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The impacts of land-use/land-cover change and climate variability on the hydrology of the Sahel

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Abstract The joint effect of climate change and of human activities on land cover is responsible for an increase of the runoff coefficients of the West African Sahelian rivers since the 1970s, as revealed by the analysis of runoff time series of rivers from Mauritania, Burkina-Faso and Niger. The runoff coefficients have increased in regions with less than 750 mm of annual rainfall, under Sahelian and sub-desertic climates, leading to increased flood peaks, occurring earlier in the season. Studies have shown a rapid change in land-use/land-cover (LUCC) since the 1970s over Sahelian river basins in Burkina-Faso and Niger. It is likely that the aridification of the environment—triggered by climatic change, especially rainfall shortage—is, to an important extent, enhanced by increasing agricultural activities. The relationships between hydrology and LUCC are studied using hydrological modelling. Rainfall/runoff modelling is improved when taking into account the spatio-temporal evolution of the LUCC through a time varying water holding capacity (WHC). The WHC, considered as the soil water reservoir in hydrological models, decreases as the natural vegetation is replaced by cultures or bare soil, leading to increased surface runoff. Long-term observations on "reference river basins" should be set from now on, to collect comparative information for the future.

Key words climate variability; hydrology; land use/land cover change; West African Sahel

INTRODUCTION

Since 1970, West Africa has experienced one of the most abrupt and long-lasting changes of climate ever in the world since the beginning of the records (1900) (Paturel *et al.*, 1997; Mahe *et al.*, 2001; Hulme *et al.*, 2001). This period of rainfall diminution is still ongoing (Lhote *et al.*, 2001, 2003; Dai *et al.*, 2004), although less strong since the mid 1990s than during the 1980s. As for 35 years annual rainfall has remained below the 1900–1970 average in this region, this might well be an impact of the global climate change induced by the increasing of the greenhouse gases concentration in the atmosphere. What the causes and the mechanisms of this lasting drought are is a matter for other studies. From a hydrological point of view, the relevant question for West Africa is: How has climate change (and especially rainfall) affected the rainfall–runoff relationships and the river regimes?

For almost all the rivers of West Africa, runoff has decreased post-1970. But the changes in the rainfall–runoff relationships are far from proportional (Mahe *et al.*, 2000), and even show paradoxical situations. The first hydrological paradox in West Africa is that in most cases the runoff diminution rate largely exceeds that of the rainfall, which is explained mainly by the long-lasting deepening of the water table, and hence a lower contribution from the baseflow to the river regime post-1970 (Mahe *et al.*, 1999, 2000). In more arid regions, as in the Sahel, only surface runoff drives the hydrological regime (Casenave & Valentin, 1989, 1992). Only a few long-time runoff series for this region have been recently studied, from which has been described the second "paradox": the increase of runoff coefficients of the Sahelian rivers since 1970. Pouyaud (1987) had already observed such an increase but only for very small catchments. Recent studies show that these hydrological changes also modified hydrological regimes of large Sahelian river basins (Amani & Nguetora, 2002; Mahe *et al.*, 2003, 2005a).

In this paper we present a synthesis of studies about land-use/cover change (LUCC) and climate variability on the hydrology of the Sahel. Some previously unreleased material about rainfall–runoff changes in the Sahelian part of Mauritania is also presented, which confirms the first observations from the central Sahel catchments.

CLIMATE VARIABILITY IN WEST AFRICA

Climate is mostly related to rainfall and temperature. Rainfall changes over West Africa have been comprehensively described for the last 30 years, after the 1970s drought. Temperature changes over West Africa have been studied less. We present some results about PE variations since the 1950s.

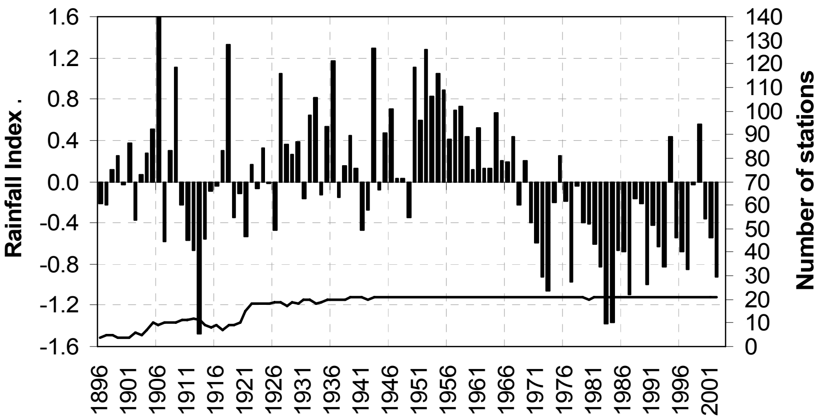

Fig. 1 Sahelian rainfall index (after L'Hote *et al.*, 2002).

The rainfall variability over West Africa and particularly over the Sahel is naturally high. The rainfall shortage during the 1980s, relative to the 1950s, is about 10–15% over tropical humid Africa, and about 15–20% over the Sahel. Since the mid 1990s the rainfall average over the region slightly increased to reach the level of 1970s rainfall (Fig. 1).

In a preliminary work, Ould (2001) studied monthly and annual PE for big river catchments in West Africa, calculated from CRU data (University of East Anglia, UK) (New *et al.*, 2000). PE is related to temperature changes, but also to cloud cover, air humidity and wind changes. This study shows a significant and systematic increase by about 1–1.5% of the annual PE (Penman-Monteith and Thom and Oliver formulas, Ardoin-Bardin *et al.*, 2005) over great rivers like the Niger and Volta. Discontinuities within monthly time series of catchments' PE have been detected by statistical tests (Pettitt and Hubert tests, Lubes-Niel *et al.*, 1998; Paturel *et al.*, 1998); they all show an increase of PE since mainly the late 1970s or the early 1980s, and mainly for the months of January, April, August and September. This is mainly due to the increase of temperature, which is slight over Africa, only 0.5°C, but significant since the late 1970s (Hulme *et al.*, 2001). The predicted increase of temperature and PE over the 21st century should affect West Africa river regimes by reducing surface runoff for most of the rivers in tropical and equatorial humid West Africa (Mahe *et al.*, 2005b), but up to now it has not been possible to predict anything for Sahelian rivers as the performances of the hydrological models are not good enough.

RELATIONSHIPS BETWEEN CLIMATE VARIABILITY/CHANGE, LUCC AND HYDROLOGY OF THE SAHEL

Recent changes in Sahelian hydrology: the counter-intuitive Sahelian paradox

The Sahel can be defined by several characteristics. The most commonly used is the annual rainfall amount. Between May and October, with a rainfall maximum usually in August, annual rainfalls reach between 250 and 750 mm from the north to the south. In this area, runoff coefficients are very low (a few %), as almost all rainfall is evaporated. Groundwater does not contribute to the surface runoff, and the surface runoff produced at each point of a basin is transferred downstream with nearly no losses. The equilibrium between soil and vegetation is very fragile, and changes in rainfall and/or changes in human activities have rapid consequences on the environment.

Rainfall and runoff for hundreds of river basins have been studied in West Africa (Mahe *et al.*, 2005b). For nearly all basins we observe a runoff reduction, except for Sahelian rivers. Figures 2 and 3 show the runoff coefficient increase relative to the rainfall variability both in the Central Sahel (Burkina-Faso and Niger, Fig. 2) and in the Western Sahel (Mauritania, Fig. 3). It is also surprising to report that this runoff increase occurs when in the same period: rainfall is decreasing, yet human consumption and dam storage capacity are increasing.

The aridification process and its impact on hydrological regimes

Natural causes Over the past 35 years, by natural equilibrium, vegetation and soil have adapted to the new climatic conditions, leading to more "arid" conditions in the Sahel. But it is

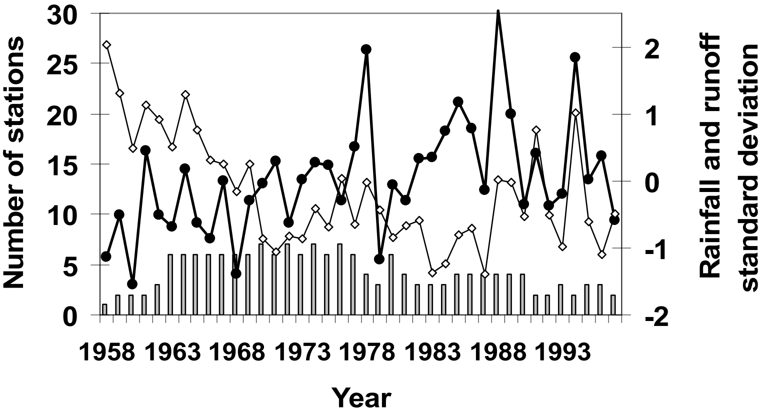

Fig. 2 Standard deviation for rainfall (white dots) and runoff coefficient (black dots) variability for Sahelian river basins of Burkina-Faso and Niger (bars: number of basins per year, maximum = 7).

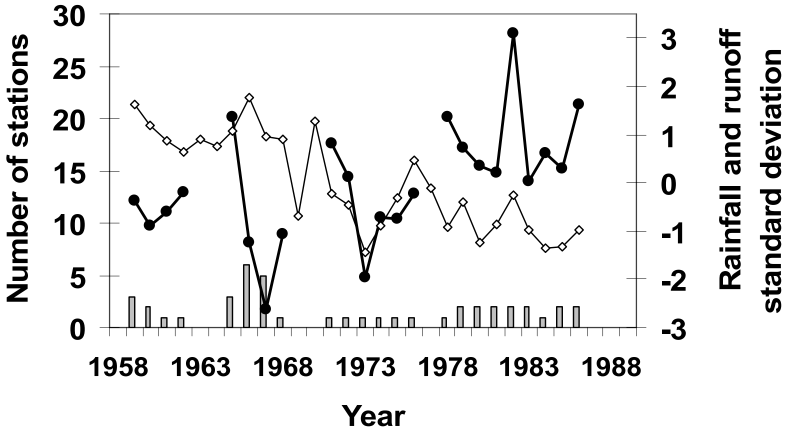

Fig. 3 Standard deviation for rainfall (white dots) and runoff coefficients (black dots) variability for Sahelian river basins of Mauritania (bars: number of basins per year, maximum = 8).

very difficult to separate natural causes from human causes, as there is no "witness" basin, protected from human impacts, which could be used for reference hydrological studies. Nevertheless, the Dargol River basin, at the boundary between Burkina-Faso and Niger, only poorly inhabited, could serve as a reference for comparison with highly anthropogenized basins like the Nakambe River. The increase of the runoff coefficient for the Dargol River at the Tera station is only 37% against 108% for the Nakambe (Mahe *et al.*, 2003).

Human impact on the Sahelian environment, is increasing the speed of the land cover change. Humans need to "deforest" to increase agricultural production. In Sahel this means that grasses, bushes and rare small trees are removed and burned. This has several impacts on the soil-vegetation relationships. It causes a reduction of the net biomass production going back to the soil after the rainy season. After several years, this leads to a soil–vegetation equilibrium which corresponds to that of a drier area. The second point is that the soil top layer becomes very sensitive to rainfall: nutrients are washed out very rapidly and an impermeable crust appears which is responsible for an increase of the surface runoff and a reduction of the water holding capacity.

Impact on the hydrological regimes Surface runoff has been measured over several small Sahelian catchments covering different kinds of environments, by agronomists, soil scientists and hydrologists. One can recall that the annual average runoff coefficient over a natural vegetation area is about 13%, over a cultivated area about 20% (average between several kinds of species and agricultural techniques), and over a bare soil 50%. These values are increased by 5% in the northern Sahel (Yacouba *et al.*, 2003). It is most likely that annual surface runoff might increase for any size of river basin, from small ones (Pouyaud, 1987) to very larges ones (Mahe *et al.*, 2005a). Increases of runoff coefficients and even of annual discharges have been observed for a lot of Sahelian basins from Mauritania to Burkina-Faso and Niger since the 1970s. In Mauritania

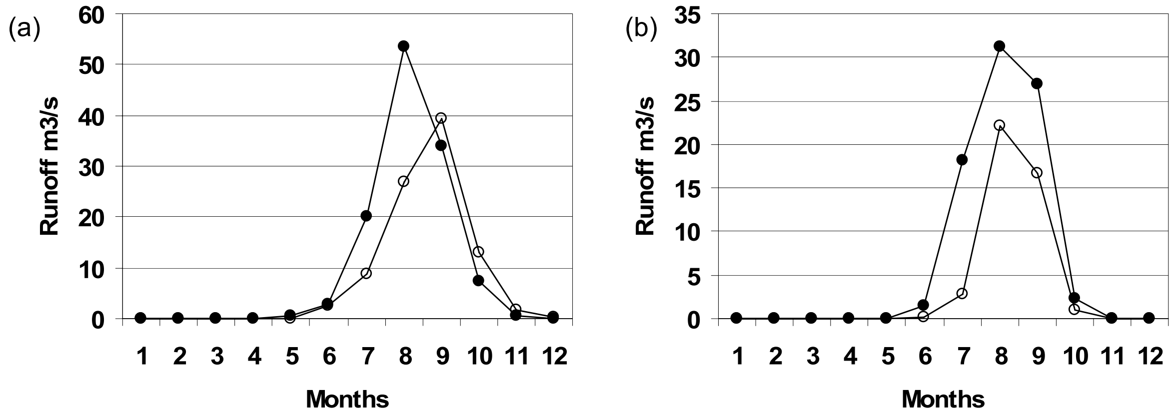

Fig. 4 (a) Runoff up to 1972 (white dots) and after 1972 (black dots), for central Sahel countries (Burkina-Faso and Niger). (b) Runoff up to 1972 (white dots) and after 1972 (black dots), for western Sahel (Mauritania).

runoff is higher for all months since 1972. In the Central Sahel, runoff is higher in July and August after 1972, but not in September. This increase is most likely due to the increasing land degradation. Flood peaks are also observed one month earlier (August instead of September) after 1970 than before, in the Central Sahel (Fig. 4(a) and (b)). Unfortunately we have no examples to show from countries like Senegal, Mali or Chad. But we assume that these hydrological changes should be of the same kind for all Sahelian rivers.

RIVER MODELLING FOR SAHELIAN RIVERS

Conceptual river modelling

Conceptual river models are commonly used for large river basins, where data are not easily available, and most often available only at the monthly time step, especially for transboundary basins. The knowledge developed around this kind of models is very useful from the perspective of the PUB decade of IAHS (Predictions in Ungauged Basins). GR2M and Water Balance Model (WBM) (Conway, 1997; Ambroise, 1999; Mahe *et al.*, 2005a) are two conceptual models with two parameters and one reservoir, the depth of which corresponds to the water holding capacity (WHC), i.e. the maximum water stored in the upper layer of the soil to the average root depth. For our studies in West Africa, the WHC has been derived from the FAO soil map of the world (FAO, 2001), and gave better results than WHC from Dunne & Willmott (1996). Ardoin *et al.* (2005) have tested the three FAO values: minimum, maximum and average, with conceptual hydrological modelling of 50 rivers in West Africa and found the best results with the FAO maximum WHC (FAO max).

Most of the hydrological models use a fixed WHC. It has been shown that in the Sahel the impermeabilization of the soil top layer leads to a proportional loss of WHC (Fournier *et al.*, 2000). River modelling in the Sahel is then very difficult after 1970, as when introducing less rainfall the models are not able to reproduce a runoff increase.

Time varying WHC data files

For Sahelian basins we developed a method for taking into account LUCC in river modelling. The idea is to create a time varying WHC data file, rather than to use a fixed value over time for WHC. WHC is then no more a constant value but varies according to environmental changes. Satellite imagery, and for years prior to 1970 aerial photography, are used to map the land-use/land cover at different periods of time. In our case study on the Nakambe River in Burkina-Faso, we set the first map for 1965. We assume that FAO WHC corresponds to a situation of land-use/land-cover prior to 1970, so that the WHC max values are considered as the initial values for the model, in 1965. Following the LUCC visible on the other maps of 1975, 1985 and 1995, we modified the WHC value. In our case study, the reduction of the area of natural vegetation leads to a decrease of the WHC (Table 1).

In the last step we created the WHC "pseudo" annual series, by increasing WHC each year by one tenth of the WHC difference between two maps. When using time varying WHC data rather than fixed WHC, the performances of the conceptual models are significantly increased (Table 2).

We are currently working on using a population model, based on the national population data, for distributing the values between the maps, more accurately. We assume that the population increase is correlated to the LUCC to some extent, and in addition with a "climatic" index. This approach will be tested in a near future over the Nakambe basin (Diello *et al.*, 2005).

Table 1 Nakambe river, Burkina-Faso, (20 800 km^2), changes in LUCC and impact on the WHC. Initial values are taken from the FAO (1981).

Year	Natural vegetation	Cultivated area	Bare soil	WHC reduction
Initial values	100%	0%	0%	0%
1965	43%	53%	4%	0%
1975	34%	58%	8%	23%
1985	15%	75%	10%	57%
1995	13%	76%	11%	62%

Table 2 Results of the river flow modelling, Nash performance criteria, for calibration and validation, for fixed and time-varying WHC data. D&W refers to Dunne and Willmott (1996), and FAO to FAO (1981).

Precipitation file	Source file WHC	Fixed WHC Calibration %	Time varying WHC Calibration %	Fixed WHC Validation %	Time varying WHC Validation %
CRU	FAO	50.6	67.3	37.0	63.2
CRU	FAO	64.5	72.2	47.7	58.3
IRD	D&W	52.3	72.5	36.8	63.7
IRD	D&W	67.7	72.2	48.9	58.2

CONCLUSION

The hydrological regime of the Sahelian rivers has changed since the 1970s, following the beginning of the lasting drought which is still ongoing over West Africa. For river basins north of the 750-mm annual isohyet, runoff coefficients have increased and flood peaks occur one month sooner, in August, according to runoff data available for Sahelian basins in Mauritania, Burkina-Faso and Niger. This is correlated with land-use/land-cover change, which leads to the impermeab-ilization of the soil top layer, and thus to the reduction of the WHC. This hypothesis is tested significantly by using conceptual hydrological models which use WHC as the soil water reservoir. WHC is modified according to the LUCC as seen from the analysis of satellite or aerial imagery. Other observations in the Sahelian area confirm this hypothesis. For example, in the country near the city of Niamey in Niger, the level of the water table has been rising for the last 50 years (Leduc *et al.*, 2001). This water table is too deep and cannot participate in increasing the baseflow of Sahelian rivers. The local geography is unusual, with small endorheic ponds being increasingly refilled by surface runoff increases from year to year.

The hydrological regime of the Niger River itself has changed at Niamey (400 000 km^2) due to this Sahelian runoff increase. Over the period 1923–1979 the flood peak coming from the Guinean and Malian upper basin (300 000 km^2) had always been the highest one. Since 1980, a higher flood peak coming from the local Sahelian tributaries (100 000 km^2) has been observed several times (Mahe *et al.*, 2003).

All studies have also noted the increasing agricultural activity, correlated with deforestation and alteration of local soil properties, specifically infiltration. It is nevertheless very difficult to separate the human induced and climate induced variability in the observed hydrological changes of Sahelian basins (Hulme, 2001; IPCC, 2003). There is a need to create a set of "reference basins" which could serve as witnesses of the natural climate/vegetation equilibrium, in regard to the ever-growing human induced changes of the environment.

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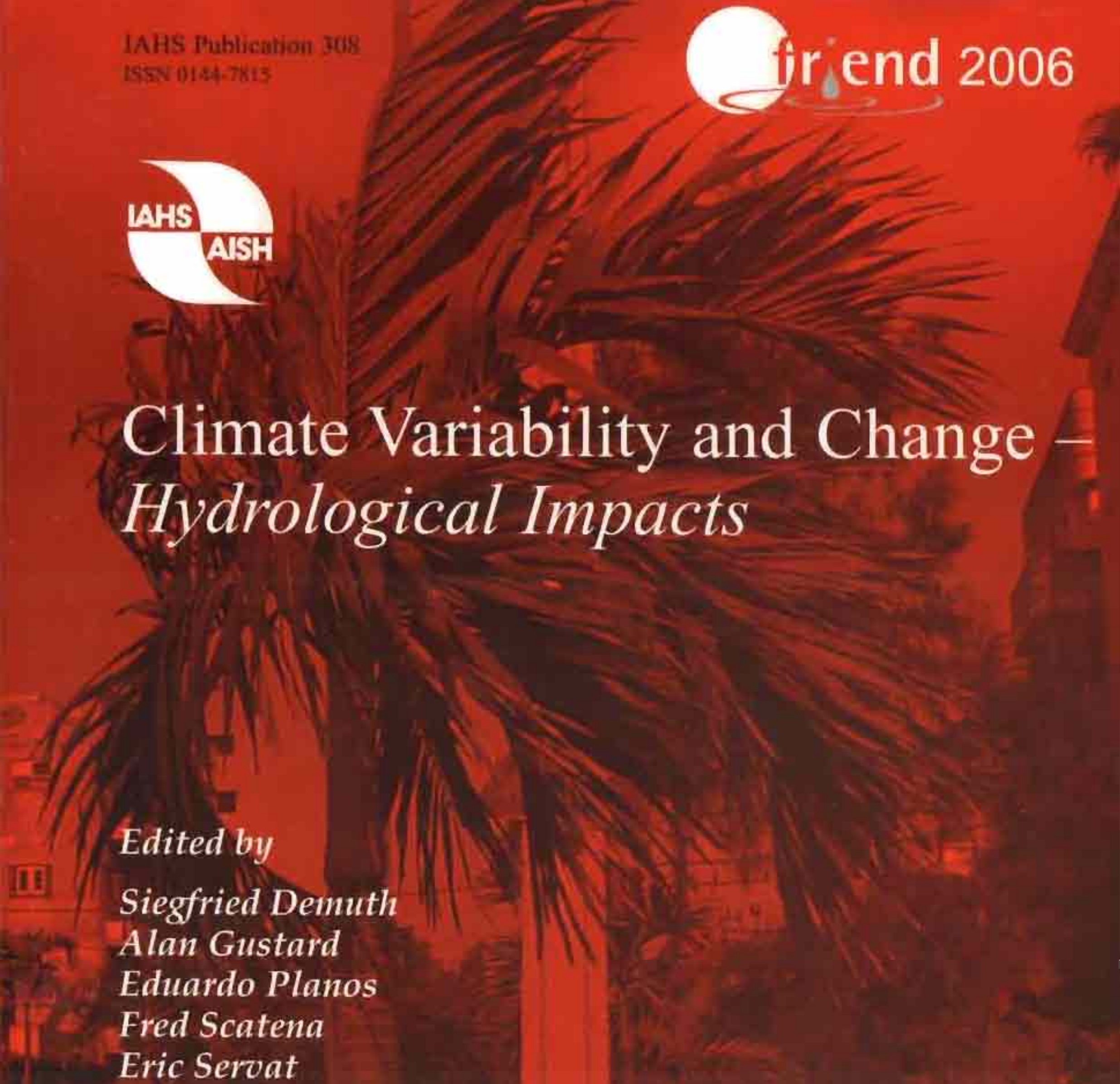

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