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**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

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## 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

1 data set collected by the AMMA-Catch observing  
2 system.

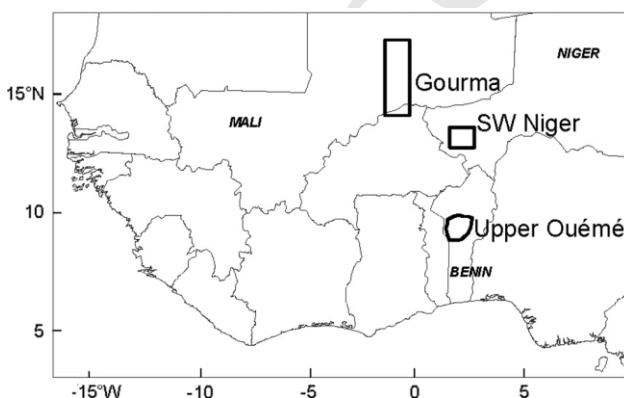
## 3 2. Data and methods

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

26 The meso-scale instrumentation (raingauges, stream-  
27 gauges and well networks) is used to study the cou-  
28 pling of surface hydrology with regional atmospheric  
29 processes (Peugeot *et al.*, 2010). Within each meso-  
30 scale site, local sites are used for the study of fine  
31 surface processes. These include soil water monitoring  
32 stations, piezometers, eddy-correlation flux stations,  
33 and vegetation monitoring. An intermediate observa-  
34 tion scale between local and mesoscale is that of small  
35 catchments used to upscale and validate the elementary  
36 processes in hydrological and land-surface models.

## 39 3. Energy partitioning: soil water 40 availability is a particularly limiting factor 41 for latent heat flux in the Sahel

42 In the Sahelian region, net radiation ( $R_n$ ) increases  
43 sharply during the short rainy season. This strong



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

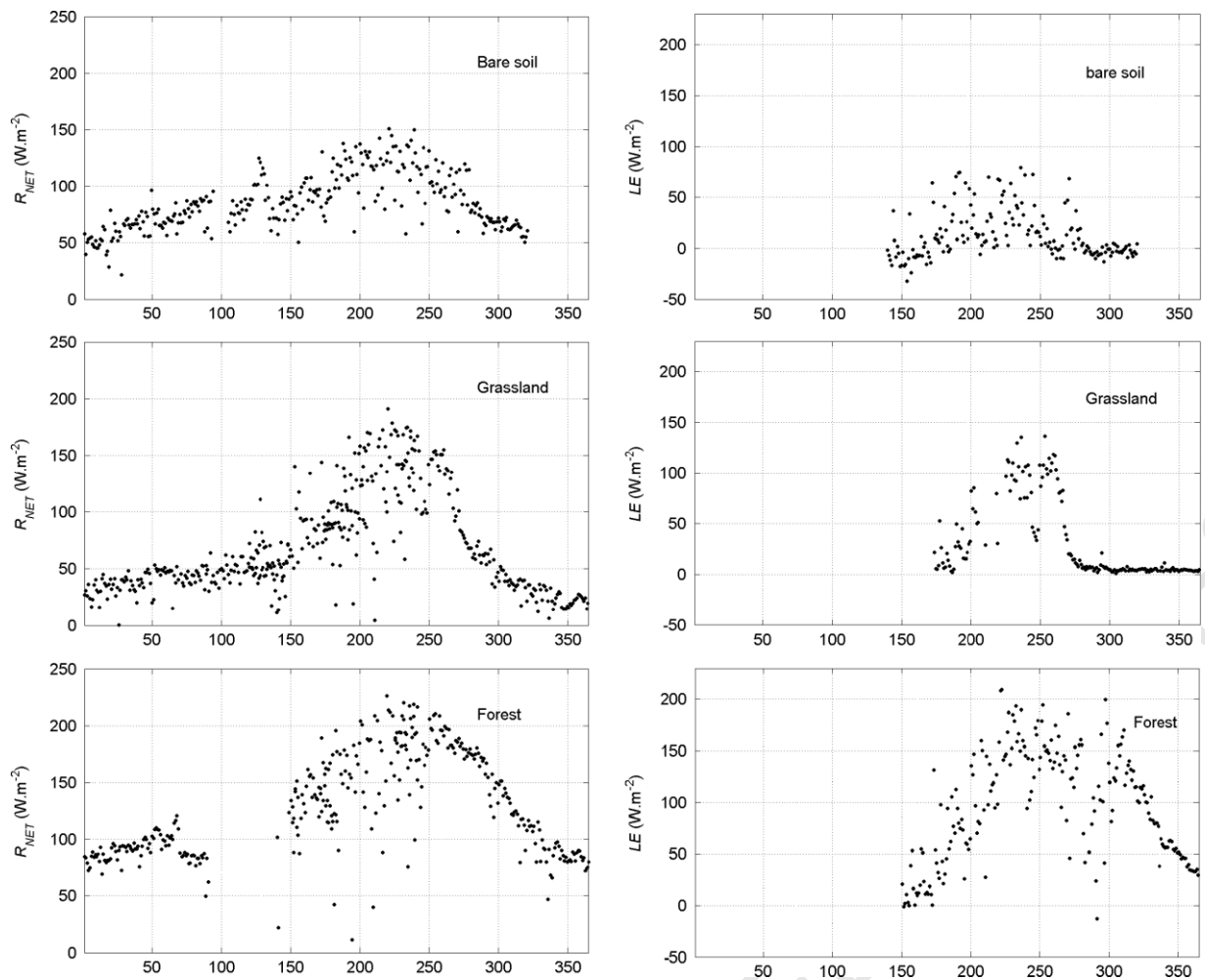
61 mono-modal seasonality results from the summer-  
62 time concomitance of high incoming radiation caused  
63 by aerosol scavenging, with low outgoing radiation  
64 related to a decrease in both the albedo (vegetation  
65 growth) and the surface temperature (Ramier *et al.*,  
66 2009; Timouk *et al.*, 2009). However, marked site-to-  
67 site variability of the seasonal cycle has been observed,  
68 in particular in Gourma, between bare soil and flooded-  
69 forest sites (Figure 2). It has been reported that both  
70 seasonal and spatial variability in energy partition-  
71 ing is mostly influenced by soil water availability  
72 through evapotranspiration (ET) processes and veg-  
73 etation growth. This pattern fails in the case of weak  
74 soil permeability or low annual rainfall (in north Sahel  
75 and at bare soil sites in Gourma) which is a direct con-  
76 sequence of soil degradation. During the rainy season,  
77 the latent heat flux replaces sensible, ground heat, and  
78 outgoing radiation fluxes, the first of which dominates  
79 during the rest of the year. Via ET, rainfall spatial het-  
80 erogeneity and scarcity increase the variability of the  
81 energy budget from the event to the interannual scale.

82 Under the Sudanian bioclimate, the longer rainy sea-  
83 son leads to smoother annual variations in  $R_n$  (Guyot,  
84 2010). A local minimum occurs at the middle of the  
85 rainy season related to cloud cover and a limited  
86 decrease in potential incident radiation due to the  
87 position closed to the equator. In the dry season,  
88 net radiation is constrained not only by atmospheric  
89 optical depth (aerosols) but also by the warmer bare  
90 land surfaces, which produce higher outgoing long-  
91 wave radiation. During a 5-month period in the rainy  
92 season, actual ET was found to be close to  $ET_0$ , con-  
93 firming that water availability is not a limiting factor for  
94 the latent heat flux during the rainy season.

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

## 112 4. Pre-eminence of surface runoff in the 113 Sahel versus subsurface exfiltration in 114 Sudanian regions and links with heat fluxes 115 and energy balance

116 Major differences in flow generation were revealed at  
117 our Sahelian and Sudanian sites. Endoreic Sahelian  
118 sites are composed of patches with contrasted infiltra-  
119 tion capacity. In low infiltrative areas, surface flow is 120



**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).

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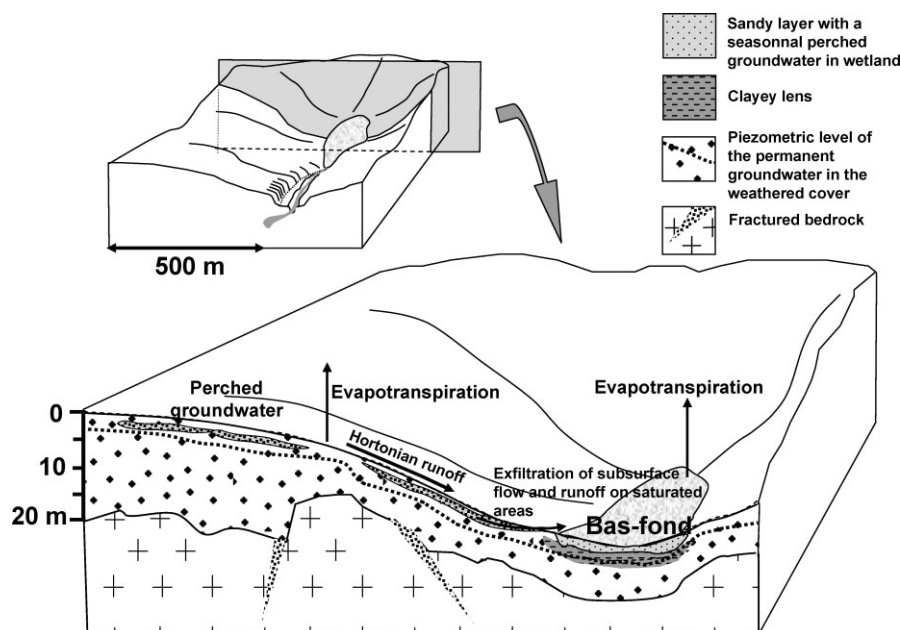
1 produced by Hortonian runoff determined by rainfall  
 2 intensity and by the infiltration capacity of the sur-  
 3 face soil. Water is routed to either highly-infiltrative  
 4 depressions (temporally flooded ponds like in Niger  
 5 or in sandy Gourma) or poorly-infiltrative depres-  
 6 sions flooded for longer periods (like in crystalline  
 7 Gourma) (Cappelaere *et al.*, 2009; Mougin *et al.*, 2009). In  
 8 sandy areas in Gourma, water routing is local from  
 9 dune hillslopes to inter-dune depressions. In crystalline  
 10 Gourma, water produced on shallow soils is routed  
 11 over longer but also ends up in depressions. At the  
 12 cultivated and wetter Niger site, runoff from the patch-  
 13 work of surfaces is channelled down the slope in sandy  
 14 gullies and ends up in ponds where water accumulates  
 15 before recharging the sedimentary aquifer (Cappelaere  
 16 *et al.*, 2009).

17 In the Sahel region, surface water redistribution by  
 18 runoff exerts strong control over the seasonal cycle  
 19 of heat fluxes and radiation balance. On outcrops or  
 20 extensively crusted soils, water is lost by runoff and  
 21 most  $R_n$  is converted into sensible heat flux. Con-  
 22 versely, infiltrating surfaces and depressions exhibit a  
 23 significant seasonal cycle in soil moisture and plant  
 24 growth, resulting in marked variation in  $R_n$ , sensible

and latent heat fluxes (Timouk *et al.*, 2009). When  
 rainfall events are particularly intense and concen-  
 trated, 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 follow-  
 ing June. The general drying up of rivers in Octo-  
 ber–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).

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

11 The absence of drainage from the permanent  
 12 groundwater into the hydrographic network from local  
 13 to mesoscale meant that another process was needed  
 14 to explain its depletion during the dry season. One  
 15 suggested hypothesis is tree transpiration (Kamagaté  
 16 *et al.*, 2007). In a detailed analysis of ET after an  
 17 isolated rainfall event in the dry season, Guyot *et al.*  
 18 (2009) demonstrated that one month after the rain-  
 19 fall event, observed ET had emptied available water  
 20 in the instrumented first metre of soil. Consequently,  
 21 the subsequently observed continuing ET could only  
 22 be explained by the contribution of water uptake from  
 23 vadose or saturated layers by vegetation.  
 24  
 25  
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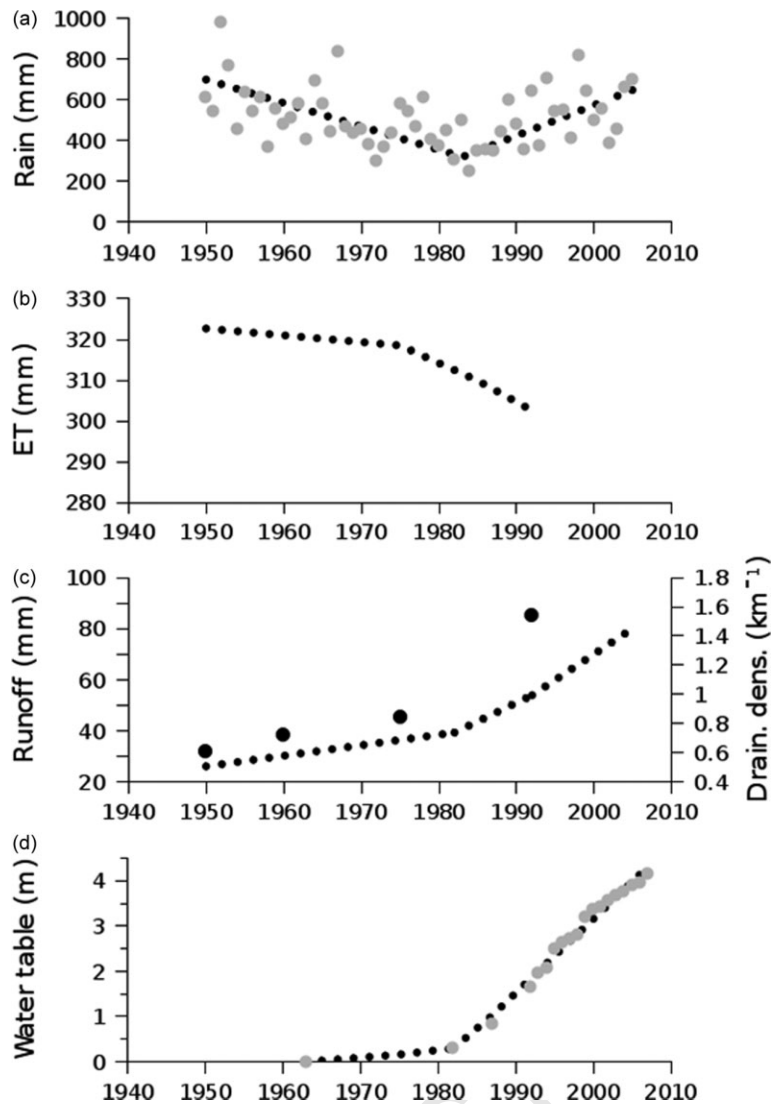
## 28 5. Surface changes, causes of the historical 29 evolution of Sahelian water resources, new 30 evidence revealed by remote sensing and 31 coupled modelling

32 At the cultivated Niger site, a continuous rise of the  
 33 water table has occurred since the 1960s, with an  
 34 acceleration of the rise starting from the middle of  
 35 the 1980s (Favreau *et al.*, 2009) (Figure 4d). Land

clearance in favour of an intensive crop-fallow system 36  
 is thought to produce more runoff. Unfortunately, no 37  
 long-term records of runoff exist for this area. At the 38  
 rangeland Gourma site, a potential change in water 39  
 resources had not been investigated before the *Amma* 40  
*Experiment*. 41

42 At both Sahelian sites, intensive use of historical  
 43 remote sensing data provided evidence of an increase  
 44 in runoff since 1950. At the Niger site, Leblanc  
 45 *et al.* (2008) showed that the density of drainage lines  
 46 retrieved from aerial photographs revealed a moderate  
 47 increase between 1950 and 1975, and a doubling from  
 48 1975 to 1992 (Figure 4c). In the pastoral Gourma 48  
 region, Gardelle *et al.* (2010) combined satellite 49  
 and aerial remote sensing information and revealed  
 50 a marked increase in the area of surface water,  
 51 starting from the 1970s and accelerating in the mid  
 52 1980s (Figure 5). This long-term increase in pond  
 53 surface area is an indication of intensification in runoff  
 54 triggered by the lasting impact of the 1970–1980s  
 55 droughts on the vegetation over the shallow soils  
 56 prevailing over a third of Gourma. Changes in land  
 57 cover due to human pressure (Niger) or to water stress  
 58 (Gourma) both resulted in increasing runoff. The same  
 59 phenomenon of runoff intensification has also been  
 60 observed outside the two Sahelian meso-scale sites,  
 61 particularly in large exoreic catchments where long  
 62 time series are available (upper catchment of Volta,  
 63 Sahelian tributaries of Niger) (Descroix *et al.*, 2009;  
 64 Karambiri *et al.*, 2011). 65

66 Modelling is needed for water balance quantifica-  
 67 tion under changing land use and climate conditions.  
 68 By coupling a physically based spatially distributed  
 69 hydrological model with an explicit model of veg-  
 70 etation dynamics over a small catchment ( $\sim 2 \text{ km}^2$ )



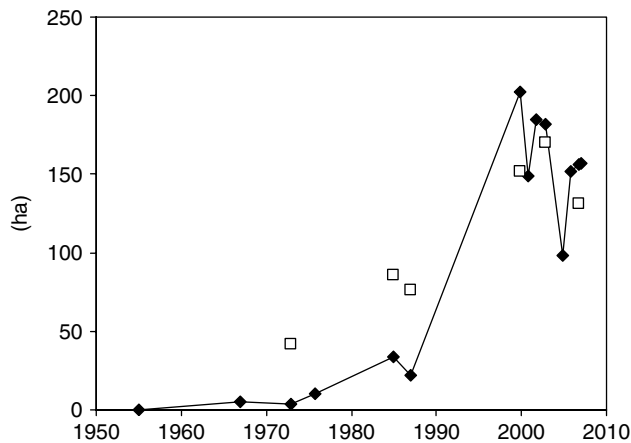
**Figure 4.** Historical trends in annual water cycle in the Niger site (reprinted from Cappelaere *et al.*, 2009): (a) rainfall; (b) rainy-season evapotranspiration (ET); (c) catchment runoff (line) and drainage density (dots), and (d) water table level. Dots correspond to field data: at Niamey airport for rainfall (courtesy DMN Niger); in a 500-km<sup>2</sup> 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).

1 at the Niger site, Boulain *et al.* (2009) assessed the  
 2 impact of three different land use/land cover (LULC)  
 3 patterns on the hydrologic cycle. The assessment con-  
 4 cerned two contrasted rainy season patterns (simulat-  
 5 ing dry and wet years respectively) with LULC maps  
 6 for 1950, 1975 and 1992. The LULC chronology illus-  
 7 trated the extension of land clearance. ET during the  
 8 rainy season appeared to be more sensitive to land-  
 9 use changes than to rainfall but with variations that  
 10 remained below 10%. The simulated ET amounted to  
 11 60–65% of annual rainfall for the wet year, and to  
 12 over 85% for the dry year. These figures are consis-  
 13 tent with point ET measurements (Ramier *et al.*,  
 14 2009). The simulated runoff appeared to be much more  
 15 sensitive to land-use changes than to climate forcing.  
 16 Beyond this sensitivity analysis, Boulain *et al.* (2009)  
 17 reconstructed the historical trend of the water bal-  
 18 ance by combining rainfall and LULC records. The  
 19 simulated trend showed a reduction in ET during the

rainy season mainly due to changes in land use after 20  
 1975 (Figure 4b) and a threefold increase in runoff to 21  
 the valley pond (Figure 4c). The increase in simulated 22  
 runoff after 1980 was due to the combined action of a 23  
 return to relatively wetter conditions (Figure 4a) and 24  
 the continuation of land clearance. This reconstruction 25  
 appears to fit well with observations (drainage density 26  
 increase (Figure 4c) retrieved from remote sensing 27  
 images (Leblanc *et al.*, 2008) and the historical rise in 28  
 the water table. 29

## 6. Discussion and conclusion

30  
 31  
 32  
 33  
 34 Studies of the changes in landscape by remote sensing  
 35 undertaken during the experiment provided evidence  
 36 for an increase in runoff in endorheic regions of the  
 37 Sahel. The complex interactions between vegetation  
 38 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.

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 runoff 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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1 at the scale of a small catchment paving the way for  
2 modelling both the water balance and vegetation at  
3 larger scales.

4 Although both Sahelian and Sudanian regions are  
5 facing a decrease in precipitation, their responses in  
6 terms of water resources are quite different: the annual  
7 flow of Sudanian rivers declined while discharge,  
8 surface water stored in ponds and the recharge of the  
9 ground water increased in the Sahel. Runoff influenced  
10 by surface features governs streamflow in the Sahel,  
11 while at the Sudanian site, annual streamflow is mainly  
12 composed of subsurface flux exfiltration, and runoff  
13 (Hortonian and on saturated areas) is secondary. The  
14 contrasted change in the two climatic regions could  
15 result from differences in the nature of the dominant  
16 streamflow generation process and of the land-surface  
17 characteristics combined. Sudanian land covers are  
18 less degraded than Sahelian ones. There are many  
19 reasons for this including weaker human pressure,  
20 better structural stability due to higher organic matter  
21 and clay contents of Sudanian soils (Valentin *et al.*,  
22 2004). In Sudanian zones, due to the predominance  
23 of shallow groundwater exfiltration in the streamflow,  
24 the decrease in streamflow is not counterbalanced by  
25 an increase in the Hortonian runoff capacity due to  
26 high land-surface degradation like in the Sahel. The  
27 surface water resource depends on the saturation level  
28 of the upper layers which are highly influenced by  
29 ET and rainfall intermittency. Mechanisms controlling  
30 the change in water resource have been identified and  
31 their modelling is in progress in the Sahel. In the  
32 Sudanian region, we have not yet reached a thorough  
33 understanding of the redistribution of surface water.  
34 Mechanisms identified in Ouémé need to be validated  
35 in other Sudanian zones before being generalised.

36 During the rainy season ET is the major component  
37 of the surface water budget in both Sahelian and  
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