Modelling the long-term impact of climate change on rainfall–runoff processes over a large Sudano-Sahelian catchment

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Abstract A conceptual hydrological model is implemented over the last 50 years on a large poorly gauged Sudano-Sahelian catchment. The purpose is to simulate the rainfall–runoff relationship over this period that has been subjected to important hydro-climatic changes. A calibration/validation exercise is performed via a lumped and semi-distributed model with a 10-day time step. Simulations based on fixed and variable parameters are compared through a multi-criteria analysis using a variety of goodness-of-fit indices. In the variable parameter option, the subsurface runoff and deep infiltration parameters are constrained by the spatio-temporal variability of a smoothed pluviometric index. The simulation results show that model efficiency is significantly improved by the integration of variable parameters. They also show a decrease of the simulated subsurface runoff and deep infiltration during the 1970s and the 1980s, which can be essentially attributed to the persistent rain deficit since the 1970s. This trend will have led to a drastic decrease of the deep water recharge and of base runoff contribution to flood composition.

Key words climate change; catchment behaviour; hydrological modelling; HydroStrahler; River Bani, West Africa

INTRODUCTION

The Sudano-Sahelian climate is controlled by a monsoon system that generates a particularly stable, well-marked seasonal precipitation cycle. Any rainfall deficit during the rainy season, even for a relatively short period, may have significant climatic and social consequences. Indeed, the rainy season (the only period where the evaporation demand can be satisfied) is a crucial period for replenishing water stores. For thousands of years, human populations have adapted to several long cycles of humid and dry periods. However, a substantial decline in rainfall has occurred over West Africa since the 1970s, and has led to an unprecedented period of persistent drought for nearly 40 years. The decrease in annual precipitation ranges from 15 to 30%, depending on the area (Nicholson *et al*., 1998; Le Barbé *et al*., 2002).

Large West African rivers have suffered severely from the drought, with runoff deficits exceeding the rainfall deficit by a factor of 2 on average (Servat *et al*., 1997). Paradoxically, small Sahelian hydrosystems have attenuated or even compensated for the rainfall deficit (Séguis *et al*., 2004). The mechanisms underlying these contrasted behaviours are far from fully understood. Hydrological modelling can help understanding of the impact of these changes on water resources, by representing the processes governing the links between climatic data and river flow regimes. In West Africa, the paucity of descriptive environmental data militates in favour of conceptual approaches for studying large poorly gauged catchments. Thus, hydrological regimes in data sparse regions can be evaluated with simple two-reservoir models, such as the HydroStrahler model (Billen *et al*., 1994). Despite its simplicity, this model was shown to be able to reproduce the rainfall–runoff relationship before the climatic divide with a high degree of realism on the Sudano-Sahelian Bani River catchment (Ruelland *et al*., 2008). However, a decrease in simulation quality was observed for periods after 1970. Obviously, the persistent rain deficits have led to lasting consequences for the hydrological cycle that are not accounted for accurately by the model (e.g. modifications in surface and infiltration conditions or groundwater refill). In fact, the model presented in Ruelland *et al*. (2008) uses constant parameters, accounting for average hydrological properties of the conceptual reservoirs over the whole simulation period. Given the extreme change in the hydro-climatic regime over the last 50 years, calibrating the model in an average sense over the complete period can be expected to hamper its predictive power. The question then arises whether constraining the model parameters via an indicator of climate change could improve model performance and thus provide a better insight into the impact of rainfall regime changes on runoff modifications.

This paper uses the assumption that a smoothed pluviometric index provides an accurate indicator of climate change. Consequently, two parameters of the HydroStrahler model are constrained with respect to this index. The ability of the rainfall–runoff model to simulate the behaviour of the Bani River catchment over the last 50 years is assessed by comparing simulations based on fixed and variable parameters. The aim is to model the water balance and its changes when subjected to climatic stress at various scales.

MATERIALS

Study area

The Bani River is the main tributary of the Niger River and is mainly located in southern Mali (Fig. 1). The confluence of the two rivers (each drains about 100 000 km^2) is situated at Mopti in the inner Niger Delta, which is a vital socio-economic centre. Consequently, any perturbation in the Bani catchment has an impact on the annual flood of the delta and its farming and economic activities. The watershed's topography is gentle, 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 located in deeper parts of the profiles. The natural vegetation is savannah woodland. Agricultural areas are growing rapidly due to demographic pressure. Typical crops are millet, sorghum, cotton, manioc and peanuts. The aquifers are fissured formations of low permeability, the basement being Birrimian mica-schists and metamorphic rocks in the southwest (60%) and Infracambrian sandstones in the northeast (40%). The downstream part of the basin is thus made of formations, the higher permeability of which can be expected to allow for a better support of low flows by groundwater (Brunet-Moret *et al*., 1986).

Hydro-climatic data

Daily rainfall series were established from 72 raingauge stations covering the basin. Over 1950–2000, an average of 65 stations per day (with a minimum of 39 stations) has been used to interpolate daily rainfall surfaces using the inverse distance weighted method, that proved to be optimally accurate among the classically available methods for data reconstruction (Ruelland *et al*., 2008). For potential evaporation data, a monthly grid provided by the Climatic Research Unit

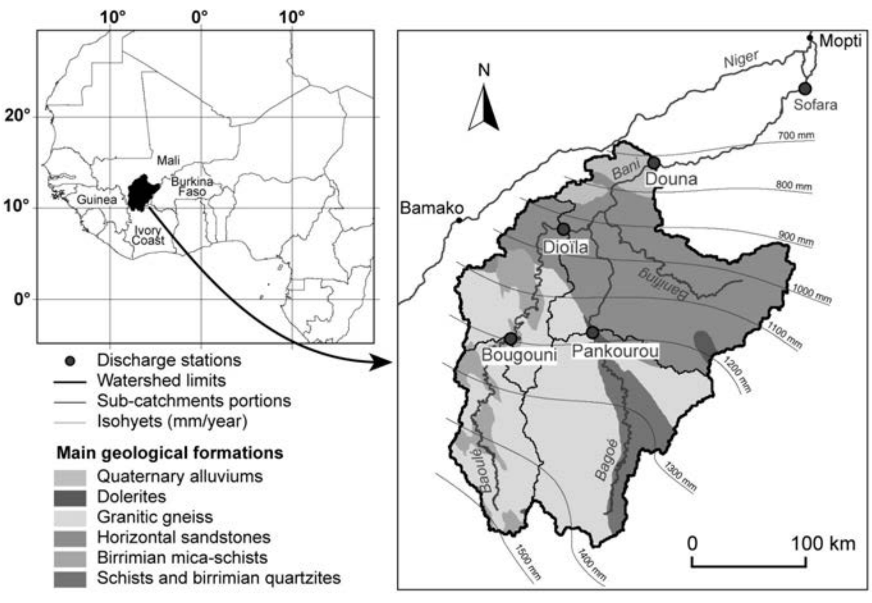

Fig. 1 The Bani catchment at Douna (104 000 km^2): hydrological and geological characteristics.

(CRU; UEA, UK) was used. This grid was obtained from approximately 100 stations spread over West Africa for the period 1950–2000. Potential evaporation was estimated using Penman's method and has been interpolated by the splines technique (New *et al*., 2000). Since potential evaporation presents few variations during the year, these monthly data have been converted into daily ones by dividing them by the number of days of each month. Lastly, four discharge gauging stations (Douna, Dioïla, Bougouni and Pankourou) corresponding to the sub-catchments of the Bani River were selected on the basis of the quantity and quality of the series available (Fig. 1). Some gaps have been completed using linear interpolations when the series had less than 30 daily gaps for a given year and when these gaps were relative to the rising or depletion phases. Although only the Douna station exhibited no gaps over 1952–2000 (except in 1998 and 1999), it was thus possible to establish 30-year series (1966–1995) with no gaps from the different gauging stations.

Hydrological processes

Located within a Sudano-Sahelian climatic regime, the Bani catchment is characterized by a strong climatic gradient (Fig. 1) with a single rainy season (average of 1085 mm/year spread between April and October). In contrast to rainfall, the annual average potential evaporation over the basin is 1850 mm/year and exhibits few variations during the year. As a result, the wet season corresponds to a short period during which the evaporation demand can be satisfied – a crucial period for replenishing surface and subsurface water stores. The steady decline in rainfall since 1971 had lasting effects on runoff. The flow observed at the Douna monitoring station fell by 68% between the 1952–1970 and 1971–2000 periods (Fig. 2(a)). Some of the low-water periods were severe, to the point where river flow at Douna stopped at times during the 1980s. This decrease in runoff time series is also found for the other discharge stations in the study area (67% for Dioïla, 61% for Pankourou, 56% for Bougouni). This change in the rainfall–runoff relationship might incorporate the effects of change in water table levels. However, due to the lack of data, the inter-dependence between the variation in groundwater discharge and the fluctuation of piezometric levels as well as the deep water recharge have not yet been studied in detail for this catchment. Regardless of time variations, it can also be noted that the specific runoff in the downstream Douna portion of the basin is characterized by a delay that could indicate a greater baseflow contribution as opposed to other portions (Fig. 2(b)).

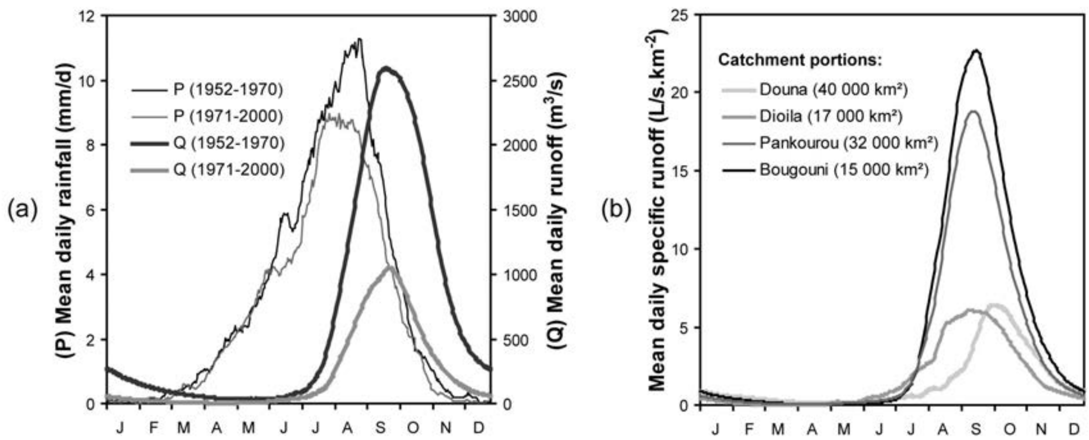

Fig. 2 (a) Hydro-climatic changes on the basin at Douna over the last 50 years; (b) Observed specific runoff for each intermediate portion of the catchment over 1966–1995.

METHODS

Hydrological model

In order to further explain the differences in mean specific discharge between the Bani sub-basins as well as their seasonal and inter-annual variations, we tried to relate the discharge to rainfall. In view of the data scarcity over the catchment, only a conceptual approach was possible. We chose to use the HydroStrahler model (Billen *et al*., 1994; Ruelland *et al*. 2008). This rainfall–runoff model considers two reservoirs in the watershed (Fig. 3): (i) a shallow (or soil) reservoir (SR), with short residence time, supplied by rainfall and feeding evaporation, surface/subsurface runoff and infiltration, and (ii) a deep (or groundwater) reservoir (DR), with longer residence time, fed by infiltration and the origin of the baseflow. The model involves four parameters: soil saturation content (*sat*) – above which all excess rainfall is evacuated as surface runoff, subsurface runoff rate (*ssrr*), deep infiltration rate (*infr*) and groundwater runoff rate (*gwrr*). These parameters must be calibrated for each catchment modelled, and make it possible to account for three sources of runoff: immediate, rapid and delayed runoff.

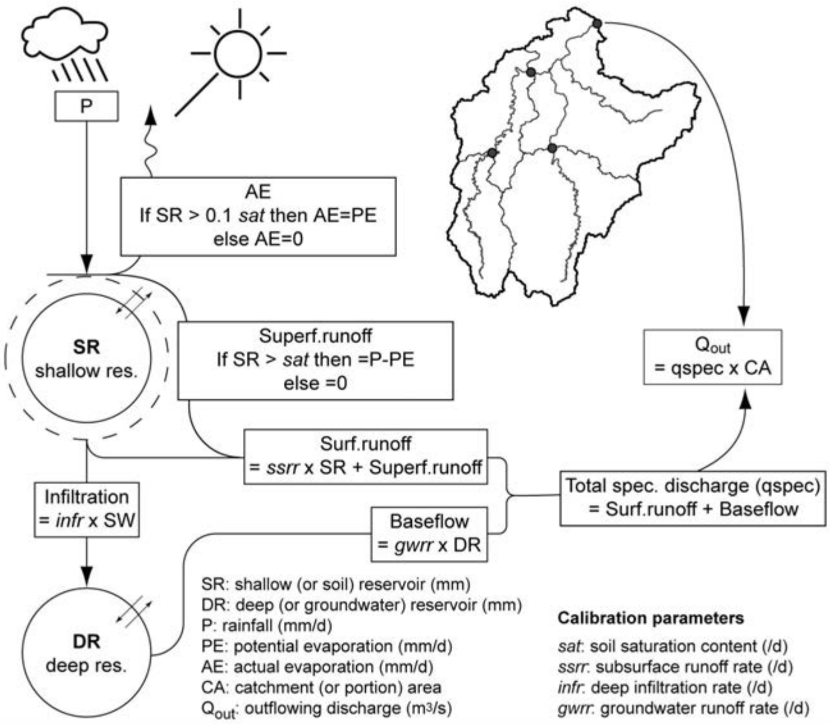

Fig. 3 Principle of the hydrological model (adapted from Billen *et al*., 1994, and Ruelland *et al*., 2008).

Model calibration and validation

A procedure was developed to automatically calibrate the model and calculate surface and groundwater runoff. For each catchment, the spatial average of daily rainfall and potential evaporation is calculated over the entire multiyear period considered. The model is then run with these data as inputs, while the four parameters are changed within a defined range. These systematic test runs aim at optimizing a given statistical criterion between the calculated and observed values of specific flows over the calibration period. In this study, the following objectives were considered: (i) a good agreement between the average simulated and observed catchment runoff volume; (ii) a good overall agreement of the shape of the hydrograph; (iii) a good agreement of the peak flows. In order to obtain a successful calibration by using automatic optimization routines, it is necessary to formulate numerical performance measures that reflect the calibration objectives (see e.g. Gupta *et al*., 1998; Madsen, 2000). This was done by considering the calibration problem in a multi-objective framework. The following numerical performance statistics (see e.g. Legates & McCabe, 1999) measure the different calibration objectives stated above:

– Nash, Nash-Sutcliffe coefficient (Nash & Sutcliffe, 1970):

$$\text{Nash} = 1 - [\sum_{t=1}^{N}\left(Q_{\text{obs},t} - Q_{\text{sim},t}\right)^2 / \sum_{t=1}^{N}\left(Q_{\text{obs},t} - \overline{Q_{\text{obs}}}\right)^2] \quad (1)$$

– VE, volume error:

$$\mathrm{VE} = (V_{\mathrm{obs}} - V_{\mathrm{sim}})/V_{\mathrm{obs}} = (\sum_{y=1}^{P} V_{\mathrm{obs},y} - \sum_{y=1}^{P} V_{\mathrm{sim},y}) / \sum_{y=1}^{P} V_{\mathrm{obs},y} \quad (2)$$

– $\mathrm{VE}_{\mathrm{avg}}$, annual average relative volume error:

$$\mathrm{VE}_{\mathrm{avg}} = \frac{1}{P} \sum_{y=1}^{P} (\left| V_{\mathrm{obs},y} - V_{\mathrm{sim},y} \right| / V_{\mathrm{obs},y}) \quad (3)$$

– $\mathrm{PE}_{\mathrm{avg}}$, annual average peak error:

$$\mathrm{PE}_{\mathrm{avg}} = \frac{1}{P} \sum_{y=1}^{P} (\left| Q^{\mathrm{peak}}_{\mathrm{obs},y} - Q^{\mathrm{peak}}_{\mathrm{sim},y} \right| / Q^{\mathrm{peak}}_{\mathrm{obs},y}) \quad (4)$$

where N and P are, respectively, the number of time steps and the number of years in the period, $Q_{\mathrm{obs},t}$ and $Q_{\mathrm{sim},t}$ are the observed and simulated discharge at time t, the $\overline{Q_{\mathrm{obs}}}$ is the average observed discharge over the period, $Q^{\mathrm{peak}}_{\mathrm{obs},y}$ and $Q^{\mathrm{peak}}_{\mathrm{sim},y}$ are the observed and simulated peak discharge for the year y, V_{obs} and V_{sim} are the total volumes of the observed and simulated hydrographs over the period, $V_{\mathrm{obs},y}$ and $V_{\mathrm{sim},y}$ are the volumes of the observed and simulated hydrographs for the year.

This multi-objective calibration problem was transformed into a single-objective optimization problem by defining a scalar objective function F_{agg} that aggregates the various objective functions:

$$F_{\mathrm{agg}} = (1 - \mathrm{Nash}) + \left|\mathrm{VE}\right| + \mathrm{VE}_{\mathrm{avg}} + \mathrm{PE}_{\mathrm{avg}} \quad (5)$$

Model calibration was then performed in a 4-D parameter space by searching for the minimum value of this aggregated function. Table 1 presents the parameter ranges tested for each simulation. As these calibration parameters are essentially theoretical, it is difficult to attribute physical values to them. Moreover, the lack of measurements on the study area would make this task very delicate. The parameter ranges were then established through many trial-and-error investigations. Besides, a second run around the optimized parameters obtained from the first run made it possible to refine the calibration.

Table 1 Ranges of calibration parameters tested with the model.

	sat (mm)			*ssrr* (d^{-1})			*infr* (d^{-1})			*gwrr* (d^{-1})		
	min	max	step	min	max	step	min	max	step	min	max	step
1st run	400	700	20	0.001	0.006	0.001	0.0001	0.002	0.0002	0.001	0.002	0.001
2nd run	400	700	10	0.001	0.006	0.0001	0.0001	0.002	0.0001	0.0001	0.025	0.0001

Two main strategies were considered for calibration/validation of the model:

– 10-day lumped modelling: the spatially distributed forcings are aggregated over the entire basin to be used in the lumped version of the model. The optimal parameter set is then estimated through calibration of the lumped model to simulate streamflow at the basin outlet.
– 10-day semi-distributed modelling: the values of Q used in equations (1)–(4) are the specific discharges for each of the sub-catchments. This strategy does not account for any transfer time between the upstream and downstream stations. However, analysis of the observed hydrographs indicates that such a transfer delay time is smaller than the 10-day simulation time step.

The 1950–2000 simulation period was divided in to three parts. Calibration was performed over the 20-year 1967–1985 period and validation was carried out over two 15-year periods. This choice is justified by many reasons. Firstly, the period 1967–1985 exhibits no gaps for any of the four gauging stations used; consequently the amount of information used for the semi-distributed calibration of the model is maximized. Secondly, the period 1967–1985 is characterized by a strong hydro-climatic variability, which is optimal in fitting variable parameters (see next subsection). Thirdly, the two validation periods exhibit contrasted climatic behaviours, the period 1952–1966 being humid and the period 1986–2000 being rather dry. Validation consisted in running the model with the parameters optimized during the calibration phase. Each simulation (both in calibration/validation phases) was preceded by a warm-up period of two years to eliminate the influence of any wrongly estimated initial conditions in the reservoirs of the model.

Variable hydrological parameters

In order to compare simulations based on fixed and variable parameters, additional calibration was performed on the basis of the fixed optimized parameters that were obtained over the calibration period. The subsurface runoff (*ssrr*) and deep infiltration (*infr*) rates parameters appeared to be particularly sensitive. Their evolution was thus constrained by the (spatio-)temporal variability of rainfall via a smoothed pluviometric index and an empirical adjusting function:

$$\text{Param}_y = \text{Param}_0 + I_y * \beta_{\text{Param}} \qquad \text{with} \qquad I_y = \frac{1}{3}\sum_{y=y-2}^{y}[(P_y - P_{\text{avg}})/\sigma_P] \tag{6}$$

where I_y is the smoothed pluviometric index for the year y, P_y the total annual rainfall for the catchment studied (or portion of intermediate catchment), P_{avg} the average rainfall over 1950–2000, σ_p is the observed standard deviation of rainfall over 1950–2000, Param_y is the annual parameter value based on the fixed-time calibrated parameter Param_0, and β_{Param} is the scaling parameter to be calibrated.

In the variable parameter version of the model, the scaling parameters β for *ssrr* and *infr* were calibrated using exactly the same 1967–1985 period as the fixed parameter version. The tested values ranged from 0 to 0.002 with a step value of 0.0001. The adjusting function thus made it possible to account for the rainfall variability and its consequences on basin behaviour, particularly when successive humid or wet years occurred. In the semi-distributed modelling, this variability was accounted for both spatially and temporally since rainfall statistics and calibration were computed for each catchment portion.

RESULTS AND DISCUSSION

Calibrated parameters

The Bani River catchment is a heterogeneous basin in terms of rainfall, vegetation, soil and geology distribution. Consequently, different parameter sets may be assumed *a priori* for each sub-catchment. Analysis of the optimized calibration parameters (Table 2) indicates that the catchment portions have indeed different hydrological properties, and shows that the lumped calibration parameters reflect an average aggregation of these various properties. Thus, it is observed that: (i) the soil saturation content (*sat*) increases between the downstream and upstream portions, which may partly be linked to an (expected) increase in soil water-holding capacity due *inter alia* to the increased density of vegetation from north to south; (ii) the subsurface runoff rate (*ssrr*) also increases from north to south in line with the rainfall increase along the climatic gradient; (iii) the infiltration rate (*infr*) is at the minimum set for each portion (0.0001) except for the Douna downstream portion (0.0019); (iv) the groundwater runoff rate (*gwrr*) dramatically decreases between the downstream and upstream portions: these differences in *infr* and *gwrr* parameters' values tend to indicate that, whereas groundwater generally contributes little to runoff in the upstream portions, base runoff has a much more important contribution to the annual flood elaboration in the Douna downstream portion. This can also be seen in the observed specific runoff for each catchment portion (Fig. 2(b)) and may be explained by the differences in hydrodynamic properties of the sub-basin aquifers link with the geological characteristics in the catchment (Fig. 1).

Analysis of the scaling parameters (β_{ssrr} and β_{infr}) obtained after calibration shows that these values depend on the base values for the different sub-basins (Table 2). Where the initial fixed values of *ssrr* and *infr* are large, the variation to be applied is also rather high. In other words, the automatic calibration procedure looked for variations of the parameters that highly influenced the flood composition; such parameters are the subsurface runoff (*ssrr*) or the deep infiltration (*infr*) rates depending on the sub-basins. Here again, scaling parameter values obtained through calibration of the lumped model reflect a mean behaviour in line with intermediate sub-basins properties.

Table 2 Lumped (LP) and semi-distributed (SD) calibrated parameters over 1967–1985.

Catchment	*sat* (mm)	*ssrr* (d^{-1})	*infr* (d^{-1})	*gwrr* (d^{-1})	β_{ssrr}	β_{infr}
Douna (LP)	490	0.0034	0.0002	0.0210	0.0014	0.0012
Douna portion (SD)	450	0.0010	0.0019	0.0250	0.0000	0.0015
Dioïla portion (SD)	430	0.0023	0.0001	0.0080	0.0010	0.0013
Pankourou portion (SD)	490	0.0036	0.0001	0.0001	0.0018	0.0000
Bougouni portion (SD)	680	0.0033	0.0001	0.0001	0.0013	0.0000

Model efficiency

Table 3 shows the efficiency of the simulations according to the goodness-of-fit scores obtained in the calibration and validation phases. Comparing the efficiency values between fixed and variable parameter-based simulations reveals several trends. First, in the lumped application of the model, all the efficiency values are systematically and significantly improved by the use of variable parameters. This is true for both the calibration and validation phases. Second, moving from a lumped to a semi-distributed strategy does not improve the simulated hydrograph at the outlet. On the contrary, the semi-distributed model generally yields poorer results. This was not expected at first because the semi-distributed model gives a better account of the local hydro-climatic conditions over each of the sub-basins. However, the flow series have been generated for each catchment portion between the gauging stations by using basic subtractions. Since series from different stations are used, errors due to the gauging calibration curves may have cumulated themselves. Moreover, subtracting the hydrographs does not account for hydrograph time lag and deformation between the stations. Despite all these uncertainties, semi-distributed aggregated results at the catchment outlet still show a rather good agreement with the observed flows for the modelling based on variable parameters (in contrast with simulations based on fixed parameters).

Comparison of the hydrographs obtained at the Douna station with fixed or variable parameters (Fig. 4) also shows that variable parameter-based simulations improve the simulated streamflow at the outlet. Over the whole 1952–2000 simulation period, all the goodness-of-fit scores are improved by the adjustment to the smoothed pluviometric index for both the lumped and semi-distributed model versions. In particular, Nash values are larger than 88% over the 50-year period. This indicates that the simulated flows correspond closely to observed flows and that

Table 3 Goodness-of-fit scores for the various simulations: (LP) lumped and (SD) semi-distributed.

		1952–1966 (validation)				1967–1985 (calibration)				1986–2000 (validation)			
Goodness-of-fit criterions		Nash	VE	VE_{avg}	PE_{avg}	Nash	VE	VE_{avg}	PE_{avg}	Nash	VE	VE_{avg}	PE_{avg}
Fixed parameters	**Douna (LP)**	**76.7%**	**+0.32**	**0.31**	**0.39**	**81.9%**	**–0.02**	**0.28**	**0.26**	**78.8%**	**–0.27**	**0.50**	**0.27**
	Douna portion (SD)	50.0%	+0.32	0.31	0.54	57.3%	+0.00	0.44	0.32	22.7%	–0.62	0.85	0.43
	Dioïla portion (SD)	47.7%	+0.29	0.34	0.50	59.2%	–0.03	0.43	0.46	14.4%	–0.54	1.05	0.73
	Pankourou portion (SD)	61.5%	+0.25	0.25	0.52	70.7%	–0.13	0.45	0.27	74.0%	–0.06	0.41	0.25
	Bougouni portion (SD)	61.3%	+0.24	0.26	0.44	70.3%	–0.06	0.26	0.35	70.4%	–0.19	0.59	0.29
	Douna – total (SD)	**71.1%**	**+0.29**	**0.28**	**0.33**	**78.2%**	**–0.09**	**0.37**	**0.26**	**77.7%**	**–0.31**	**0.56**	**0.22**
Variable parameters	**Douna (LP)**	**94.2%**	**+0.00**	**0.06**	**0.13**	**90.2%**	**–0.01**	**0.16**	**0.21**	**89.3%**	**+0.05**	**0.17**	**0.18**
	Douna portion (SD)	70.3%	+0.08	0.11	0.42	63.1%	+0.09	0.32	0.34	52.2%	–0.29	0.33	0.18
	Dioïla portion (SD)	73.9%	–0.05	0.37	0.26	66.4%	+0.03	0.27	0.35	34.3%	–0.20	0.73	0.70
	Pankourou portion (SD)	76.9%	+0.11	0.16	0.39	77.1%	–0.09	0.29	0.25	67.9%	+0.22	0.22	0.44
	Bougouni portion (SD)	70.6%	+0.09	0.19	0.45	72.1%	–0.07	0.20	0.34	70.3%	+0.09	0.17	0.40
	Douna – total (SD)	**88.2%**	**+0.07**	**0.09**	**0.24**	**85.4%**	**–0.06**	**0.20**	**0.23**	**84.7%**	**+0.01**	**0.19**	**0.26**

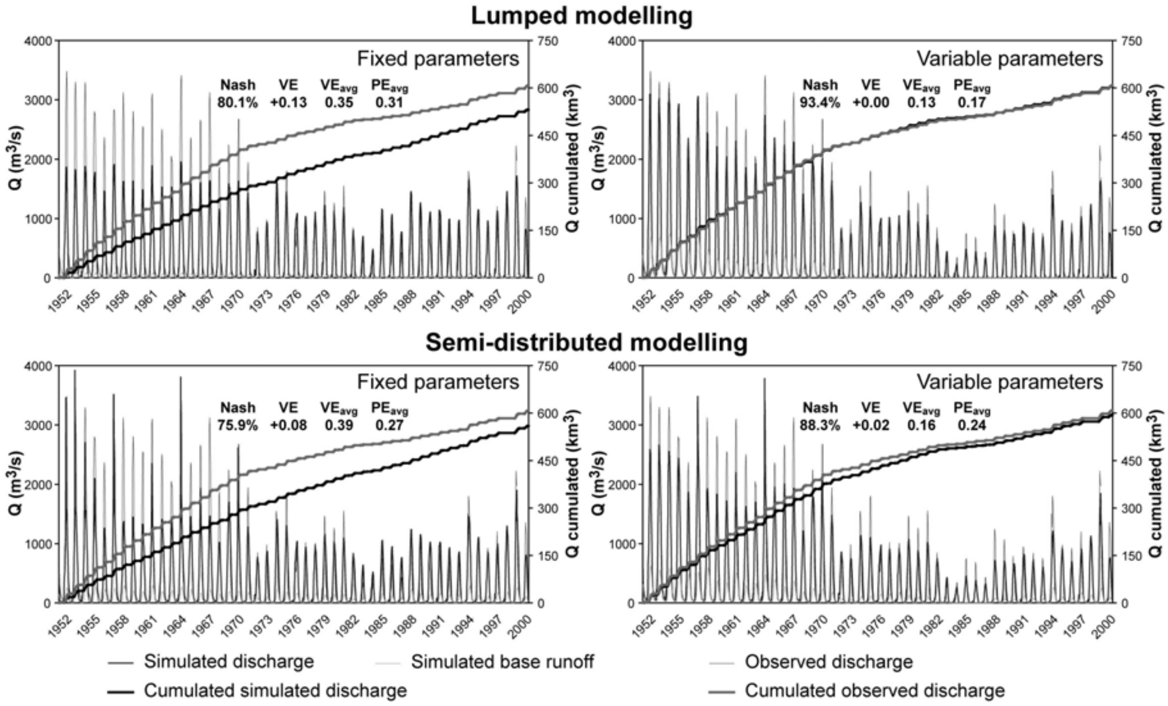

Fig. 4 Comparison of the hydrographs obtained at the Douna station from 10-day lumped and semi-distributed modelling with fixed or variable parameters; goodness-of-fit scores correspond to the whole 1952–2000 period.

the model fits the rainfall–runoff relationship rather well during both wet and dry periods. With this approach, the simulated base runoff is shown to drastically decrease, particularly in the 1970s and 1980s.

Water levels in the model reservoirs

As the lumped modelling based on variable parameters had provided the best efficiency according to the goodness-of-fit scores, it served to analyse the variations of the water levels in the model reservoirs (SR and DR, see Fig. 3) over 1952–2000 (Fig. 5). It should be noted that these reservoirs are conceptual; therefore, only their relative variations through time may have a potential meaning. Several observations can be made. Firstly, river discharge is mostly composed by surface runoff. Since the SR saturation level (calibrated value of 490 mm, Table 2) is never reached, the simulated surface runoff is only composed by a rapid (or subsurface) runoff and according to the model, immediate surface runoff never occurs. This can probably be explained by the necessary time-transfer of both surface and subsurface water fluxes at the considered scale. Secondly, the SR water level presents important variations over the studied period; this can strongly be linked to the inter-annual rainfall variability (R^2 = 0.69). Lastly, it appears that the DR water levels would have undergone a huge decrease from the 1960s and would have practically never contributed anymore to the flood composition since 1973. This trend may be seen as unrealistic; however, the semi-distributed modelling provides a less pronounced decrease of base runoff that substantially contributes to the flood in the 1990s (Fig. 4). Nevertheless, there is apparently a strong relation between the overall decrease in water table levels and the exceptional severe low-water periods in the 1980s. Olivry (1996) has reported that the depletion coefficient has increased since the 1970s over the catchment. This increase tends to show a faster groundwater emptying, and might also be linked to a significant and durable impoverishment of the water tables. Simulating the basin functioning via a conceptual long-term approach then makes it possible to reinforce the assumption that this impoverishment would be the origin of the gap between the rain deficit and the larger decrease in the basin's discharge. Indeed, low flows are

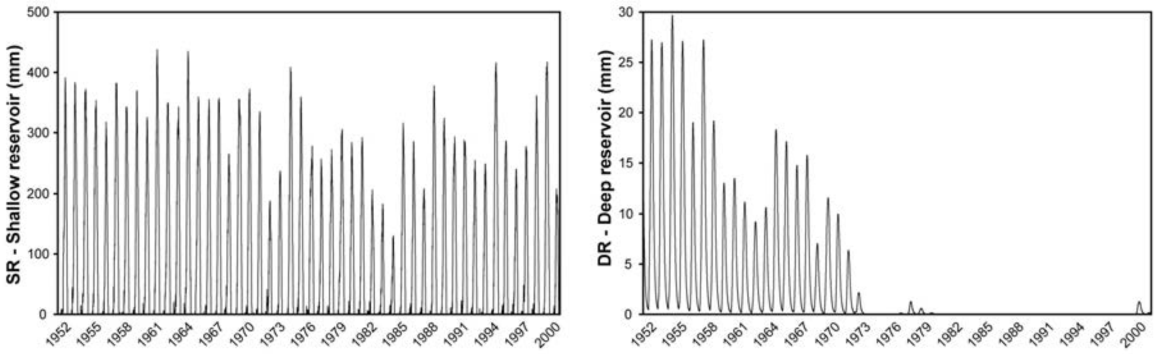

Fig. 5 Variations of the water levels in the model reservoirs (SR and DR) over 1952–2000.

generally related to the aquifer rising above the stream network. This occurs only if the water tables have been recharged during the wet season. The persistent rain deficit observed from the 1970s would have then entailed modifications in aquifer response because groundwater stocks were insufficiently refilled.

CONCLUSION

This paper details the preliminary results of a modelling strategy developed over the last 50 years on a large poorly-gauged Sudano-Sahelian catchment. This approach relies on a compromise between the availability of data, the large spatio-temporal scale considered and our limited ability to represent hydrological processes in order to: (i) correctly represent the discharge variations on a tropical data sparse catchment; and (ii) investigate the key functioning processes that may have led to the drastic runoff decrease since the early 1970s.

Model efficiency was assessed from the sub-basin scale to the catchment scale using semi-distributed and lumped approaches. Hence, we have taken advantage of all information provided at the best gauging stations in the basin. The overall good agreement between the simulations based on variable adjusted parameters and the observed flows at the basin outlet supports several general hydrological assumptions: (i) river discharge is mostly composed of surface flows from the top few metres of the soil; (ii) an aquifer exists in the downstream part of the basin and contributes an essential part of baseflow to the annual flood at the outlet; (iii) the drastic decrease in runoff in the 1970s and 1980s can essentially be attributed to the persistent rain deficit over the catchment since the 1970s: this trend would have led to a decrease of the deep water recharge and of base runoff to the annual flood composition. Furthermore, noticeable robustness of the simulations based on rainfall-index-adjusted parameters means the model can be applied in various conditions in the catchment since its validation proved to be satisfactory during both humid and dry periods. Thus, the model offers an original and fairly robust structure allowing its prospective use based on mid-term climatic scenarios over the basin.

However, it should be noted that a number of limitations still preclude a reliable application of the model to highly non stationary climatic and anthropogenic conditions, for a number of reasons. Firstly, some of the modelling assumptions remain unverifiable, namely: (i) the absence of immediate surface runoff at the catchment scale (most of the runoff being simulated by the model through the subsurface runoff), (ii) the differences in the hydrological characteristics of the shallow and deep reservoirs between the upstream portions of the basin and the downstream ones, and (iii) the absence of water withdrawals that could, however, also explain some losses in the stream or in the groundwater. Secondly, the model cannot be forced using land cover change scenarios, because vegetation is not explicitly taken into account in model parameterization. However, recent remote sensing studies (Ruelland *et al*., 2009a,b) indicate that the downstream Sahelian part of the catchment has undergone drastic cropland expansion and deforestation since the 1960s. These changes in vegetation cover may have had an impact on runoff since surface features might have been altered (D'Herbès & Valentin, 1997). Nevertheless, in the most productive sub-basins (in the upstream part), relatively small changes in land cover have been observed due to a weaker demographic pressure and a greater regeneration capacity of the natural environment (Ruelland *et al*., 2009b).

Lastly, the model process representation, as presented in this paper, is currently being improved via the use of additional environmental forcing data. Since hydrological variability is essentially driven by the spatio-temporal variability of rainfall (as shown in this paper) but may also partly be explained by the modifications in runoff and infiltration conditions due to land cover changes, we believe it is possible to account for these two sources of variability through the assimilation of satellite imagery data. Instead of using a smoothed rainfall index, monthly vegetation indices from low-resolution data will be integrated in order to adjust the model to climate and land-use changes in the basin. Comparing the improvement of such an approach over the currently developed one will allow the sufficiency of the smoothed pluviometric index as an indicator of climate variability to be identified.

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