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How could hydro-climatic conditions evolve in the long term in West Africa? The case study of the Bani River catchment

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Abstract This paper assesses the future variability of water resources in the long term over a large Sudano-Sahelian catchment in West Africa. Flow simulations were performed with a daily conceptual model. The climate models HadCM3 and MPI-M (based on SRES-A2) were used to provide future climate scenarios over the catchment. Outputs from these models were used to generate daily rainfall and temperature series for the 21st century according to: (i) application of the unbias and delta methods, and (ii) spatial and temporal downscaling. A temperature-based formula was used to calculate present and future potential evapotranspiration (PE). The daily rainfall and PE series were introduced into the calibrated and validated hydrological model to simulate future discharge. The model correctly reproduces the observed discharge at the basin outlet with the Nash-Sutcliffe efficiency criterion over 0.89, and the volume error close to null over 1952–2000. With regard to future climate, the results show clear trends of reduced rainfall with a continuing increase in PE over the catchment. This suggests that the catchment discharge could fall in the long term to the same levels as those observed during the severe drought of the 1980s.

Key words hydro-climatic variability; climatic scenarios; hydrological modelling; River Bani; West Africa

INTRODUCTION

Global climatic change, partly linked to anthropogenic activity, should lead to significant modifications in local and regional climatic conditions. The ability to anticipate the impacts of such changes on hydrosystems, and thus on the availability of water resources, is essential in order to face up to the adaptations of our societies. This is particularly true in West Africa, where the severe drought over the last 40 years has had significant hydrological impacts (see e.g. Lebel *et al.*, 2003; Andersen *et al.*, 2005; Ruelland *et al.*, 2008). These changes are extremely worrying for the local populations, especially since demographic growth has been accelerating in recent decades. The question then arises whether water resources availability can be expected to improve or deteriorate depending on the future climate in this region.

To assess the hydrological impacts of climate change, one must have both (i) a hydrological model that is adapted to various climatic conditions, and (ii) climatic scenarios in accordance with the spatio-temporal scales of the catchments considered. Where hydrological modelling is concerned, the paucity of descriptive data in West Africa militates in favour of a conceptual approach for studying large, poorly gauged catchments (Ruelland *et al.*, 2009, 2010). However, the question remains whether such an approach is adequate for simulating the long-term rainfall–runoff relationship in large catchments that are subject to significant hydro-climatic variability. Moreover, although these hydrological models are simple, they require high-resolution climate data, at least for variables such as precipitation and temperature. Global climate models (GCMs) provide such data and constitute powerful tools accounting for the complex set of processes that will produce future climate change. However, modelling the climatic system is a complex exercise, and climate projections are not easy to incorporate into hydrological impact studies (Allen & Ingram, 2002). The use of GCMs' outputs currently faces three major problems: (i) the resolution of these models is not in line with that of hydrological modelling and hence requires spatial and temporal downscaling; (ii) the climatic projections produced by different GCMs and greenhouse gas scenarios (Special Report on Emissions Scenarios (SRES)) show very marked differences; (iii) precipitation projections for West Africa are generally less consistent (in comparison to projections for other regions) with large inter-model ranges for seasonal mean rainfall responses (see e.g. Lebel *et al.*, 2000; d'Orgeval, 2008). As a result of these problems,

direct use of the meteorological variables produced by GCMs for hydrological impact studies is a delicate matter. Climatic scenarios must thus be developed by correction of the GCMs' outputs.

This paper aims to forecast future water availability using climatic scenarios at the end of the 21st century in a large, poorly-gauged Sudano-Sahelian catchment.

STUDY AREA

The Bani River runs mainly through southern Mali (Fig. 1). Its catchment drains an area of around 100 000 km^2 at the Douna gauging station. The river flows into the Inner Niger Delta at Mopti and contributes about one-third of the annual flooding in this vast plain. Consequently, any disruption in the Bani catchment impacts on the delta and its vital economic activities. The watershed's topography is gently sloping, with elevations between 270 and 700 m. Soils are mostly ferralitic and lessivated with high sand and clay contents. Sandy hillwash is often found at the surface, while basal gravels are found in deeper parts of the profiles. Agricultural areas are growing rapidly because of demographic pressure.

The Bani catchment, located in a Sudano-Sahelian climatic regime, is characterized by a monsoon climate with a strong north–south rainfall gradient (Fig. 1) and considerable rainfall variability since the mid-20th century. As a result of this variability, the flow at the Douna gauging station fell by 68% between the 1952–1970 and 1971–2000 periods, with a decrease in the deep water recharge and baseflow contribution to the annual flood (Ruelland *et al.*, 2009). Some of the low-water periods were so severe that the river flow stopped periodically at Douna during the 1980s.
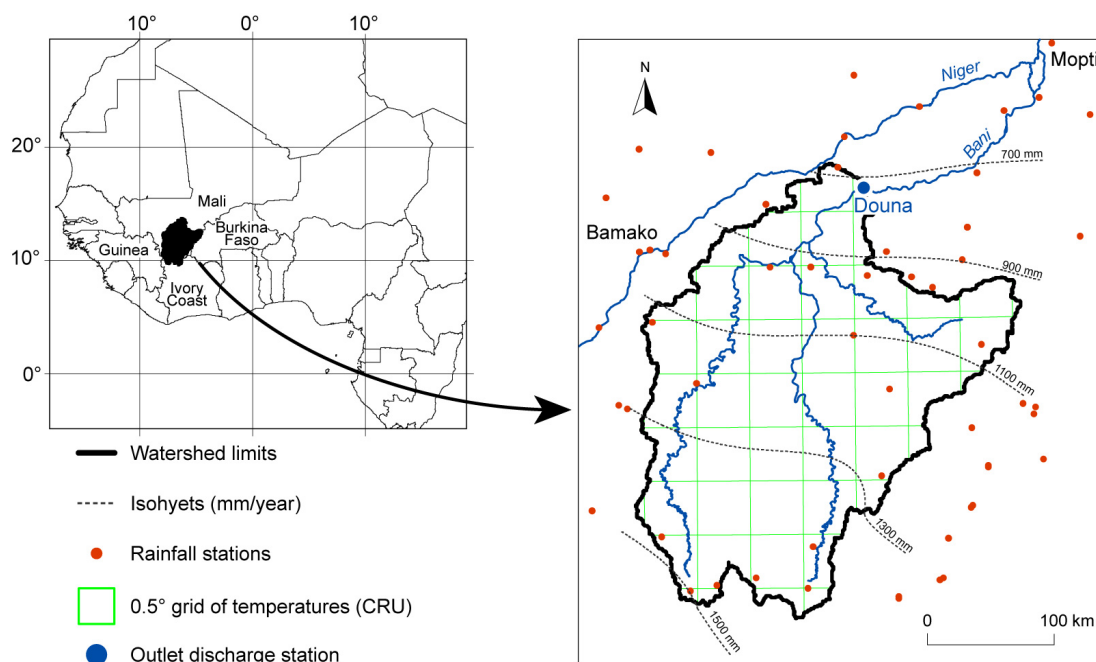
Fig. 1 The Bani catchment at Douna (104 000 km^2).

MATERIALS AND METHODS

Hydro-climatic data over the reference and future periods

In order to represent the hydro-climatic variability over the catchment, a 50-year period was chosen according to data availability. Daily rainfall series were derived from 72 raingauges covering the area (Fig. 1). For the 1950–2000 period, an average of 65 gauges per day (with a minimum of 39) was used to interpolate rainfall maps by the inverse distance weighted method,

which proved to be optimally accurate among the classic methods available for data reconstruction in the given context (Ruelland *et al.*, 2008). Potential evapotranspiration (PE) was estimated based on a 0.5° square grid from the CRU TS 2.1 World Database (Mitchell & Jones, 2005). Since the only data available for calculating PE were temperature data, a formula relying on solar radiation and mean temperature was selected (Oudin *et al.*, 2005). This formula was applied with a monthly temperature time step. However, solar radiation is a daily variable that depends on latitude and the Julian day of the year. Thus, PE was finally calculated with a daily time step.

Discharge data are from the Douna gauging station. This station appeared to have a high-quality daily discharge series (less than 0.5% missing daily runoff values over 1952–2000) and covers more than 75% of the entire catchment (Fig. 1).

Outputs from the GCMs HadCM3 and MPI-M were downloaded from the IPCC's Data Distribution Centre. All simulations of climate change were based on the SRES 20C3M scenario over the control period (1961–1990) and the SRES-A2 for the future period (2071–2099).

Hydrological model: calibration and validation

In order to represent the seasonal and interannual variations in runoff from the catchment, discharge was linked to climatic series. In view of the scarcity of data on the catchment, the HydroStrahler conceptual model was chosen since it has yielded satisfactory results in West Africa (see Ruelland *et al.*, 2008, 2009, 2010). Using daily rainfall/PE data, this rainfall–runoff model represents, in a conceptual manner, the flow processes in a catchment and makes it possible to simulate runoff at its outlet with a daily time step. The model considers two reservoirs in the watershed (Fig. 2): (i) a shallow reservoir supplied by rainfall and feeding evapotranspiration, surface/subsurface runoff and infiltration, and (ii) a deep reservoir fed by infiltration and generating the baseflow. The model involves four parameters that need to be calibrated in order to account for three sources of runoff: immediate, rapid and delayed runoff.

Model calibration was realized based on a multi-objective function that aggregates a variety of goodness-of-fit indices (for more details on this function, see Ruelland *et al.*, 2009, 2010):

$$F_{agg} = (1 - NSE) + |VE| + VE_{avg} + PE_{avg} \qquad (1)$$

with NSE being the Nash-Sutcliffe efficiency criterion (Nash & Sutcliffe, 1970), VE the cumulative volume error, VE_{avg} the annual average relative volume error, and PE_{avg} the annual average peak error.

Model calibration was then performed in a 4-D parameter space by searching for the minimum value of F_{agg}. A 10-day time step was used in order to limit problems related to time transfer. In both calibration and validation, the first two years of simulations were used as a warm-up, to eliminate the influence of initial conditions in the model reservoirs. The 1952–2000
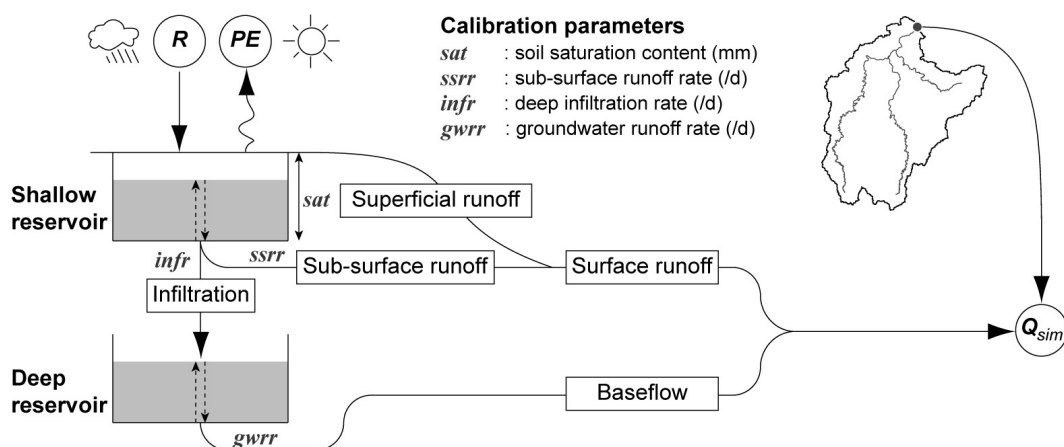

Fig. 2 Principle of the hydrological model (based on Ruelland *et al.*, 2008).

simulation period was divided into three parts: calibration was performed for a 30-year period (1961–1990) and validation was carried out in two periods of roughly 10 years (1952–1960 and 1991–2000). The two validation periods display contrasting climatic behaviours, the period 1952–1960 being wet and the period 1991–2000 being dry, which allowed us to test the model for suitability under different climatic conditions.

Building and introducing climatic scenarios in the model

Rainfall simulated by the GCMs is not sufficiently accurate to be used directly in impact studies to drive hydrological models (IPCC, 2007). This is particularly true in West Africa, as shown by Ardoin-Bardin *et al.* (2009). Therefore, it is recommended that climatic scenarios be constructed using the ranges of variation between future climate and a baseline period in order to take climate variability changes and mean climate change into account (Carter *et al.*, 1999). Projected climatic scenarios were thus developed based on the perturbation method. This method consists of producing future climatic scenarios by simply perturbing the observed climatic series over the control period (see e.g. Etchevers *et al.*, 2002; Prudhomme *et al.*, 2002; Shabalova *et al.*, 2003). For this purpose, the observed series for each hydrological model cell were simply translated and dilated so as to reproduce the changes of variance obtained between the control and future climatic simulations from both GCMs. Projected climatic scenarios were constructed in three steps. First, the average of the simulated and observed series was calculated over the reference period (1961–1990). The second step consisted of computing the monthly adjustments that would allow projected scenarios to be built. This was done by applying the unbiasing (for precipitation) and delta (for temperatures) methods between, respectively, the mean monthly hyetographs and thermographs simulated over the reference period (1961–1990) and the monthly rainfall and temperatures simulated over the future period (2071–2099). The third step was to construct climatic scenarios for each hydrological model cell on a daily time step using a simple spatial and temporal downscaling. This was done by applying the adjustments calculated in step 2 to the daily mean hyetograph and thermograph calculated with the observed series over the reference period (1961–1990) and for each cell of the hydrological model. The series generated represent simulated daily rainfall and temperature in the long term (2071–2099). PE was then calculated with the formula proposed by Oudin et *al.* (2005) using monthly temperature series, yielding future daily series. This three-step method made it possible to construct climatic scenarios in the long term using a high-resolution grid and a daily time step. The future daily rainfall and PE series were used to feed the hydrological model. The latter was then run with the calibrated parameters to simulate future discharge based on those input data in the future simulation periods.

RESULTS

Model efficiency

Analysis of the fit of the hydrological model (Fig. 3) clearly shows that simulated discharge corresponds precisely to the observed values, although simulated discharge tends to end the hydrological season too abruptly. NSE values are over 0.89 in both the calibration and validation periods, and F_{agg} close to null. Taking a closer look at the results, the 1952–1960 validation period provides better results than the calibration period, with the exception of VE. All the goodness-of-fit scores are quite well constrained. It can be noted that VE_{avg} and PE_{avg} do not exceed 0.2, which means that the interannual variability of water volume and the discharge peak are reproduced accurately in the simulations. Overall, the simulations correspond to the range of the observations. Concerning variation in water availability, the main issue of this study, it can be noted that the simulated and observed values for cumulated discharge fit particularly well. This is an important result because it shows that the model is capable of providing simulations that are useful for water resource management.
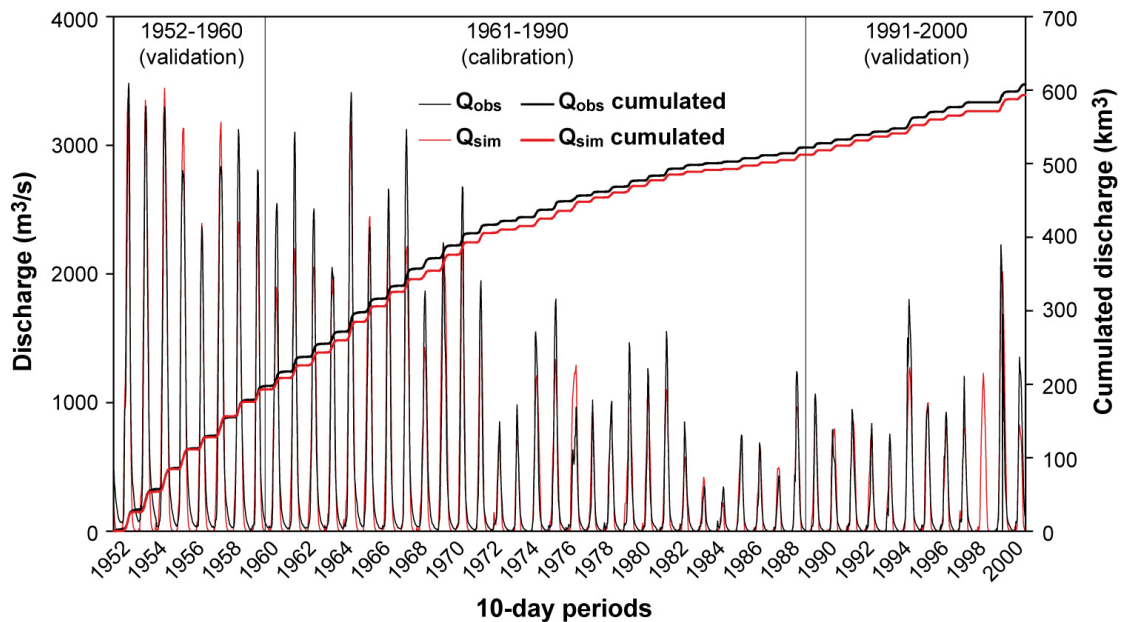
Fig. 3 Comparison of the observed and simulated hydrographs at the Douna gauging station over the 1952–2000 period.
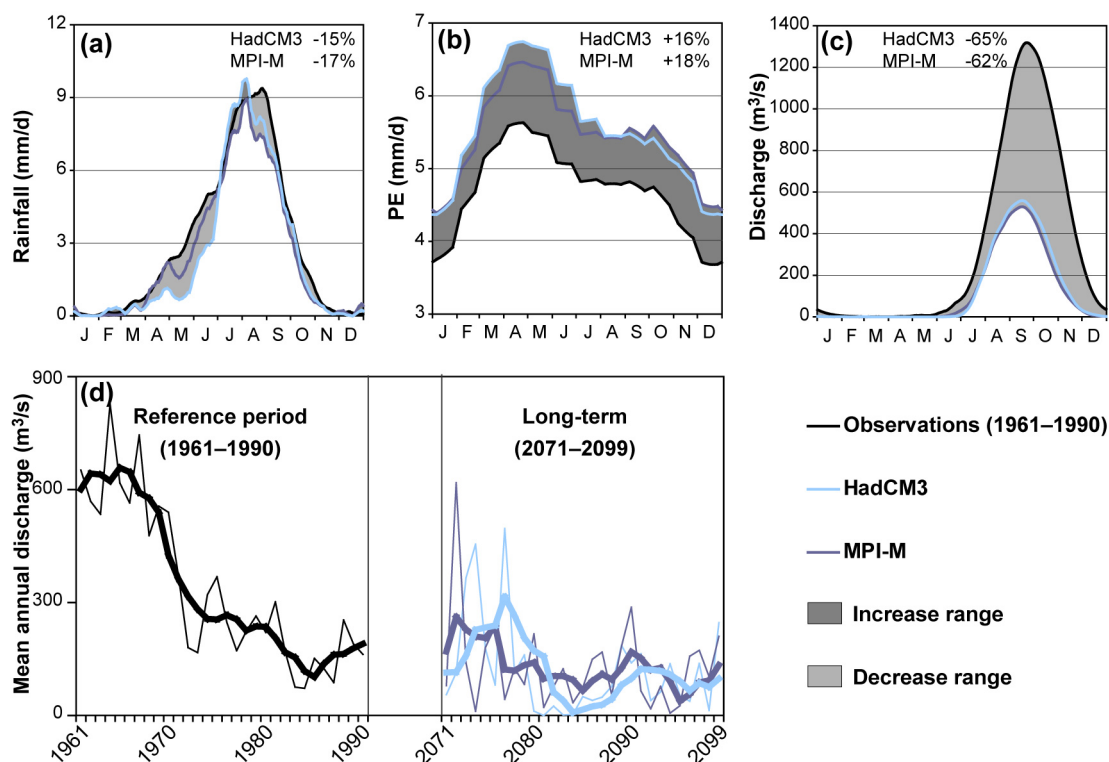
Future climatic trends

On the whole, rainfall as projected by HadCM3 and MPI-M decreases to 15–17% in the future relative to the reference observed period (Fig. 4(a)). This would reduce annual rainfall from 1081 mm/year (1961–1990 reference period) to 898–920 mm/year in the long term, depending on the GCM. Minor changes in seasonal rainfall dynamics can be observed. While rainfall regularly increases with an annual peak in August over the reference period, future rainfall trends indicate that a peak would appear at the end of April, and another at the beginning of August. The decrease is significant at the beginning of the rainy season (which comes in May–June instead of March–April) and also during the heart of the rainy season, despite a peak at the beginning of August. Both GCMs also predict an earlier end of the rains (mid-October instead of end-October). Not only does the beginning of the rains come late, but also the appearance of peaks in April and July–August does not compensate the loss of precipitated volume in the heart of the rainy season.

Both GCMs predict a continuing rise in temperature over the 21st century that may lead to a 5.1–5.7°C increase in the long term over the catchment. This warming would lead to a large increase (16–18%) in PE over the catchment (Fig. 4(b)). This would raise annual PE from 1723 mm/year (1961–1990 reference period) to 1995–2028 mm/year in the long term, depending on which GCM is considered. The PE values simulated by the two climatic models are similar in size, although those simulated by HadCM3 are slightly higher than those simulated by MPI-M from February to July. No modification of the seasonal dynamics of PE is observed: the lowest values are always in December–January and the highest in April–May. PE increases by a constant factor in every month of the year. This trend leads to July–October PE values that are comparable to those observed in April–May over the reference period.

The decline in rainfall accompanied by a PE increase in the long term thus shows an intensification of the trends observed since the late 1960s over the catchment.

Future hydrological trends

The projected rainfall deficit and continuing increase in PE suggest that runoff from the basin could be substantially reduced in the long term compared to the 1961–1990 reference period (Fig. 4(c)). The two models would lead to a similar decrease in discharge: when compared to the 1961–1990 reference period, the mean annual discharge would decline by 62–65% to only

Fig. 4 Future climatic and hydrological trends in the long term (2071–2099) over the catchment: (a) changes in seasonal rainfall cycle; (b) changes in seasonal PE cycle; (c) changes in seasonal regime of river flows from the catchment; (d) interannual variations in flows during the late 21st century (bold lines indicate a five-year moving average of the values). Percentages indicate the future variations in rainfall, PE and discharge when compared, respectively, to mean annual precipitation (1081 mm/year), mean annual PE (1723 mm/year) and mean annual discharge (340 m³/s) over the 1961–1990 period.

120–130 m³/s, depending on the GCM considered. This decrease is due to some extent to the increase in PE, but more significantly to the decrease in precipitated volumes during the rainy season. The hydrological simulations predict earlier peak floods (about 15 days) than in the reference period, which can be linked to the peaks of rainfall in July simulated by the climatic scenarios. A premature depletion phase is also projected because of the loss of precipitated volume at the end of the rainy season.

The interannual variations in flows (Fig. 4(d)) simulated with both GCMs in the long term are similar and remain within the range observed over the 1961–1990 period. The hydrological situation remains overdrawn with regard to the reference period. The levels of mean annual discharge would fall to the same levels (about 100–200 m³/s) as those observed during the severe drought of the 1980s.

CONCLUSION

This paper aimed to assess the possible evolution of water resources in the Bani catchment and has shown that: (i) the spatial and temporal variability of GCMs' simulations in West Africa necessitated adjustment of these series for use in impact studies; (ii) daily future climatic scenarios can be constructed with simple spatial and temporal downscaling methods; (iii) a daily conceptual hydrological model yielded high-quality simulations in a large West African catchment subject to considerable hydro-climatic variability. The paper also proposes hydrological scenarios in the long term in this catchment (changes in hydrological dynamics and in interannual discharge). The results indicate that the hydrological model simulates discharge efficiently enough in the reference period to be considered an appropriate model for the Bani catchment. It should not induce

substantial errors that would need to be taken into account. The future climatic trends simulated by the HadCM3 and MPI-M GCMs present the same patterns. Rainfall should decrease by 15–17% in the long term, while increasing temperature would induce a 16–18% increase in PE over the same horizon. The seasonal pattern of precipitation should change slightly, with a slower start of the rains and a loss of precipitated volume in the heart of the rainy season. In contrast, no modification of seasonal PE variability is expected. These conditions lead to the simulation of future discharge levels that are critical in terms of water availability for the end of the 21st century. Both GCMs predict a large reduction in runoff in the long term (62–65%), with a later beginning of the floods and an earlier depletion phase. Simulated flows were as low as the values observed during the severe drought of the 1980s.

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