one of the goals of the AMMA project, which was designed to investigate the interactions between atmospheric, oceanic and terrestrial systems and their joint control of tropical monsoon dynamics in West Africa. This article highlights the most original results obtained thanks to the large data set collected by the AMMA-Catch observing system.

2. Data and methods

The AMMA-CATCH long-term observing system (www.amma-catch.org; Lebel *et al.*, 2009) is based on three meso-scale sites (Figure 1) that represent the West African eco-climatic gradient. Owing to the low annual rainfall (100–450 mm), the northern Sahelian Gourma-Mali site (Mougin *et al.*, 2009) is mainly rangeland with semi-arid vegetation. It is divided into a sandy part with dunes and a crystalline part with large outcrops. The south-west Niger site (Cappelaere *et al.*, 2009), with ∼500 mm rainfall, is typical of the cultivated sandy Sahel with fallows and millet crops. The vegetation at the Upper Ouémé catchment site in crystalline Benin (1200–1300 mm) is composed of open forests interspersed with mosaics of crops and fallows. Observation of the continental water cycle is based on a multi-scale (spatial and temporal) approach, combining local sites and meso-scale basins, and long-term and enhanced observation periods. A particular effort was made to document water and energy fluxes on an extensive set of surface types.

The meso-scale instrumentation (raingauges, stream-gauges and well networks) is used to study the coupling of surface hydrology with regional atmospheric processes (Peugeot *et al.*, ~~2010~~). Within each meso-scale site, local sites are used for the study of fine surface processes. These include soil water monitoring stations, piezometers, eddy-correlation flux stations, and vegetation monitoring. An intermediate observation scale between local and mesoscale is that of small catchments used to upscale and validate the elementary processes in hydrological and land-surface models.

3. Energy partitioning: soil water availability is a particularly limiting factor for latent heat flux in the Sahel

In the Sahelian region, net radiation (Rn) increases sharply during the short rainy season. This strong mono-modal seasonality results from the summer-time concomitance of high incoming radiation caused by aerosol scavenging, with low outgoing radiation related to a decrease in both the albedo (vegetation growth) and the surface temperature (Ramier *et al.*, 2009; Timouk *et al.*, 2009). However, marked site-to-site variability of the seasonal cycle has been observed, in particular in Gourma, between bare soil and flooded-forest sites (Figure 2). It has been reported that both seasonal and spatial variability in energy partitioning is mostly influenced by soil water availability through evapotranspiration (ET) processes and vegetation growth. This pattern fails in the case of weak soil permeability or low annual rainfall (in north Sahel and at bare soil sites in Gourma) which is a direct consequence of soil degradation. During the rainy season, the latent heat flux replaces sensible, ground heat, and outgoing radiation fluxes, the first of which dominates during the rest of the year. Via ET, rainfall spatial heterogeneity and scarcity increase the variability of the energy budget from the event to the interannual scale.

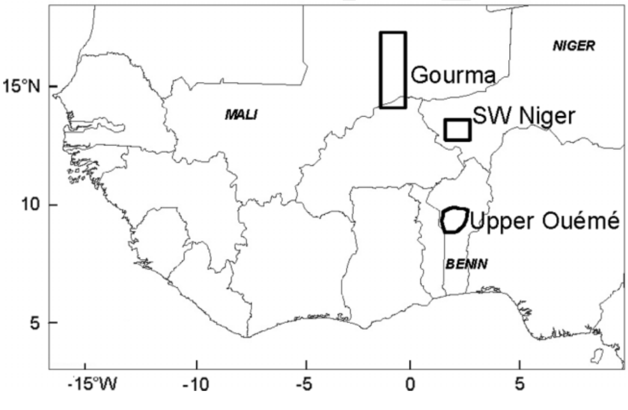

Figure 1. Location of the three meso-scale sites of the AMMA-CATCH observing system.

Under the Sudanian bioclimate, the longer rainy season leads to smoother annual variations in Rn (Guyot, 2010). A local minimum occurs at the middle of the rainy season related to cloud cover and a limited decrease in potential incident radiation due to the position closed to the equator. In the dry season, net radiation is constrained not only by atmospheric optical depth (aerosols) but also by the warmer bare land surfaces, which produce higher outgoing long-wave radiation. During a 5-month period in the rainy season, actual ET was found to be close to ~~ET0~~, confirming that water availably is not a limiting factor for the latent heat flux during the rainy season.

Both at the Sahelian and Sudanian sites, ET dominates the water balance. In cultivated Niger, Ramier *et al.* (2009) showed that millet evaporated less than fallow during two crop cycles. Over the year, ET on sandy soils with natural vegetation (fallow in Niger or grassland in Gourma) accounted for 65–85% of the rainfall whereas in the millet field, it only accounted for about half the rainfall. In the context of general land clearing in the cultivable area of the Sahel, this significant difference could have a major impact on the coupled land-atmosphere water cycle. In the Sudanian region, on a mixed cover of shrub savannah and fallow-crop at a small catchment scale, ET ~~at a small catchment scale~~ (deduced from a scintillometer (Guyot *et al.*, 2009)) represented 83% of the annual rainfall.

4. Pre-eminence of surface runoff in the Sahel *versus* subsurface exfiltration in Sudanian regions and links with heat fluxes and energy balance

Major differences in flow generation were revealed at our Sahelian and Sudanian sites. Endoreic Sahelian sites are composed of patches with contrasted infiltration capacity. In low infiltrative areas, surface flow is

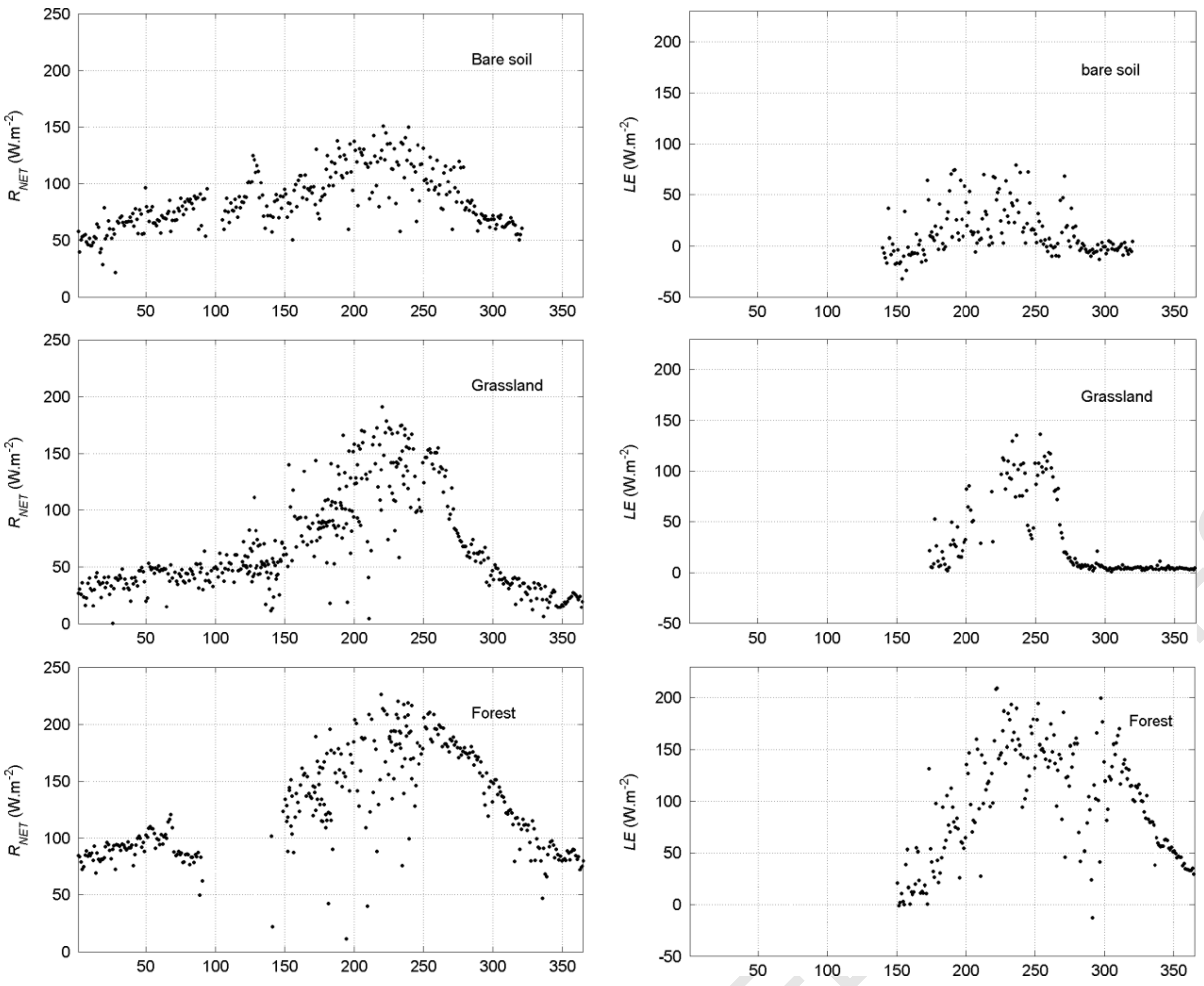

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Figure 2. Course of 24-h average net radiation and latent heat flux for three surfaces of the Gourma site (bare soil with runoff and no vegetation, grassland with vegetation and a moderate soil water availability and a forested seasonally flooded depression) (•~~from~~ Timouk *et al*., 2009).

produced by Hortonian runoff determined by rainfall intensity and by the infiltration capacity of the surface soil. Water is routed to either highly-infiltrative depressions (temporally flooded ponds like in Niger or in sandy Gourma) or poorly-infiltrative depressions flooded for longer periods (like in crystalline Gourma) (Cappelaere *et al*., 2009; Mougin *et al*., 2009). In sandy areas in Gourma, water routing is local from dune hillslopes to inter-dune depressions. In crystalline Gourma, water produced on shallow soils is routed over longer but also ends up in depressions. At the cultivated and wetter Niger site, runoff from the patchwork of surfaces is channelled down the slope in sandy gullies and ends up in ponds where water accumulates before recharging the sedimentary aquifer (Cappelaere *et al*., 2009).

In the Sahel region, surface water redistribution by runoff exerts strong control over the seasonal cycle of heat fluxes and radiation balance. On outcrops or extensively crusted soils, water is lost by runoff and most Rn is converted into sensible heat flux. Conversely, infiltrating surfaces and depressions exhibit a significant seasonal cycle in soil moisture and plant growth, resulting in marked variation ~~in~~ Rn, sensible and latent heat fluxes (Timouk *et al*., 2009). When rainfall events are particularly intense and concentrated, infiltration can exceed ET and deep drainage can occur. On a millet cover in Niger, Ramier *et al.* (2009) observed variations in humidity at a depth of 2.5 m.

In the sub-humid zones of West Africa, infiltration rates are generally higher than in the Sahel due to the higher organic matter content of the top soils (Valentin *et al*., 2004). At the hillslope scale, previous studies showed that most infiltration excess water infiltrates before reaching an expanse of open water (van de Giesen *et al*., 2000; •Masiyandima *et al*., 2003; Giertz *et al*., 2006). Consequently, Hortonian runoff should contribute little to total streamflow. At the Ouémé site, two saturated ground layers coexist from July to September. The deeper one is the permanent water table located on the saprolite of the crystalline bedrock. It is recharged during this period and is then depleted slowly and regularly from September to the following June. The general drying up of rivers in October–November follows the end of the rains but does not coincide with the lowest level of the water table (June), reflecting the weakness or even absence of

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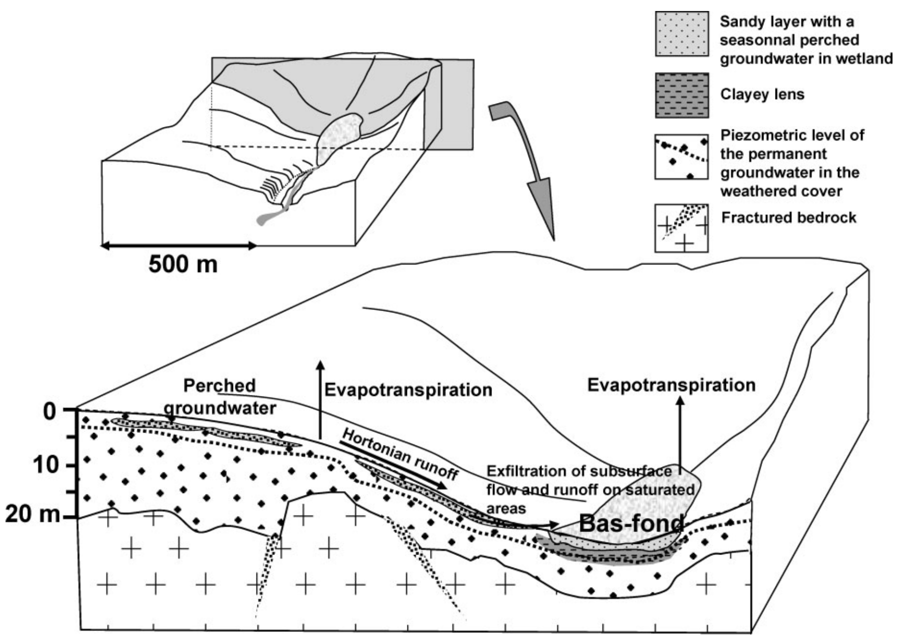

Figure 3. Hydrological functioning of a headwater channel with its wetland (*Bas-fond*) in the Ouémé site. During the rainy season, baseflow, the principal component of annual discharge, is provided by perched groundwater located on hillslopes and in shallow sandy layers of *bas-fonds*. The permanent groundwater in the weathered cover of the fractured bedrock is disconnected from the hydrograph network (~~from~~ Kamagaté *et al*., 2007).

permanent groundwater inputs to the base flow (Kamagaté *et al*., 2007). The second seasonally saturated layer is located close to the surface. It emerges locally in the headwaters (called *bas-fonds*) of the hydrograph networks. Streamflow can be explained by drainage of these seasonal shallow groundwaters and excess runoff on saturated areas around the waterlogged *bas-fonds* (Figure 3). In the upper Ouémé, the drainage of the shallow groundwaters into the *bas-fonds* represents 60–80% of the annual discharge (Kamagaté *et al*., 2007).

The absence of drainage from the permanent groundwater into the hydrographic network from local to mesoscale meant that another process was needed to explain its depletion during the dry season. One suggested hypothesis is tree transpiration (Kamagaté *et al*., 2007). In a detailed analysis of ET after an isolated rainfall event in the dry season, Guyot *et al.* (2009) demonstrated that one month after the rainfall event, observed ET had emptied available water in the instrumented first metre of soil. Consequently, the subsequently observed continuing ET could only be explained by the contribution of water uptake from vadose or saturated layers by vegetation.

5. Surface changes, causes of the historical evolution of Sahelian water resources, new evidence revealed by remote sensing and coupled modelling

At the cultivated Niger site, a continuous rise of the water table has occurred since the 1960s, with an acceleration of the rise starting from the middle of the 1980s (Favreau *et al*., 2009) (Figure 4d). Land clearance in favour of an intensive crop-fallow system is thought to produce more runoff. Unfortunately, no long-term records of runoff exist for this area. At the rangeland Gourma site, a potential change in water resources had not been investigated before the ~~Amma Experiment~~.

At both Sahelian sites, intensive use of historical remote sensing data provided evidence of an increase in runoff since 1950. At the Niger site, Leblanc *et al.* (2008) showed that the density of drainage lines retrieved from aerial photographs revealed a moderate increase between 1950 and 1975, and a doubling from 1975 to 1992 (Figure 4c). In the pastoral Gourma region, •Gardelle *et al.* (2010) combined satellite and aerial remote sensing information and revealed a marked increase in the area of surface water, starting from the 1970s and accelerating in the mid 1980s (Figure 5). This long-term increase in pond surface area is an indication of intensification in runoff triggered by the lasting impact of the 1970–1980s droughts on the vegetation over the shallow soils prevailing over a third of Gourma. Changes in land cover due to human pressure (Niger) or to water stress (Gourma) both resulted in increasing runoff. The same phenomenon of runoff intensification has also been observed outside the two Sahelian meso-scale sites, particularly in large exoreic catchments where long time series are available (upper catchment of Volta, Sahelian tributaries of Niger) (Descroix *et al*., 2009; Karambiri *et al*., 2011).

Modelling is needed for water balance quantification under changing land use and climate conditions. By coupling a physically based spatially distributed hydrological model with an explicit model of vegetation dynamics over a small catchment (~2 km^2)

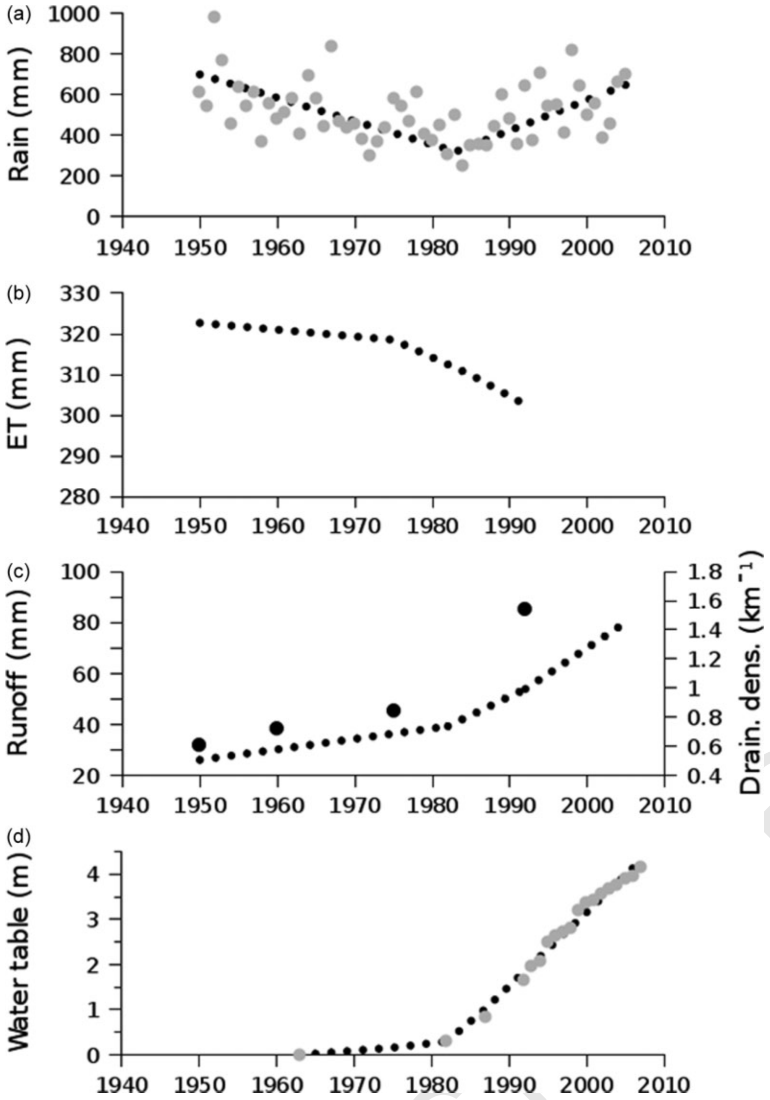

Figure 4. Historical trends in annual water cycle in the Niger site (~~reprinted from~~ Cappelaere *et al.*, 2009); (a) rainfall; (b) rainy-season evapotranspiration (ET); (c) catchment runoff (line) and drainage density (dots), and (d) water table level. Dots correspond to field data: at Niamey airport for rainfall (courtesy DMN Niger); in a 500-km^2 section of Niger site for drainage density (Leblanc *et al.*, 2008); areal mean difference with 1963 for water table (Favreau *et al.*, 2009). Lines for ET and runoff are simulations for a small intensive catchment (Boulain *et al.*, 2009).

at the Niger site, Boulain *et al.* (2009) assessed the impact of three different land use/land cover (LULC) patterns on the hydrologic cycle. The assessment concerned two contrasted rainy season patterns (simulating dry and wet years respectively) with LULC maps for 1950, 1975 and 1992. The LULC chronology illustrated the extension of land clearance. ET during the rainy season appeared to be more sensitive to land-use changes than to rainfall but with variations that remained below 10%. The simulated ET amounted to 60–65% of annual rainfall for the wet year, and to over 85% for the dry year. These figures are consistent with point ET measurements (Ramier *et al.*, 2009). The simulated runoff appeared to be much more sensitive to land-use changes than to climate forcing. Beyond this sensitivity analysis, Boulain *et al.* (2009) reconstructed the historical trend of the water balance by combining rainfall and LULC records. The simulated trend showed a reduction in ET during the rainy season mainly due to changes in land use after 1975 (Figure 4b) and a threefold increase in runoff to the valley pond (Figure 4c). The increase in simulated runoff after 1980 was due to the combined action of a return to relatively wetter conditions (Figure 4a) and the continuation of land clearance. This reconstruction appears to fit well with observations (drainage density increase (Figure 4c) retrieved from remote sensing images (Leblanc *et al.*, 2008) and the historical rise in the water table.

6. Discussion and conclusion

Studies of the changes in landscape by remote sensing undertaken during the experiment provided evidence for an increase in runoff in endorheic regions of the Sahel. The complex interactions between vegetation and hydrology in a changing context were modelled

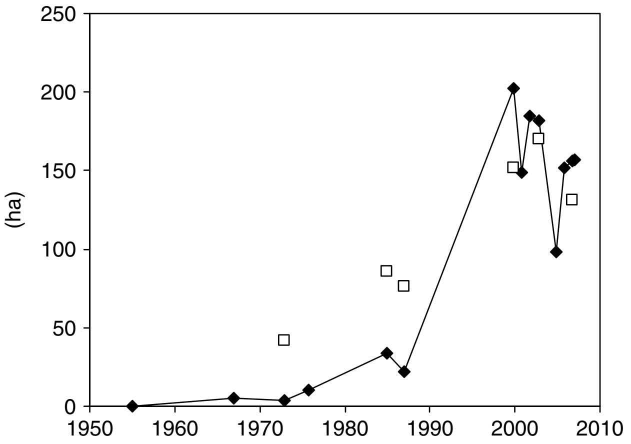

Figure 5. Average surface of water per pond (open square) in the Gourma site for the 51 ponds present in all Landsat images at the peaks of the pond's annual flood and surface of the case study pond (full diamond) where Landsat images were completed by aerial photographs for the oldest dates (data from Gardelle *et al*., 2010). The increase of the pond area in Gourma is an indicator of the increase of runoff.

at the scale of a small catchment paving the way for modelling both the water balance and vegetation at larger scales.

Although both Sahelian and Sudanian regions are facing a decrease in precipitation, their responses in terms of water resources are quite different: the annual flow of Sudanian rivers declined while discharge, surface water stored in ponds and the recharge of the ground water increased in the Sahel. Runoff influenced by surface features governs streamflow in the Sahel, while at the Sudanian site, annual streamflow is mainly composed of subsurface flux exfiltration, and runoff (Hortonian and on saturated areas) is secondary. The contrasted change in the two climatic regions could result from differences in the nature of the dominant streamflow generation process and of the land-surface characteristics combined. Sudanian land covers are less degraded than Sahelian ones. There are many reasons for this including weaker human pressure, better structural stability due to higher organic matter and clay contents of Sudanian soils (Valentin *et al*., 2004). In Sudanian zones, due to the predominance of shallow groundwater exfiltration in the streamflow, the decrease in streamflow is not counterbalanced by an increase in the Hortonian runoff capacity due to high land-surface degradation like in the Sahel. The surface water ~~resource~~ depend~~s~~ on the saturation level of the upper layers which are highly influenced by ET and rainfall intermittency. Mechanisms controlling the change in water resource have been identified and their modelling is in progress in the Sahel. In the Sudanian region, we have not yet reached a thorough understanding of the redistribution of surface water. Mechanisms identified in Ouémé need to be validated in other Sudanian zones before being generalised.

During the rainy season ET is the major component of the surface water budget in both Sahelian and Sudanian regions. Pluri-annual monitoring of energy and water budgets shed new light on the interactions between the land surface and the atmosphere. In the energy balance, the latent heat flux influenced by soil water availability (as forcing radiation is not a limiting factor in the Sahel) supplants the sensible heat flux during the rainy season. ~~First, rainfall~~ amount and distribution govern soil humidity. The interannual variability of rainfall has a direct impact on the radiation distribution between latent and sensible heat fluxes. But our understanding of exchanges between the land surface and the atmosphere cannot be limited to strictly vertical processes. In the cultivated or dryer pastoral Sahel, runoff redistribution controlled by soil surface is also a key factor to explain spatial variability of the energy balance. If runoff and runon surfaces comprise large landscape units as is the case in Gourma, their contrasts in energy partitioning could create horizontal gradients of surface heat flux which persist throughout the rainy season and have an impact on meso-scale atmospheric circulations.

Clearance will go on. Thanks to the AMMA ~~Experiment~~, advances in our understanding of land-surface processes will enable us to suggest possible changes in the future. In the cultivated Sahel, the weaker evaporation of crops or degraded surfaces could lead to less water returning to the atmosphere which could have a general impact on the monsoon (Taylor *et al*., 2011). In the Sudanian region, the process involved in streamflow generation reduces the role of soil surface features. Surface water resources influenced by the storage of the shallow groundwater with low capacity depend directly on the distribution and frequency of major rainfall events. With the increase in deforestation, the tree water uptake could be reduced and if, as assumed, the annual depletion of the permanent groundwater is controlled by tree uptake, the water table could thus end up rising as it did in the Sahel. However, all these scenarios are still largely hypothetical and call for the continuation of surface water cycle observations at dedicated sites.

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