



**HAL**  
open science

**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**

L. Seguis, N. Boulain, B. Cappelaere, J.M. Cohard, Guillaume Favreau, Sylvie Galle, A. Guyot, Pierre Hiernaux, Éric Mougin, C. Peugeot, et al.

► **To cite this version:**

L. Seguis, N. Boulain, B. Cappelaere, J.M. Cohard, Guillaume Favreau, et al.. 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. Atmospheric Science Letters, 2011, 12 (1), pp.31-37. 10.1002/asl.327. ird-02153235v1

**HAL Id: ird-02153235**

**<https://ird.hal.science/ird-02153235v1>**

Submitted on 12 Jun 2019 (v1), last revised 24 Jul 2021 (v2)

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



JOHN WILEY & SONS, LTD., THE ATRIUM, SOUTHERN GATE, CHICHESTER P019 8SQ, UK

**\*\*\*PROOF OF YOUR ARTICLE ATTACHED, PLEASE READ CAREFULLY\*\*\***

After receipt of your corrections your article will be published initially within the online version of the journal.

**PLEASE AIM TO RETURN YOUR CORRECTIONS WITHIN 48 HOURS OF RECEIPT OF YOUR PROOF, THIS WILL ENSURE THAT THERE ARE NO UNNECESSARY DELAYS IN THE PUBLICATION OF YOUR ARTICLE**

**READ PROOFS CAREFULLY**

**ONCE PUBLISHED ONLINE OR IN PRINT IT IS NOT POSSIBLE TO MAKE ANY FURTHER CORRECTIONS TO YOUR ARTICLE**

- This will be your only chance to correct your proof
- Please note that the volume and page numbers shown on the proofs are for position only

**ANSWER ALL QUERIES ON PROOFS** (Queries are attached as the last page of your proof.)

- List all corrections and send back via e-mail to the production contact as detailed in the covering e-mail, or mark all corrections directly on the proofs and send the scanned copy via e-mail. Please do not send corrections by fax or post

**CHECK FIGURES AND TABLES CAREFULLY**

- Check size, numbering, and orientation of figures
- All images in the PDF are downsampled (reduced to lower resolution and file size) to facilitate Internet delivery. These images will appear at higher resolution and sharpness in the printed article
- Review figure legends to ensure that they are complete
- Check all tables. Review layout, title, and footnotes

**COMPLETE COPYRIGHT TRANSFER AGREEMENT (CTA) if you have not already signed one**

- Please send a scanned signed copy with your proofs by e-mail. **Your article cannot be published unless we have received the signed CTA**

**OFFPRINTS**

- Free access to the final PDF offprint or your article will be available via Author Services only. Please therefore sign up for Author Services if you would like to access your article PDF offprint and enjoy the many other benefits the service offers.

**Additional reprint and journal issue purchases**

- Should you wish to purchase additional copies of your article, please click on the link and follow the instructions provided: <http://offprint.cosprinters.com/cos/bw/>
- Corresponding authors are invited to inform their co-authors of the reprint options available.
- Please note that regardless of the form in which they are acquired, reprints should not be resold, nor further disseminated in electronic form, nor deployed in part or in whole in any marketing, promotional or educational contexts without authorization from Wiley. Permissions requests should be directed to mailto: [permissionsuk@wiley.com](mailto:permissionsuk@wiley.com)
- For information about 'Pay-Per-View and Article Select' click on the following link: <http://olabout.wiley.com/WileyCDA/Section/id-404512.html>

AQ1

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

L. Séguis,<sup>1\*</sup> N. Boulain,<sup>1,2</sup> B. Cappelaere,<sup>1</sup> J.M. Cohard,<sup>3</sup> G. Favreau,<sup>1</sup> S. Galle,<sup>3</sup> A. Guyot,<sup>3</sup> P. Hiernaux,<sup>4</sup> É. Mougin,<sup>4</sup> C. Peugeot,<sup>1</sup> D. Ramier,<sup>1,5</sup> J. Seghier,<sup>1</sup> F. Timouk,<sup>6</sup> V. Demarez,<sup>6</sup> J. Demarty,<sup>1</sup> L. Descroix,<sup>3</sup> M. Desclotres,<sup>3</sup> M. Grippa,<sup>4</sup> F. Guichard,<sup>7</sup> B. S., Kamagaté,<sup>8</sup> L. Kergoat,<sup>4</sup> T. Lebel,<sup>3</sup> V. Le Dantec,<sup>6</sup> M. Le Lay,<sup>9</sup> S. Massuel,<sup>1,10</sup> and V. Trichon<sup>11</sup>

AQ2

<sup>1</sup>HSM, IRD, France

<sup>2</sup>Climate Change Cluster, UTS, Australia

<sup>3</sup>LTHE, Grenoble, France

<sup>4</sup>LMTG, Toulouse, France

<sup>5</sup>DREIF/Laboratoire Régional de l'Ouest Parisien

<sup>6</sup>CESBIO, Toulouse, France

<sup>7</sup>CNRM-GAME, Toulouse, France

<sup>8</sup>Sciences et Gestion de l'Environnement, Abidjan, Ivory Coast

<sup>9</sup>EDF-DTG, Grenoble, France

<sup>10</sup>CSIRO Land and Water, Australia

<sup>11</sup>ECOLAB, Toulouse, France

AQ3

AQ4

\*Correspondence to:

L. Séguis, HydroSciences  
Montpellier, Université  
Montpellier II, CC-MSE, place  
Eugène Bataillon, 34905  
Montpellier cedex, France.  
E-mail: luc.seguis@ird.fr

## 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

Received: 14 February 2010  
Revised: 6 October 2010  
Accepted: 14 December 2010

## 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.

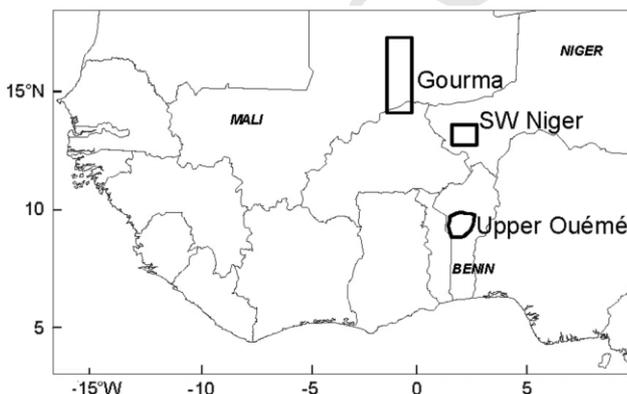
## 3 2. Data and methods

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.

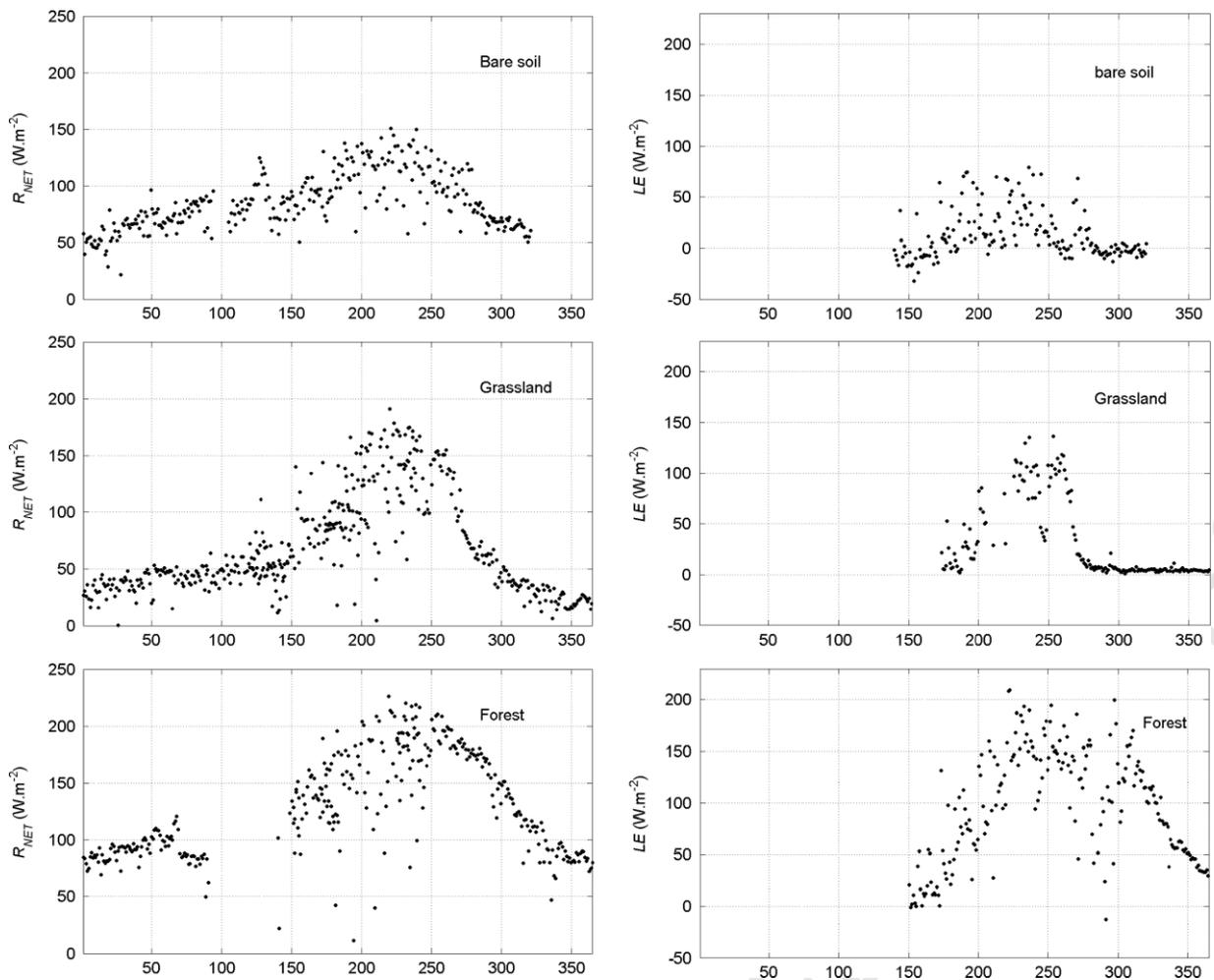
61 mono-modal seasonality results from the summer-  
62 time concomitance of high incoming radiation caused  
63 by aerosol scavenging, with low outgoing radiation  
64 related to a decrease in both the albedo (vegetation  
65 growth) and the surface temperature (Ramier *et al.*,  
66 2009; Timouk *et 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).

AQ5

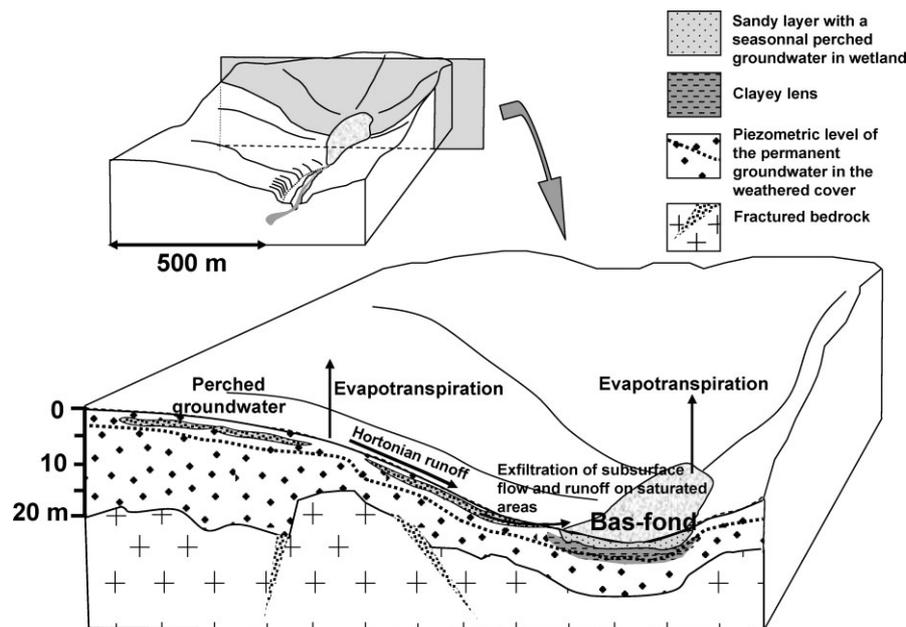
1 produced by Hortonian runoff determined by rainfall  
 2 intensity and by the infiltration capacity of the sur-  
 3 face soil. Water is routed to either highly-infiltrative  
 4 depressions (temporally flooded ponds like in Niger  
 5 or in sandy Gourma) or poorly-infiltrative depressions  
 6 flooded for longer periods (like in crystalline Gourma)  
 7 (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

AQ6



**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

12 The absence of drainage from the permanent  
 13 groundwater into the hydrographic network from local  
 14 to mesoscale meant that another process was needed  
 15 to explain its depletion during the dry season. One  
 16 suggested hypothesis is tree transpiration (Kamagaté  
 17 et al., 2007). In a detailed analysis of ET after an  
 18 isolated rainfall event in the dry season, Guyot et al.  
 19 (2009) demonstrated that one month after the rain-  
 20 fall event, observed ET had emptied available water  
 21 in the instrumented first metre of soil. Consequently,  
 22 the subsequently observed continuing ET could only  
 23 be explained by the contribution of water uptake from  
 24 vadose or saturated layers by vegetation.  
 25  
 26  
 27

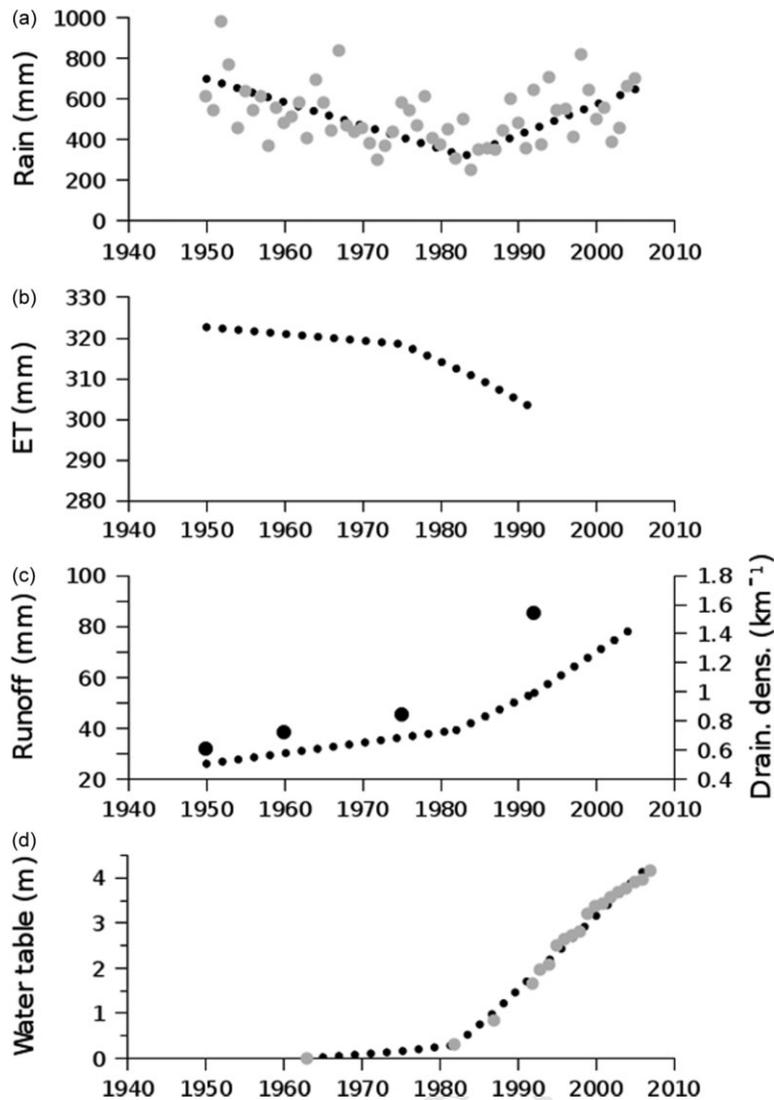
## 28 5. Surface changes, causes of the historical 29 evolution of Sahelian water resources, new 30 evidence revealed by remote sensing and 31 coupled modelling

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 *Aamma* 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  
 49 region, Gardelle et al. (2010) combined satellite  
 50 and aerial remote sensing information and revealed  
 51 a marked increase in the area of surface water,  
 52 starting from the 1970s and accelerating in the mid  
 53 1980s (Figure 5). This long-term increase in pond  
 54 surface area is an indication of intensification in runoff  
 55 triggered by the lasting impact of the 1970–1980s  
 56 droughts on the vegetation over the shallow soils  
 57 prevailing over a third of Gourma. Changes in land  
 58 cover due to human pressure (Niger) or to water stress  
 59 (Gourma) both resulted in increasing runoff. The same  
 60 phenomenon of runoff intensification has also been  
 61 observed outside the two Sahelian meso-scale sites,  
 62 particularly in large exoreic catchments where long  
 63 time series are available (upper catchment of Volta,  
 64 Sahelian tributaries of Niger) (Descroix et al., 2009;  
 65 Karambiri et al., 2011).  
 66

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



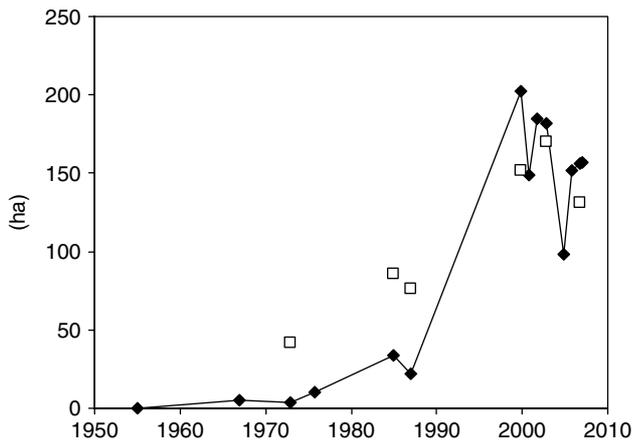
**Figure 4.** Historical trends in annual water cycle in the Niger site (reprinted from Cappelaere *et al.*, 2009): (a) rainfall; (b) rainy-season evapotranspiration (ET); (c) catchment runoff (line) and drainage density (dots), and (d) water table level. Dots correspond to field data: at Niamey airport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

## References

- Boulain N, Cappelaere B, Séguis L, Favreau G, Gignoux J. 2009. Water balance and vegetation change in the Sahel: a case study at the watershed scale with an eco-hydrological model. *Journal of Arid Environments* **73**: 1125–1135.
- Cappelaere B, Descroix L, Lebel T, et al. 2009. The AMMA-CATCH experiment in the cultivated Sahelian area of south-west Niger investigating water cycle response to a fluctuating climate and changing environment. *Journal of Hydrology* **375**: 34–51. DOI: 10.1016/j.jhydrol.2009.06.021.
- Descroix L, Mahé G, Lebel T, et al. 2009. Spatio-temporal variability of hydrological regimes around the boundaries between Sahelian and Sudanian areas of West Africa: a synthesis. *Journal of Hydrology* **375**: 90–102. DOI: 10.1016/j.jhydrol.2008.12.012.
- FAO. 2004. *FAOSTAT, Food and Agriculture Organization of the United Nations*. Available online at <http://apps.fao.org>.
- Favreau G, Cappelaere B, Massuel S, et al. 2009. Land clearing, climate variability and water resources increase in semiarid southwest Niger: a review. *Water Resources Research* **45**: W00A16. DOI: 10.1029/2007WR006785.

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  
38 Sudanian regions. Pluri-annual monitoring of energy  
39

1 Gardelle J, Hiernaux P, Kergoat L, Grippa M. 2009. Less rain, more  
2 water in ponds: a remote sensing study of the dynamics of surface  
3 waters from 1950 to present in pastoral Sahel (Gourma region, Mali).  
4 *Hydrology and Earth System Sciences Discussions* **6**: 5047–5083.  
5 Giertz S, Diekkrüger B, Steup G. 2006. Physically-based modelling of  
6 hydrological processes in a tropical headwater catchment in Benin  
7 (West Africa) – process representation and multi-criteria validation.  
8 *Hydrology and Earth System Sciences Discussions* **3**(2): 595–651.  
9 Guyot A. 2010. *Estimation de l'évapotranspiration sur un couvert*  
10 *complexe par utilisation de la scintillométrie infrarouge. Application*  
11 *à un bassin versant de zone soudano-sahélienne (Bénin)*. PhD thesis.  
12 University of Grenoble (France); 230.  
13 Guyot A, Cohard J-M, Anquetin S, *et al.* 2009. Combined analysis of  
14 energy and water budgets to consolidate latent heat flux estimation  
15 using an infrared scintillometer. *Journal of Hydrology* **375**: 227–240.  
16 DOI: 10.1016/j.jhydrol.2008.12.027.  
17 Kamagaté B, Séguis L, Favreau G, *et al.* 2007. Hydrological processes  
18 and water balance of a tropical crystalline bedrock catchment in  
19 Benin (Donga, upper Ouémé River). *C.R. Geoscience* **339**: 418–429.  
20 DOI: 10.1016/j.crte.2007.04.003.  
21 Karambiri H, García S, Giraldo J, *et al.* 2011. Climate variability  
22 analysis and impacts assessment on water resources in West Africa.  
23 *Lafore J-P, Flamand C, Giraud V, et al.* 2011. Evolution of our  
24 understanding of weather systems in West Africa.  
25 Lebel T, Ali A. 2009. Recent trends in the Central Sahel rainfall  
26 regime (1990–2007). *Journal of Hydrology* **375**: 52–64. DOI:  
27 10.1016/j.jhydrol.2008.11.030.  
28 Lebel T, Cappelaere B, Galle S, Hanan N, Kergoat L, Levis S, *et al.*  
29 2009. AMMA-CATCH studies in the Sahelian region of West-Africa:  
30 an overview. *Journal of Hydrology* **375**: 3–13.  
31 Leblanc M, Favreau G, Massuel S, *et al.* 2008. Land clearance and  
32 hydrological change in the Sahel: SW Niger. *Global and Planetary*  
33 *Change* **61**: 135–150.  
34 Mahé G, Paturel JE. 2009. 1896–2006 Sahelian annual rainfall  
35 variability and runoff increase of Sahelian Rivers. *C. R. Geoscience*  
36 **341**: 538–546. DOI: 10.1016/j.crte.2009.05.002.  
37 Masiyandima MC, van de Giesen N, Diatta S, Windmeijer PN,  
38 Steenhuis TS. 2003. The hydrology of inland valleys in the sub-  
39 humid zone of West Africa: rainfall-runoff processes in the M'bé  
40 experimental watershed. *Hydrological Processes* **17**(6): 1213–1225.  
41 DOI: wiley.com/10.1002/hyp.1191.  
42 Mougín E, Hiernaux P, Kergoat L, *et al.* 2009. The AMMA-  
43 CATCH Gourma observatory site in Mali: relating climatic  
44 variations to changes in vegetation, surface hydrology, fluxes  
45 and natural resources. *Journal of Hydrology* **375**: 14–33.  
46 DOI:10.1016/j.jhydrol.2009.06.045.  
47 Peugeot C, Guichard F, Bock O, *et al.* 2011. Meso-scale water cycle  
48 within the West African monsoon.  
49 Ramier D, Boulain N, Cappelaere B, *et al.* 2009. Towards an  
50 understanding of coupled physical and biological processes in the  
51 cultivated Sahel – 1: energy and water. *Journal of Hydrology* **375**:  
52 204–216. DOI: 10.1016/j.jhydrol.2008.12.002.  
53 Taylor CM, Parker DJ, Kalthoff N, *et al.* 2011. New perspectives  
54 on land-atmosphere feedbacks from the African Monsoon  
55 Multidisciplinary Analysis (AMMA).  
56 Timouk F, Kergoat L, Mougín E, *et al.* 2009. Response of sensible  
57 heat flux to water regime and vegetation development in a central  
58 Sahelian landscape. *Journal of Hydrology* **375**: 178–189. DOI:  
59 10.1016/j.jhydrol.2009.04.022.  
60 Valentin C, Rajot JL, Mitja D. 2004. Responses of soil crusting, runoff  
61 and erosion to fallowing in the sub-humid and semi-arid regions of  
62 West Africa. *Agriculture Ecosystems & Environment* **104**: 287–302.  
63 van De Giesen NC, Stomph TJ, de Ridder N. 2000. Scale effects of  
64 Hortonian overland flow and rainfall-runoff dynamics in a West  
65 African catena landscape. *Hydrological Processes* **14**: 165–175.  
66  
67  
68  
69  
70  
71  
72  
73  
74  
75  
76  
77  
78  
79  
80  
81  
82  
83  
84  
85  
86  
87  
88

---

1 **QUERIES TO BE ANSWERED BY AUTHOR** 61

2 62  
3 **IMPORTANT NOTE: Please mark your corrections and answers to these queries directly onto the proof** 63  
4 **at the relevant place. Do NOT mark your corrections on this query sheet.** 64  
5 65

---

6 66  
7 **Queries from the Copyeditor:** 67

- 8 AQ1 ‘We have provided “Contrasted land surface processes” as the “Running head” for this article. It will 68  
9 appear on the top of the third page and all the recto pages of the article. Please confirm if this is 69  
10 appropriate.’ 70  
11 AQ2 Please provide city for affiliations (1, 2, and 10). 71  
12 AQ3 Please provide city and country for affiliation (5). 72  
13 AQ4 Please provide the department for all the affiliations. 73  
14 AQ5 As per the journal style the captions of figures (2–5) need to indicate the exact source (not just the 74  
15 reference citation), that we have permission to use the artwork, and who the copyright holder is, as 75  
16 they been published in another source. Please check and provide. 76  
17 AQ6 The reference citation (Masayandima *et al.*, 2004) has been changed to (Masiyandima *et al.*, 2003) in 77  
18 order to match with the reference list. Please check and confirm whether this is correct. 78  
19 AQ7 This reference Gardelle *et al.* (2010) has not been listed in the reference list. Please provide the reference 79  
20 details. 80  
21 AQ8 Please provide all the authors’ names for the following references: (Cappelaere, *et al.*, 2009; Descroix, 81  
22 *et al.*, 2009; Favreau, *et al.*, 2009; Guyot, *et al.*, 2009; Kamagate, *et al.*, 2007; Karambiri, *et al.*, 2011; 82  
23 Lafore, *et al.*, 2010; Lebel, *et al.*, 2009; Leblanc, *et al.*, 2008; Mougin, *et al.*, 2009; Peugeot, *et al.*, 83  
24 2010; Ramier, *et al.*, 2009; Taylor, *et al.*, 2010; and Timouk, *et al.*, 2009). 84  
25 AQ9 Please provide the accessed date for the reference (FAO 2004). 85  
26 86  
27 87
- 

28 88  
29 89  
30 90  
31 91  
32 92  
33 93  
34 94  
35 95  
36 96  
37 97  
38 98  
39 99  
40 100  
41 101  
42 102  
43 103  
44 104  
45 105  
46 106  
47 107  
48 108  
49 109  
50 110  
51 111  
52 112  
53 113  
54 114  
55 115  
56 116  
57 117  
58 118  
59 119  
60 120

UNCORRECTED PROOF



## WILEY AUTHOR DISCOUNT CLUB

We would like to show our appreciation to you, a highly valued contributor to Wiley's publications, by offering a **unique 25% discount** off the published price of any of our books\*.

All you need to do is apply for the **Wiley Author Discount Card** by completing the attached form and returning it to us at the following address:

The Database Group (Author Club)  
John Wiley & Sons Ltd  
The Atrium  
Southern Gate  
Chichester  
PO19 8SQ  
UK

Alternatively, you can **register online** at [www.wileyeurope.com/go/authordiscount](http://www.wileyeurope.com/go/authordiscount)  
Please pass on details of this offer to any co-authors or fellow contributors.

After registering you will receive your Wiley Author Discount Card with a special promotion code, which you will need to quote whenever you order books direct from us.

The quickest way to order your books from us is via our European website at:

**<http://www.wileyeurope.com>**

Key benefits to using the site and ordering online include:

- Real-time SECURE on-line ordering
- Easy catalogue browsing
- Dedicated Author resource centre
- Opportunity to sign up for subject-orientated e-mail alerts

Alternatively, you can order direct through Customer Services at:  
[cs-books@wiley.co.uk](mailto:cs-books@wiley.co.uk), or call +44 (0)1243 843294, fax +44 (0)1243 843303

So take advantage of this great offer and return your completed form today.

Yours sincerely,

A handwritten signature in black ink that reads 'V Leaver'.

Verity Leaver  
Group Marketing Manager  
[author@wiley.co.uk](mailto:author@wiley.co.uk)

### \*TERMS AND CONDITIONS

This offer is exclusive to Wiley Authors, Editors, Contributors and Editorial Board Members in acquiring books for their personal use. There must be no resale through any channel. The offer is subject to stock availability and cannot be applied retrospectively. This entitlement cannot be used in conjunction with any other special offer. Wiley reserves the right to amend the terms of the offer at any time.

# REGISTRATION FORM

## For Wiley Author Club Discount Card

To enjoy your 25% discount, tell us your areas of interest and you will receive relevant catalogues or leaflets from which to select your books. Please indicate your specific subject areas below.

<p><b>Accounting</b> <input type="checkbox"/></p> <ul style="list-style-type: none"> <li>• Public <input type="checkbox"/></li> <li>• Corporate <input type="checkbox"/></li> </ul> <p><b>Chemistry</b> <input type="checkbox"/></p> <ul style="list-style-type: none"> <li>• Analytical <input type="checkbox"/></li> <li>• Industrial/Safety <input type="checkbox"/></li> <li>• Organic <input type="checkbox"/></li> <li>• Inorganic <input type="checkbox"/></li> <li>• Polymer <input type="checkbox"/></li> <li>• Spectroscopy <input type="checkbox"/></li> </ul> <p><b>Encyclopedia/Reference</b> <input type="checkbox"/></p> <ul style="list-style-type: none"> <li>• Business/Finance <input type="checkbox"/></li> <li>• Life Sciences <input type="checkbox"/></li> <li>• Medical Sciences <input type="checkbox"/></li> <li>• Physical Sciences <input type="checkbox"/></li> <li>• Technology <input type="checkbox"/></li> </ul> <p><b>Earth &amp; Environmental Science</b> <input type="checkbox"/></p> <p><b>Hospitality</b> <input type="checkbox"/></p> <p><b>Genetics</b> <input type="checkbox"/></p> <ul style="list-style-type: none"> <li>• Bioinformatics/   Computational Biology <input type="checkbox"/></li> <li>• Proteomics <input type="checkbox"/></li> <li>• Genomics <input type="checkbox"/></li> <li>• Gene Mapping <input type="checkbox"/></li> <li>• Clinical Genetics <input type="checkbox"/></li> </ul> <p><b>Medical Science</b> <input type="checkbox"/></p> <ul style="list-style-type: none"> <li>• Cardiovascular <input type="checkbox"/></li> <li>• Diabetes <input type="checkbox"/></li> <li>• Endocrinology <input type="checkbox"/></li> <li>• Imaging <input type="checkbox"/></li> <li>• Obstetrics/Gynaecology <input type="checkbox"/></li> <li>• Oncology <input type="checkbox"/></li> <li>• Pharmacology <input type="checkbox"/></li> <li>• Psychiatry <input type="checkbox"/></li> </ul> <p><b>Non-Profit</b> <input type="checkbox"/></p>	<p><b>Architecture</b> <input type="checkbox"/></p> <p><b>Business/Management</b> <input type="checkbox"/></p> <p><b>Computer Science</b> <input type="checkbox"/></p> <ul style="list-style-type: none"> <li>• Database/Data Warehouse <input type="checkbox"/></li> <li>• Internet Business <input type="checkbox"/></li> <li>• Networking <input type="checkbox"/></li> <li>• Programming/Software   Development <input type="checkbox"/></li> <li>• Object Technology <input type="checkbox"/></li> </ul> <p><b>Engineering</b> <input type="checkbox"/></p> <ul style="list-style-type: none"> <li>• Civil <input type="checkbox"/></li> <li>• Communications Technology <input type="checkbox"/></li> <li>• Electronic <input type="checkbox"/></li> <li>• Environmental <input type="checkbox"/></li> <li>• Industrial <input type="checkbox"/></li> <li>• Mechanical <input type="checkbox"/></li> </ul> <p><b>Finance/Investing</b> <input type="checkbox"/></p> <ul style="list-style-type: none"> <li>• Economics <input type="checkbox"/></li> <li>• Institutional <input type="checkbox"/></li> <li>• Personal Finance <input type="checkbox"/></li> </ul> <p><b>Life Science</b> <input type="checkbox"/></p> <p><b>Landscape Architecture</b> <input type="checkbox"/></p> <p><b>Mathematics Statistics</b> <input type="checkbox"/></p> <p><b>Manufacturing</b> <input type="checkbox"/></p> <p><b>Materials Science</b> <input type="checkbox"/></p> <p><b>Psychology</b> <input type="checkbox"/></p> <ul style="list-style-type: none"> <li>• Clinical <input type="checkbox"/></li> <li>• Forensic <input type="checkbox"/></li> <li>• Social &amp; Personality <input type="checkbox"/></li> <li>• Health &amp; Sport <input type="checkbox"/></li> <li>• Cognitive <input type="checkbox"/></li> <li>• Organizational <input type="checkbox"/></li> <li>• Developmental &amp; Special Ed <input type="checkbox"/></li> <li>• Child Welfare <input type="checkbox"/></li> <li>• Self-Help <input type="checkbox"/></li> </ul> <p><b>Physics/Physical Science</b> <input type="checkbox"/></p>
---	--

Please complete the next page /



I confirm that I am (\*delete where not applicable):

a **Wiley** Book Author/Editor/Contributor\* of the following book(s):  
ISBN:  
ISBN:

a **Wiley** Journal Editor/Contributor/Editorial Board Member\* of the following journal(s):

SIGNATURE: ..... Date: .....

**PLEASE COMPLETE THE FOLLOWING DETAILS IN BLOCK CAPITALS:**

TITLE: (e.g. Mr, Mrs, Dr) ..... FULL NAME: .....

JOB TITLE (or Occupation): .....

DEPARTMENT: .....

COMPANY/INSTITUTION: .....

ADDRESS: .....

TOWN/CITY: .....

COUNTY/STATE: .....

COUNTRY: .....

POSTCODE/ZIP CODE: .....

DAYTIME TEL: .....

FAX: .....

E-MAIL: .....

**YOUR PERSONAL DATA**

We, John Wiley & Sons Ltd, will use the information you have provided to fulfil your request. In addition, we would like to:

1. Use your information to keep you informed by post of titles and offers of interest to you and available from us or other Wiley Group companies worldwide, and may supply your details to members of the Wiley Group for this purpose.  
[ ] Please tick the box if you do **NOT** wish to receive this information
2. Share your information with other carefully selected companies so that they may contact you by post with details of titles and offers that may be of interest to you.  
[ ] Please tick the box if you do **NOT** wish to receive this information.

**E-MAIL ALERTING SERVICE**

We also offer an alerting service to our author base via e-mail, with regular special offers and competitions. If you **DO** wish to receive these, please opt in by ticking the box [ ].

If, at any time, you wish to stop receiving information, please contact the Database Group ([databasegroup@wiley.co.uk](mailto:databasegroup@wiley.co.uk)) at John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, PO19 8SQ, UK.

**TERMS & CONDITIONS**

This offer is exclusive to Wiley Authors, Editors, Contributors and Editorial Board Members in acquiring books for their personal use. There should be no resale through any channel. The offer is subject to stock availability and may not be applied retrospectively. This entitlement cannot be used in conjunction with any other special offer. Wiley reserves the right to vary the terms of the offer at any time.

**PLEASE RETURN THIS FORM TO:**

Database Group (Author Club), John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, PO19 8SQ, UK [author@wiley.co.uk](mailto:author@wiley.co.uk)  
Fax: +44 (0)1243 770154