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How changing rainfall regimes may affect the water balance: a modelling approach in West Africa

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Abstract West Africa is subject to large rainfall variability, on both interannual and decadal scales. The drought and famines that struck this region during the 1970s and the 1980s illustrate the impact of such variability on water resources. To gain a better understanding on how long-scale rainfall variability may affect the water resources in this region, use was made of a data set collected on the Upper Ouémé catchment (10 050 km^2 in a Sudanian environment) in Benin, as part of the AMMA (African Monsoon Multidisciplinary Analysis) observing system. A lumped hydrological model (GR4J) is successfully applied to the catchment, and is forced with different rainfall regime scenarios. The results show a large variability of hydrological response with respect to given regional climatic changes, and thus emphasize the relevance of fine time-scale studies.

Key words rainfall–runoff modelling; scenarios; water resources; West African monsoon

INTRODUCTION

During the last 50 years, West Africa has been subject to significant rainfall variability, characterized both by large interannual fluctuations and by periods of long-lasting droughts, such as during the period 1970–1990. Numerous studies have described this variability and its controlling factors, more often at large space–time scales. The hydrological impacts of these climatic fluctuations are not as well understood, because they require studies at smaller scales, with high-resolution observing systems, to link the climatic and hydrological scales (Lebel *et al*., 2003). Indeed, realistic water resource impacts need to deal with rainfall intermittence and seasonal distribution, especially in arid and semiarid regions, where evapotranspiration is a key factor in the runoff generation process. The aim of this work is to quantify the sensitivity of a simple rainfall–runoff model forced by different rainfall regimes, using three hydrological variables: runoff, evapotranspiration and soil moisture. The results are discussed in terms of hydrological behaviour and scale relevance for water resource impact assessment.

MODEL, DATA AND METHODOLOGY

Methodology

The classical framework for estimating the impacts of climate change on hydrological behaviour includes the following stages: (a) determination of the parameters of a hydrological model in the study catchment, using current hydroclimatic inputs, and model validation on a period not used for calibration; (b) perturbation of the historical time series of climatic data according to some climate change scenario; (c) simulation of the hydrological characteristics of the catchment under the perturbed climate, using the calibrated hydrological model; and (d) comparison of the model simulations of current and possible future hydrological characteristics. This methodology involving parameter calibration, is based on an important hypothesis, which is the consistency of catchment behaviour under different climatic conditions. We assume, using a large and rich calibration period and considering moderate climatic change, that this hypothesis is verified. Furthermore, historic hydroclimatic data allow us to verify the results obtained and thus validate our modelling strategy.

The hydrological model

Numerous authors have discussed the model types used for climatic impacts studies (e.g. Beven, 1989; Arnell, 1992; Jakeman & Hornberger, 1993; Michaud & Soorooshian, 1994; Refsgaard & Knudsen, 1996; Kokkonen & Jakeman, 2001; Dagnachew *et al.*, 2003). To summarize, it appears that although physically-based models may offer the best potential, their utilization is widely complicated by the high-resolution data required in both space and time. For most catchments, data are not available at such scales and models need to be calibrated. Therefore, as model robustness is the most important criterion in impact studies, parsimonious conceptual models are often preferred (see Vieux *et al.* (1998) for a physical approach in semiarid West Africa). A comparison of two model concepts for the Upper Ouémé region, made by Bormann & Diekkrüger (2003), illustrates the difficulties of physically-distributed approaches.

For this study, we have used the GR4J model, from the family of models developed at Cemagref (Perrin *et al.*, 2003). This is a conceptual, lumped model, which operates on a daily basis. Its structure is composed of two stores and four free parameters, and the input variables are spatially averaged daily rainfall and evapotranspiration. For a complete description see Perrin *et al.* (2003).

Catchment and data description

This study focuses on the Upper Ouémé catchment, covering 10 050 km^2 in Benin, within the square degree (1.5°–2.5°E, 9°–10°N). Situated within the Sudanian climatic regime, this area is characterized by a single rainy season, with an average amount of 1200 mm spread between April and October. The rainfall is primarily linked to meso-scale convective systems, although local convective cells are responsible for a high degree of spatial and temporal variability in rainfall patterns. Annual rainfall displays this variability, at both the decadal and the inter-annual scales, as shown in Fig. 1. The long-term annual average of potential evapotranspiration is about 1500 mm. The catchment streamflows are intermittent, with river discharge occurring between the end of June and January. The average runoff coefficient is about 10%, which should imply *a priori*, according to Arnell (1992) and Chiew *et al.* (1995), a large sensitivity of the watershed to climatic changes. This area is one of the AMMA international programme sites, on which atmospheric and continental interactions are investigated.

Daily series of rainfall and discharge were collected throughout the 1954–2002 period. The 12 raingauge stations located in this region were used to compute the mean daily rainfall in the catchment using a kriging process. Six years of daily climatic variables permitted the computation of Penman Monteith evapotranspiration at a single station located in the catchment. These values were smoothed in a long-term average of daily evapotranspiration and used as the mean values for the catchment.

The annual rainfall–runoff relationship over the 1954–2002 period, presented in Fig. 2 at the catchment scale, is strongly non-linear, with changes in runoff approximately twice as large as changes in rainfall. Furthermore, the significant dispersion observed emphasizes the need of a finer scale approach.

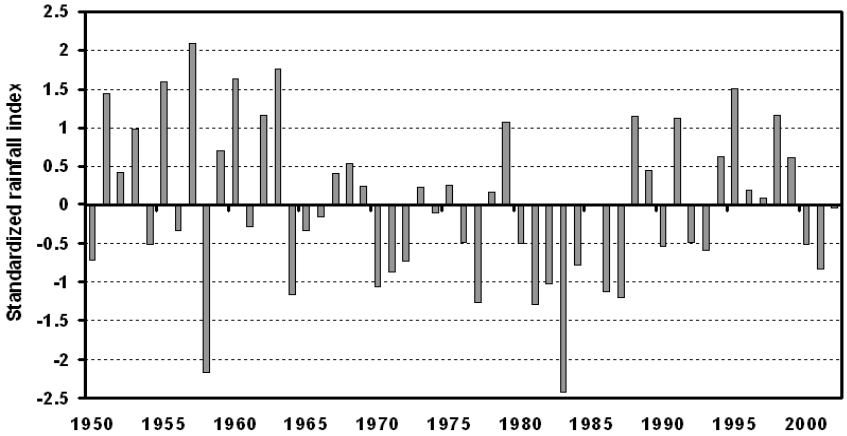

Fig. 1 Evolution of the standardized rainfall index over the Upper Ouémé catchment between 1950 and 2002.

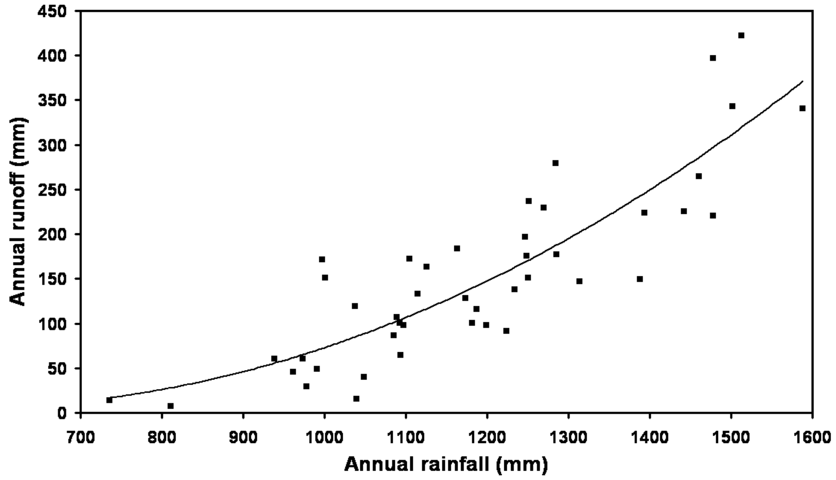

Fig. 2 Annual rainfall–runoff relationship for the Upper Ouémé catchment between 1954 and 2002.

Model calibration and validation

Non-stationarity of hydroclimatic conditions in West Africa during the last 50 years has been indicated by different studies (Paturel *et al.*, 1997; Le Barbé *et al.*, 2002), and a break in the time series characteristics has been identified around 1970. Hydrological model behaviour under non-stationary conditions (Niel *et al.*, 2003) is outside the scope of this paper; therefore, the simulation period is restricted to the years after 1970. Model calibration was performed on the years from 1971 to 1989 (with one year warm-up period) and the years from 1990 to 2002 were used for model validation. The use of a long calibration period (19 years) allows us to infer model parameters with a rich data set, composed both by dry and humid years. Therefore, the resulting model (GR4J structure + inferred parameters) should be robust and able to simulate very different hydrological conditions.

The calibration process, combining automatic and manual methods, uses two objective functions: the Nash-Sutcliffe efficiency (E) and a water balance criterion (B), defined as follows.

$$E = 1 - \frac{\sum_{i=1}^{n} \left(Q_{obs,i} - Q_{sim,i}\right)^2}{\sum_{i=1}^{n} \left(Q_{obs,i} - \overline{Q_{obs}}\right)^2}$$

$$B = \frac{\sum_{i=1}^{n} Q_{sim,i}}{\sum_{i=1}^{n} Q_{obs,i}} - 1$$

with n the number of days during the simulation period, $Q_{obs,i}$ the observed daily flows, $Q_{sim,i}$ the simulated daily flows, and $\overline{Q_{obs}}$ the average observed daily flows. These statistics judge different aspects of model performance: the efficiency formulation focuses on high flows, and the water balance criterion is indicative of the model ability to predict the volume of stream discharge. From a water resource perspective, these two criteria allow a robust evaluation of model performances. The good global efficiencies for calibration and validation ($E > 0.8$), associated with accurate volumes simulations ($B < 5\%$) and non-biased results (verification using flow duration curves of daily runoff), give a good *a priori* confidence in the modelling strategy.

RAINFALL SCENARIOS

A dry spell will not have the same hydrological impact when it occurs through a reduction in the average intensity of rain events, as a reduction in the number of events over a given period, or as a mixture of both. The aim of this paper is therefore to quantify the impact of intra-seasonal rainfall distribution and rainfall intermittence on the hydrological response.

Several annual rainfall reductions (–10%, –20%, –30%, –40%), based on the daily rainfall of the 1990–2002 period, are simulated using four different scenarios, defined as follows: (S_1)—the same percentage change is applied to each rainy day of the observed data. Daily rainfall is reduced but intermittence is the same as in the observed data set; (S_2)—the occurrence of rain events is modified, by randomly removing rainy days during the rainy season; (S_3)—the length of the rainy season is reduced, by symmetrically removing the first and last rainy days; and (S_4)—the most intense storms at the core of the rainy season (July–September) are removed first.

In a previous study of the long-lasting drought (1970–1990) over West Africa from Le Barbé *et al.* (2002), the decrease in the occurrence rate of large rain events during the core of the rainy season was shown to be the primary cause of the rainfall deficit. Therefore, S_4 is probably the most realistic scenario of droughts in the studied region.

RESULTS AND DISCUSSION

Hydrological sensitivity to drought is investigated through different variables in the rainfall–runoff model: (a) the total annual discharge (*Q*) at the outlet of the catchment; (b) the actual evapotranspiration rate (*ET*); and (c) a soil moisture index, defined as the ratio of the amount of water in the production store. It should be noted that GR4J is a conceptual rainfall–runoff model, developed to compute reliable runoffs, and as with most hydrological models, calibrated only against the streamflow data. Therefore, the reliability of the internal fluxes calculated by the model such as the *ET* and the soil moisture is unknown, and the absolute values of these estimates should not be used directly. However, their relative changes between the different simulations may be considered as the changes in water balance components of the catchment described by the model.

Runoff depth

As expected, significant differences in the total discharge can be seen, depending on the scenario in which the drought manifests itself (Fig. 3). Firstly, S_3 clearly appears to be the less critical scenario with respect to water resources, as it does not result in an amplification of the runoff deficit compared to the rainfall reduction. In contrast, the three other scenarios provide a discharge deficit up to twice as large, S_4 having the most serious consequences. Surprisingly, S_1 and S_2 result in a similar runoff deficit, although rainfall intermittency is clearly different. Moreover, S_2 shows a slightly smaller runoff reduction, although the larger inter-event lag could have been considered as a factor reducing runoff by increasing the infiltration. Scenario S_4 reveals the importance of intense events on the discharge, especially in the core of the rainy season when the soil is saturated most of time. It should be noted that our modelling results provide a similar non-linearity in the rainfall–runoff relationship to the observations (Fig. 2), and display a large part of the observed variability.

However, hydrological and human impacts are strongly dependent on the nature of the runoff decrease. We have therefore investigated the conditional non-zero runoff distribution, by assessing the reduction quantiles Q_{90} and Q_{10} for the different scenarios (Fig. 4). Except for the S_3 scenario, peaks flows are shown to be much more reduced than low flows. On the contrary, S_3 produces a similar relative decrease of both peak and low flows.

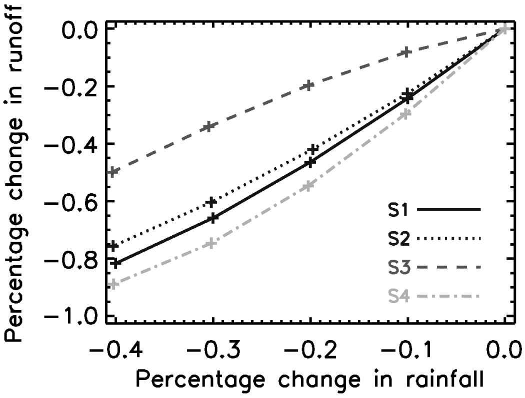

Fig. 3 Percentage change in runoff for various rainfall decrease scenarios.

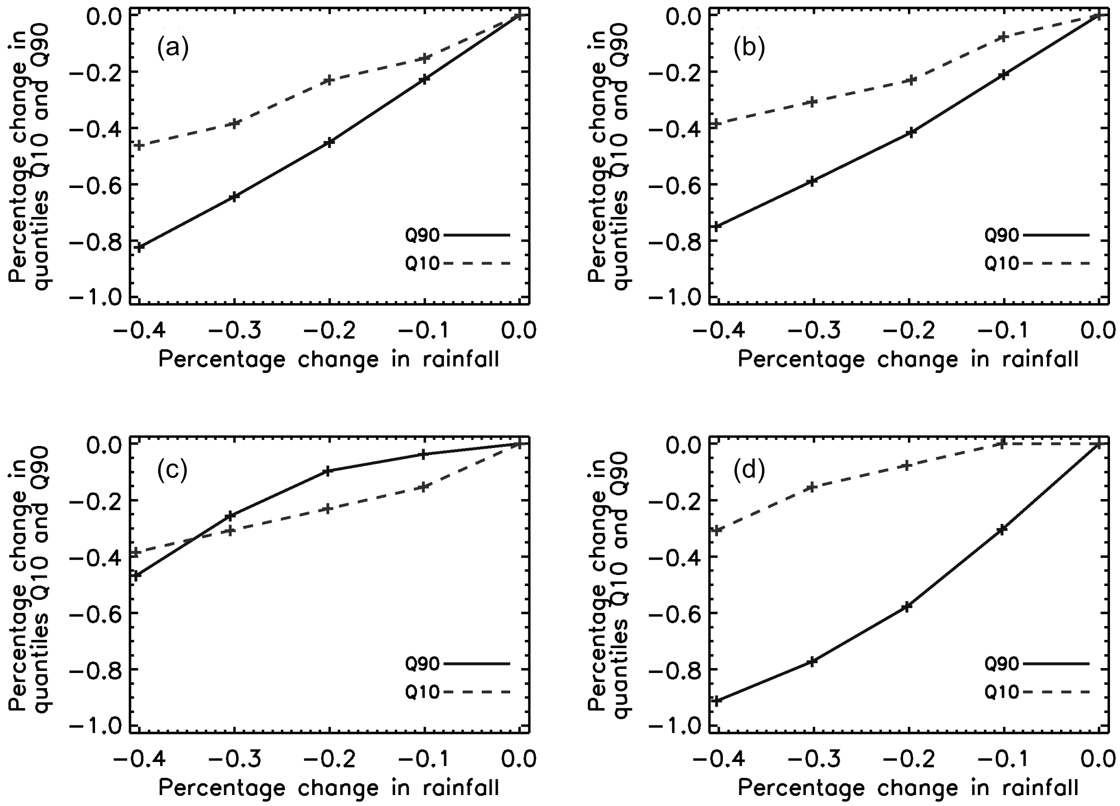

Fig. 4 Percentage change in quantiles Q_{10} and Q_{90} of the daily runoff distribution, for (a) scenario S_1, (b) scenario S_2, (c) scenario S_3 and (d) scenario S_4.

Water balance

In order to get a better understanding of the processes resulting in dispersion of runoff simulations, an internal flux and an internal state variable of the model structure were analysed for the different scenarios.

First of all, the total evapotranspiration rate calculated by the model is analysed. As may be seen in Fig. 5, S_3 produces the most important *ET* reduction of approximately 40% for a 40% rainfall reduction. Explanations may be derived from two sources: firstly, the catchment has a specific behaviour with nearly two months between the onset of the rainy season and the streamflow appearance, during which most of the rainfall returns to the atmosphere through evaporation; secondly, the potential evapotranspiration rate is stronger at the beginning and the end rather than in the core of the rainy season. In contrast, S_1, S_2 and S_4 scenarios show a twice or three times less *ET* deficit.

As a second consideration, the soil moisture index, was observed (Fig. 6). The simulation results show quite small differences between scenarios, and the soil moisture levels change at approximately half the rate of change in rainfall. As in many other hydrological models, *ET* is partly calculated from the soil moisture level, and the differences observed between these two variables features are directly linked with the temporal distribution of rainfall.

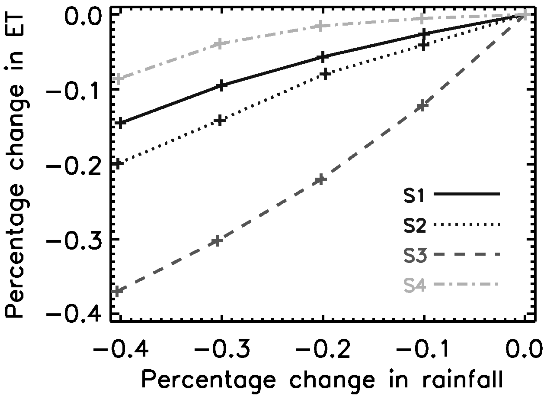

Fig. 5 Percentage change in actual evapotranspiration for various rainfall decrease scenarios.

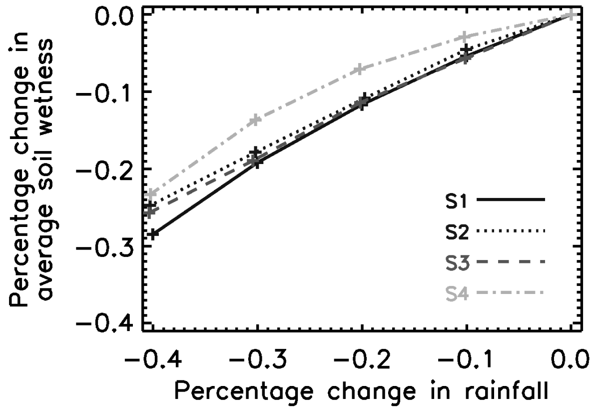

Fig. 6 Percentage change in soil moisture index for various rainfall decrease scenarios.

CONCLUSIONS

Assessing the hydrological impacts of climate changes requires dealing with the scale gap between the models commonly used for climate simulations and those used for hydrological studies. In this paper, we have shown the variability of the hydrological response with respect to given regional climatic changes, and thus the need of a fine time scale to take account of the nonlinearity of the hydrological response and the rainfall intermittence. For a given annual rainfall decrease, the different time downscaling scenarios provide very different hydrological sensitivities, with the results showing reduction ratios between 1:1 and 2:1 in runoff with respect to rainfall volume. The most realistic drought scenario yields a relative reduction of more than 2:1, having the most serious consequences on water resources. The simulation results are also analysed in terms of evapotranspiration and soil moisture. It is shown that the soil moisture has less sensitivity to rainfall changes than the two other water balance components. Future research, involving other modelling concepts and uncertainty assessment, should permit a more reliable and useful investigation of the climatic impacts on water resources.

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