Global Change: Facing Risks and Threats to Water Resources (Proc. of the Sixth World FRIEND Conference, Fez, Morocco, October 2010). IAHS Publ. 340, 2010.

A comparison of two conceptual models for the simulation of hydro-climatic variability over 50 years in a large Sudano-Sahelian catchment

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Abstract Environmental and climatic changes have occurred in western African regions over many decades. These changes, which are variable in space and time, can have lasting effects on water resources. Hydrological modelling can help to assess the impact of these changes by representing the processes governing the relationship between climatic data and river flow regimes. This paper compares two reservoir-based hydrological models (HydroStrahler and GR4J) operating on a daily time step. The models are tested over an approx. 50-year period in a large, poorly gauged Sudano-Sahelian catchment that has undergone significant hydro-climatic variability. A calibration/validation exercise is performed using lumped and semi-distributed approaches. The simulations are compared via a multicriteria analysis based on a variety of goodness-of-fit indices. Both models simulate the rainfall–runoff relationship over the catchment area with a fair degree of realism. Given the calibration strategy, the flood dynamics are better reproduced using the HydroStrahler model, while the GR4J model gives a more accurate estimate of cumulated discharge. The semi-distributed approach allows for a better representation of the hydrological processes within the watershed, which does not necessarily lead to improved outlet simulations compared to the lumped approach. A sensitivity analysis of the parameters also shows that equifinality problems are reduced when the calibration is considered within a multiobjective framework. Furthermore, the robustness of the simulations indicates that the models can be applied to various climatic conditions. The performance indexes prove satisfactory in validation periods containing either wet or dry spells. As a result, these models can be used to forecast future water availability using mid-term climatic scenarios in the basin.

Key words rainfall–runoff modelling; hydro-climatic variability; hydrostrahler; GR4J; spatialization; sensitivity; River Bani

INTRODUCTION

The severe drought that West Africa has endured over the last 40 years has had significant hydrological impacts. It is well established that the decrease in mean annual discharge of the region's largest rivers has sometimes doubled the decrease in rainfall for the 1970–2000 period (see e.g. Lebel *et al.*, 2003; Andersen *et al.*, 2005). For example, since the 1970s, the Bani River (the main tributary of the Niger River) has undergone drastic decreases in runoff (around 68%) compared with the 1950–1960s (Ruelland *et al.*, 2009). Among the main western African river systems, a deficit of this magnitude has only ever been observed in the Senegal catchment (Servat *et al.*, 1997). The reduction of water resources constitutes one of the main factors limiting development in those areas. The flood of the inner Niger delta, fed by the Niger River and the Bani River, has decreased dramatically (Mariko, 2003) and led to deterioration in living conditions for fishermen, farmers and herdsmen who depend on annual floods. Over one million people live off the delta's resources, and the social balance is threatened by the declining floods (Marie *et al.*, 2007). This is extremely worrying for the local populations, even more so due to demographic growth that has been accelerating in the last decades.

Facing the global changes that particularly affect the region requires further insight into the flow phenomena in upstream catchments of the delta and improved capacity of environmental risk forecasting. Hydrological modelling can give us a greater understanding into the impact of the changes on water resources, by representing the processes governing the relationship between climatic data and river flow regimes. Before a model can be used to make predictions it must be adapted to various climatic conditions. For this purpose, a wide spatiotemporal scale is recommended. In West Africa, the paucity of descriptive data on such a scale militates in favour of

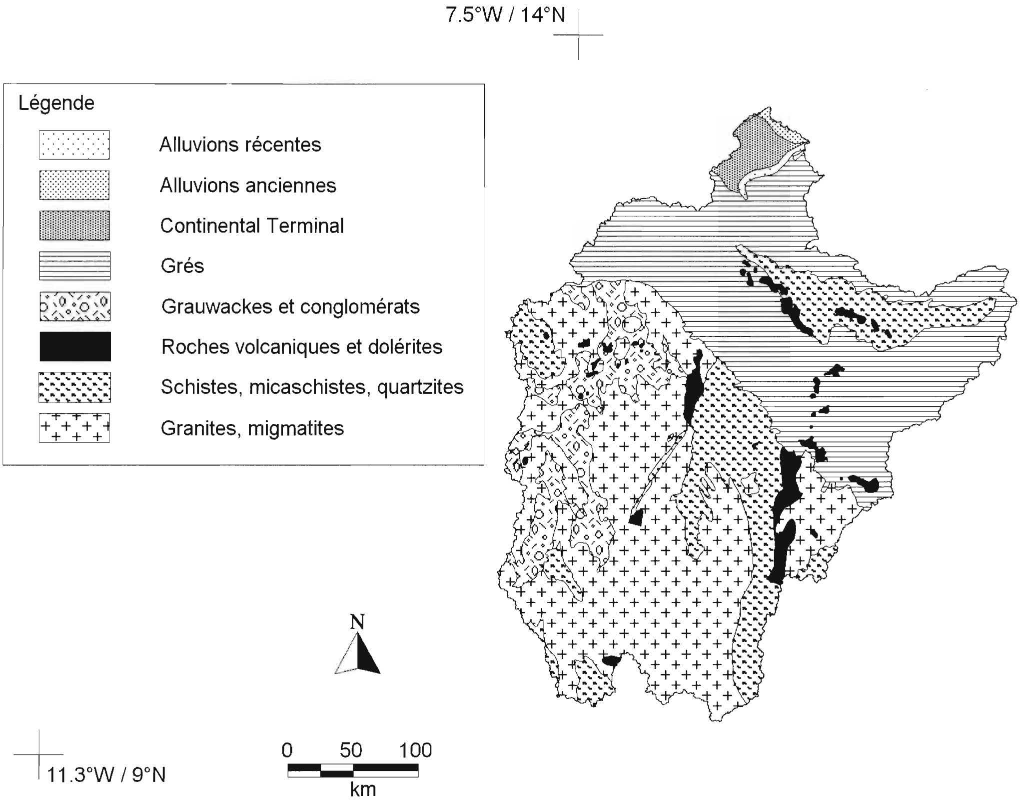

Fig. 2 Carte géologique du bassin du Bani à Douna (d'après DNGM *et al.*, 1980; Brunet-Moret *et al.*, 1986).

caractère aléatoire ou non de la série (Kendall & Stuart, 1943), le test de Pettitt (Pettitt, 1979) teste la présence ou l'absence de rupture (changement de moyenne au sein de la série) et fournit une date de rupture, la procédure de segmentation (Hubert *et al.*, 1989) est une méthode appropriée à la recherche de multiples changements de moyenne.

Pour ce qui est de l'analyse pluviométrique, les tests ont concerné des séries de cumuls annuels et mensuels. Des calculs d'indices pluviométriques, de variation relative de cumuls de pluie, de profils pluviométriques journaliers et de caractéristiques des pluies journalières (date et jour pluvieux) complèteront cette analyse.

Pour ce qui est de l'analyse des écoulements, les tests ont concerné des modules annuels et mensuels et des débits caractéristiques des différentes phases de l'hydrogramme de crue: débits maximum et minimum (Qmax et Qmin), débits égalés ou dépassé 10 jours et 355 jours par an (DCC et DCE), débits égalés ou dépassés 1, 3, 6 et 9 mois par an (DC1, DC3, DC6 et DC9) , débits moyens maxima annuels de 5 et 30 jours consécutifs (VCX5 et VCX30), débits moyens minimum annuel de 60 jours consécutifs (VCN60). Des calculs de variabilité relative complèteront cette analyse.

Analyse pluviométrique

52 stations ont été retenues pour une analyse de leurs séries annuelles et mensuelles d'après les critères suivants: stations situées à l'intérieur ou à moins de 150 kms du bassin sans lacunes et dont les séries débutent avant 1960 et se terminent après 1980.

L'analyse des résultats des tests ou procédures statistiques révèle que l'ensemble du bassin du Bani a été touché par une diminution de sa pluviométrie annuelle et mensuelle mais à des degrés

Located in a Sudano-Sahelian climatic regime, the Bani catchment 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, the flow at the Douna gauging station fell by 68% between 1952–1970 and 1971–2000, 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. This decrease in runoff time series is also found at other discharge stations in the study area (67% for Dioïla, 61% for Pankourou, 56% for Bougouni).

MATERIALS AND METHODS

Hydrological models

In order to represent the seasonal and inter-annual variations in runoff from the catchment, discharge was linked to rainfall. In light of the data scarcity in the catchment, a conceptual approach was favoured. Two rainfall–runoff models were compared: the HydroStrahler model (Billen *et al.*, 1994; Ruelland *et al.* 2008, 2009) and the GR4J model (Perrin *et al.*, 2003). Using daily rainfall/PE data, these models represent, in a simplified manner, the flow processes in a catchment and make it possible to simulate runoff at its outlet with a daily time step.

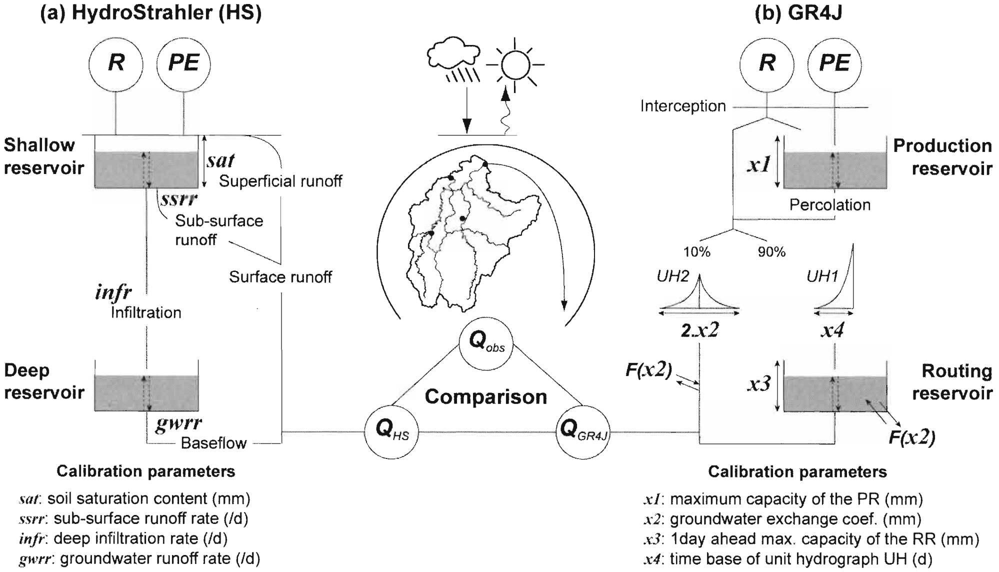

Fig. 2 Schemes of (a) HydroStrahler (after Ruelland *et al.*, 2009) and of (b) GR4J (adapted from Perrin *et al.*, 2003) (*R*: rainfall; *PE*: potential evapotranspiration; *Q*: streamflow).

HydroStrahler takes into account two reservoirs in the watershed (Fig. 2(a)): (i) a shallow reservoir, with short residence time, supplied by rainfall and feeding evaporation, surface/subsurface runoff and infiltration, and (ii) a deep reservoir, with longer residence time, fed by infiltration and generating the baseflow. The model involves four parameters as shown in Fig. 2(a). These parameters need to be calibrated for each catchment being modelled in order to account for three sources of runoff: immediate, rapid and delayed runoff.

GR4J simulates runoff *via* two functions (Fig. 2(b)). First, a production function that accounts for rainfall (net rainfall) and evapotranspiration, determines the rainfall fraction (effective rainfall) participating to flow and supplying the production reservoir (interception and percolation). Next, a routing function calculates runoff at the catchment outlet. The water quantity feeding the routing part of the model is then made up from the percolation added to the water remaining fraction. This flow is then divided into two fractions: (i) 90% compose a rapid runoff that is routed through a unit hydrograph (UH1) and a routing reservoir; (ii) 10% are attributed to a more delayed runoff that is routed through a unit hydrograph (HU2). The objective of the unit hydrographs is to account for differences in runoff delays between the two conceptual reservoirs. GR4J also requires the calibration of four parameters as shown in Fig. 2(b).

Hydro-climatic data

Daily rainfall series were derived from 72 raingauges covering the area (Fig. 1). During the 1950–2000 period an average of 65 gauges per day (with a minimum of 39) was used to interpolate daily rainfall maps by the inverse distance weighted method that proved to be optimally accurate among the classically available methods for data reconstruction in the given context (Ruelland *et al.*, 2008). Potential evapotranspiration (PE) forcing consisted of monthly maps (Fig. 1) produced by the Climatic Research Unit (University of East Anglia, UK) from about 100 stations spread over West Africa, using Penman's method and spline interpolation (Mitchell & Jones, 2005). Since PE presents low variations during the year, monthly data were disaggregated evenly to the daily time step within 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 number and quality of the time series available (Fig. 1).

Model calibration and validation

A procedure was developed to automatically calibrate the models and to calculate runoff. For each catchment, the spatial average of daily rainfall and PE is calculated over the entire multiyear period under examination. The models were then run with these data as inputs, while their respective four parameters were changed within a defined range. These systematic test runs aimed to optimize a given statistical criterion between the calculated and observed values of specific flows over the calibration period. In this study, the following criteria 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 was necessary to formulate numerical performance measures that reflect the calibration objectives. This was done by considering the calibration problem in a multi-objective framework (see Madsen, 2000; Ruelland *et al.*, 2009). The following numerical performance statistics measure the different calibration objectives stated above:

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

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

- VE, volume error:

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

- VE_{avg}, annual average relative volume error:

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

- PE_{avg}, annual average peak error:

$$\text{PE}_{\text{avg}} = \frac{1}{P} \sum_{y=1}^{P} (|Q_{\text{obs},y}^{\text{peak}} - Q_{\text{sim},y}^{\text{peak}}| / Q_{\text{obs},y}^{\text{peak}}) \qquad (4)$$

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

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

$$\mathrm{F}_{\mathrm{agg}} = (1 - \mathrm{Nash}) + |\mathrm{VE}| + \mathrm{VE}_{\mathrm{avg}} + \mathrm{PE}_{\mathrm{avg}} \tag{5}$$

Model calibration was then performed in a 4-D parameter space by searching for the minimum value of this aggregated function. Two main strategies were considered for calibration/validation of the models:

- 10-day lumped modelling: spatially-distributed forcings are aggregated over the entire basin for use in the lumped version of the models. The optimal parameter set is then estimated by calibrating 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, an 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 into three parts. Calibration was performed for a 20-year period (1967–1985) and validation was carried out over two 15-year periods. This choice was made for several reasons. First, the period 1967–1985 exhibited no data gaps for any of the four reference gauging stations; consequently the amount of information used for the semi-distributed calibration of the model was maximized. Secondly, the two validation periods are distinguished by contrasted climatic behaviours, the period 1952–1966 being wet and the period 1986–2000 being rather dry, which allowed the models to be tested for their suitability in differing climatic situations. Validation consisted of running the models with the parameters optimized during the calibration phase. The first two years of simulations (both in calibration/validation) were used as a model warm-up to eliminate the influence of initial conditions in the models' reservoirs.

RESULTS

Efficiency of the models

A comparison of the efficiency of the models is summarised in Table 1 and Fig. 3. Goodness-of-fit scores are rather good for both the calibration and validation phases, even if they tend to deteriorate slightly during the validation periods for both models (Table 1). Over the whole 1952–2000 simulation period, HydroStrahler gives better results in lumped mode (values of Nash index of 88% *vs* 81% in semi-distributed mode) while better performances are observed for the semi-distributed application of GR4J (83% *vs* 79% in lumped mode). Nevertheless, simulations based on HydroStrahler seem to more accurately represent the hydrograph shape regardless of the chosen mode used for spatial discretization of the catchment. In particular, simulations based on GR4J tend to shorten the flood event by making the flood ascent phase begin too late and the depletion phase start too early (Fig. 3).

Figure 4 illustrates these observations in greater detail. Indeed, an analysis of annual scores of the aggregated objective function (extracted from simulations with both models) confirms that in lumped mode, HydroStrahler is more accurate than GR4J (the obtained values being mainly situated below the first bisector). However, for the most recent years (1986–2000), which are also among the driest, GR4J tends to give results that correspond with those of HydroStrahler. However, in semi-distributed mode, this graph confirms that GR4J is more accurate than HydroStrahler for both validation periods.

Table 1 Goodness-of-fit scores for the various simulations: (LP) lumped and (SD) semi-distributed models.

		1952–1966 (validation)					1967–1985 (calibration)					1986–2000 (validation)				
	Goodness-of-fit criterions	Nash	VE	VE_{avg}	PE_{avg}	F_{agg}	Nash	VE	VE_{avg}	PE_{avg}	F_{agg}	Nash	VE	VE_{avg}	PE_{avg}	F_{agg}
HS	Douna (LP)	87%	+0.27	0.26	0.25	0.9	88%	+0.00	0.23	0.22	0.6	81%	–0.24	0.45	0.32	1.2
	Douna (SD)	77%	+0.29	0.29	0.31	1.1	84%	–0.03	0.27	0.22	0.7	84%	–0.25	0.46	0.22	1.1
GR4J	Douna (LP)	76%	+0.17	0.18	0.25	0.8	82%	+0.00	0.22	0.26	0.7	70%	–0.26	0.67	0.52	1.7
	Douna (SD)	81%	+0.23	0.23	0.14	0.8	82%	+0.00	0.24	0.16	0.6	85%	–0.18	0.39	0.25	1.0

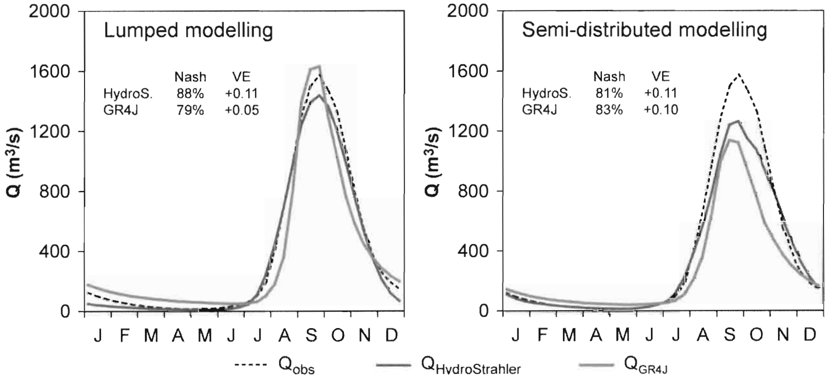

Fig. 3 Comparison of the mean observed and simulated hydrographs at the Douna station for both models over 1952–2000 (goodness-of-fit scores correspond to the whole 1952–2000 period).

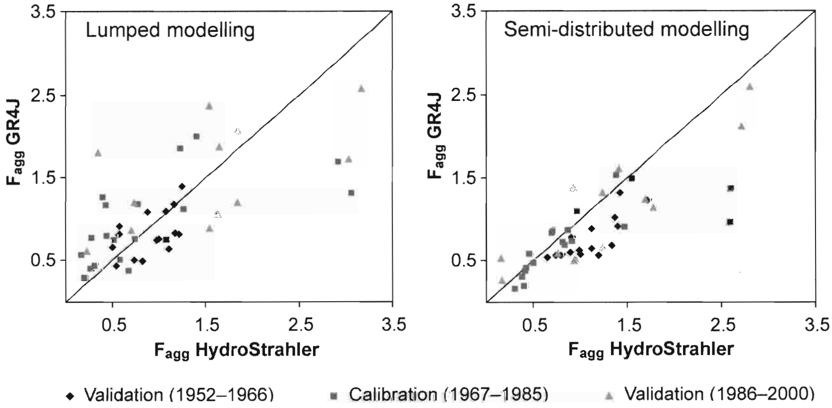

Fig. 4 Annual results of the scalar objective function F_{agg} at the Douna station for both models.

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. The analysis of the optimized calibration parameters (Table 2) confirms that the catchment portions have different hydrological properties, and shows that the lumped calibration parameters (for both models) reflect an intermediate level of these various properties.

In the case of HydroStrahler, it is observed that the soil saturation content (*sat*) increases between downstream and upstream portions, which may be partly linked to an (expected) increase in soil water-holding capacity due *inter alia* to the increased density of vegetation from north to south. The subsurface runoff rate (*ssrr*) also increases from north to south in line with the climatic gradient: as the rain intensifies, more water is available to flow through the shallow reservoir. In fact, rainfall is more significant in the upstream sub-basins (Bougouni, Pankourou), which explains their major contribution to the annual flood. In contrast, the infiltration rate (*infr*) and most importantly the groundwater runoff rate (*gwrr*) drastically decrease between downstream and upstream portions: water flows rapidly through the surface horizons in the upstream sub-basins in contrast with the downstream Douna portion where base runoff has a much more important contribution to the specific discharge. This can be explained by the differences in hydrodynamic properties of the sub-basin aquifers as a result of the geological characteristics in the catchment (Ruelland *et al.*, 2009). In the same way, with GR4J, the capacity of the production reservoir (*x1*) increases between downstream and upstream portions while the 1-day capacity of the routing reservoir (*x3*) decreases. Once again, the behaviour of these parameters can be explained by the limited contribution of baseflow to runoff in the upstream portions.

However, these assumptions need to be qualified. The calibration parameters are essentially theoretical; their values have a limited physical meaning and can result from numeric solutions that have few links with reality. For instance, some GR4J parameters like the groundwater exchange coefficient (*x2*) and the time base of unit hydrograph (*x4*) were fairly unresponsive during calibration, which shows no obvious correlation with physical phenomenon. For instance, variations of *x4* below a value of less than 10 days did not lead to significant degradations of the aggregated objective function.

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

	HydroStrahler				GR4J			
Catchment	*sat* (mm)	*ssrr* (d^{-1})	*infr* (d^{-1})	*gwrr* (d^{-1})	*x1* (mm)	*x2* (mm)	*x3* (mm)	*x4* (d)
Douna (LP)	470	0.000 29	0.000 03	0.012 90	580	0.036	180	3.5
Douna portion (SD)	450	0.000 08	0.000 21	0.018 40	590	0.076	220	10.5
Dioïla portion (SD)	460	0.000 14	0.000 07	0.015 60	800	0.023	125	1.5
Pankourou portion (SD)	500	0.000 26	0.000 03	0.000 01	940	0.260	100	4.0
Bougouni portion (SD)	500	0.000 34	0.000 07	0.000 01	1420	0.001	75	7.5

Sensitivity analysis of the parameters

Sensitivity analysis of the calibrated parameters clearly shows that some parameters of the models are subject to greater variability than others during the calibration phase. The more sensitive parameters were shown to be: (i) the subsurface runoff rate (*ssrr*) and the infiltration rate (*infr*), for HydroStrahler; (ii) the production reservoir capacity (*x1*) and the 1-day capacity of the routing reservoir (*x3*), for GR4J. For these parameters, it is seen from Fig. 5 that only one numerical area allows for optimal calibration to be attained. Well-known equifinality problems are then reduced. In contrast, the least sensitive parameters (*sat* and *x4*) present thresholds below which the goodness-of-fit scores do not significantly deteriorate, which reveals problems of equifinality (notably in the case of GR4J). The threshold effect of *sat* can be explained by the fact that the optimal calibration never leads to generate immediate runoff through the shallow reservoir: as far as *sat* is sufficiently high, the soil saturation content is never affected, and the simulated surface runoff is only composed of rapid (or subsurface) runoff. This is probably due to the necessary time-transfer of both surface and subsurface water fluxes at the study scale. The threshold effect of *x4* can be explained by the fact that the *x3* parameter controlling the routing reservoir would be the main factor in determining the water flux delay between the two conceptual reservoirs. For the purposes of this study it was then pointless to place too much importance on these parameters in the calibration phase: once the threshold values were found, it was just a matter of fixing them and varying the other parameters. In light of this, it might be interesting to make changes to the equations controlled by these parameters in order to strengthen their roles, or, in contrast, to use models with fewer parameters (e.g. GR3J, see Edijatno *et al.*, 1999).

Figure 5 also shows that each objective function can constitute a source of equifinality. Aggregating the various functions into a single-objective calibration could then emphasise the problem rather than reducing it. Therefore, it is essential to make sure that the chosen aggregating function F_{agg} (see equation (5)) does not interfere with the search for the calibration optimum. It is interesting to note that in both models the equifinality area produced by F_{agg} mirrors the one produced by the Nash criterion (Fig. 5). This latter criterion would have a particular discriminant role in the constitution of F_{agg}. Nonetheless, for both models, and for every pair of parameters studied, F_{agg} is able to reduce the equifinality area in comparison to the use of a single criterion (Nash or VE for example, Fig. 5). Consequently, this function does not prevent us finding the optimal parameters, but makes it possible to minimize uncertainties resulting from calibration. It represents a suitable solution for calibrating models by offering an objective function that is rich, easy-to-use, and that allows us to efficiently target the most efficient parameters.

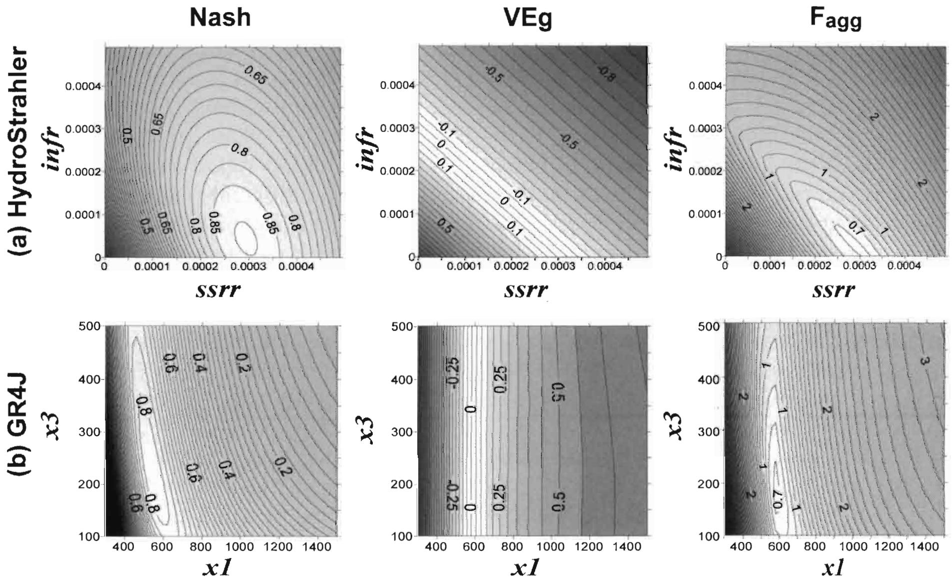

Fig. 5 Sensitivity of the "key-parameters" depending on the goodness-of-fit indices used (Nash, volume error, aggregated function): (a) HydroStrahler; (b) GR4J.

DISCUSSION: ABILITY OF THE TWO MODELS IN SIMULATING THE LONG-TERM HYDRO-CLIMATIC VARIABILITY OVER THE CATCHMENT

In western Africa, as in numerous regions where water availability causes severe problems, it is crucial to understand how river systems function. In order to represent the rainfall–runoff processes in a large, poorly-gauged tropical catchment, two conceptual hydrological models (HydroStrahler and GR4J) were compared using lumped and semi-distributed approaches. The aim was to model the water balance and its changes when subject to climatic stress at various scales.

This study shows that in these regions it is difficult to accurately reproduce the rainfall–runoff relationship in a wide spatiotemporal scale. The conceptual character of the models, in conjunction with the lack of, and\or quality of the data, makes it a delicate task. Nevertheless, both of the hydrological models studied here allow the runoff in the catchment to be correctly simulated over a nearly 50-year period characterized by significant hydro-climatic variability. The Nash coefficients obtained at the Douna gauging station with HydroStrahler (in lumped mode) and with GR4J (in semi-distributed mode) are always over 80%, in both calibration and validation (Table 1). Consequently, the simulation results show a good agreement with the flows observed at the outlet during both wet and dry periods. Even if the semi-distributed approach generally yields poorer results with HydroStrahler than with GR4J, the simulation quality remains acceptable. The spatial heterogeneousness of the basin is found through the calibrated parameters. The spatial variability between these parameters mainly reflects the different volumes of precipitated water between the catchment's portions. They can also be explained by variable capacities of infiltration linked to the geologic characteristics. Nevertheless, even though the semi-distributed modelling gives a better account of the hydrological processes inside the watershed, this study shows that moving from a lumped to a semi-distributed approach does not necessarily improve the simulated hydrograph at the outlet of a watershed with heterogeneous physical characteristics. These findings contradict the work of some authors (see e.g. Baudez *et al.*, 1999; Bourqui *et al.*, 2006; Das *et al.* 2008) and reinforce the idea that distributed or semi-distributed approaches do not clearly demonstrate any practical superiority over a lumped approach in simulating streamflow (see also Loague & Freeze, 1985; Michaud & Soroshian, 1994; Refsgaard & Knudsen, 1996; Loumagne *et al.*, 1999).

Few hydrological studies have been carried out on this kind of spatiotemporal scale in western Africa. However, one can refer to Schuol *et al.* (2008) who tested the daily physically-based SWAT model (Soil Water Assessment Tool) in several large West African catchments and over a dry period (1970–1995). The simulations with this model (that runs according to a distributed spatial approach) were confronted with the observations of several stations. The Nash coefficients between 0 and 70% (depending on the validation/calibration phase at the Douna station, respectively) show a less accurate representation of the rainfall–runoff relationship than that obtained with the daily models used in the present study. The difference between the input data obviously explains those poorer results as we recently showed (Laurent & Ruelland, 2010) that it was also possible to obtain satisfactory simulations over the Bani catchment with SWAT. The conceptual GR2M model (modèle du Génie Rural Mensuel à 2 paramètres) has also been applied in West Africa (Dezetter *et al.*, 2008), notably over the Bani catchment. In that study, the efficiency of the model is estimated via the Nash coefficient. The best coefficient obtained by calibration (at a monthly time step) at the Douna station over 1922–1995 is 74%. For the same catchment and over the 1952–2000 period, we obtain a Nash criterion value of 88% with HydroStrahler (lumped mode) and 83% with GR4J (semi-distributed mode) at a 10-day time step. Even then, the models used in this study seem to be more accurate. The use of four parameters (compared with two with GR2M) can partially explain those better results. Furthermore, the use of other objective functions criteria, such as the VE or PE, allows the simulations to be tested more thoroughly. Still, it can be argued that the time period in the present study is shorter (1952–2000 *vs* 1922–1995). Meanwhile, the simulation period used with GR2M includes mainly wet years in which the rainfall–runoff relationship seems easier to reproduce. In addition, the Nash coefficient tends to give more weight to high values and thus to wet years through its very design (see e.g. Perrin, 2000).

There are still some questions that need to be addressed regarding our simulations. The analysis of the results does not allow us to make any conclusions to categorically determine the superiority of one model over the other (HydroStrahler *vs* GR4J) in the study context. HydroStrahler simulations more accurately reproduce the shape of the hydrograph (Fig. 3) while GR4J parameters tend to raise more equifinality problems. On the other hand, the simulated cumulated discharge over a 50-year period presents a significant gap in comparison to the observed cumulated discharge, in particular with HydroStrahler (Fig. 6), which may be problematic in terms of a long-term prospective assessment of water resources. Moreover, many anthropogenic issues that might have disrupted the hydrological functioning of the catchment have not been considered. First, land cover changes are not explicitly taken into account in the parameterization of the models. However, recent remote sensing studies (Ruelland *et al.*, 2010a,b)

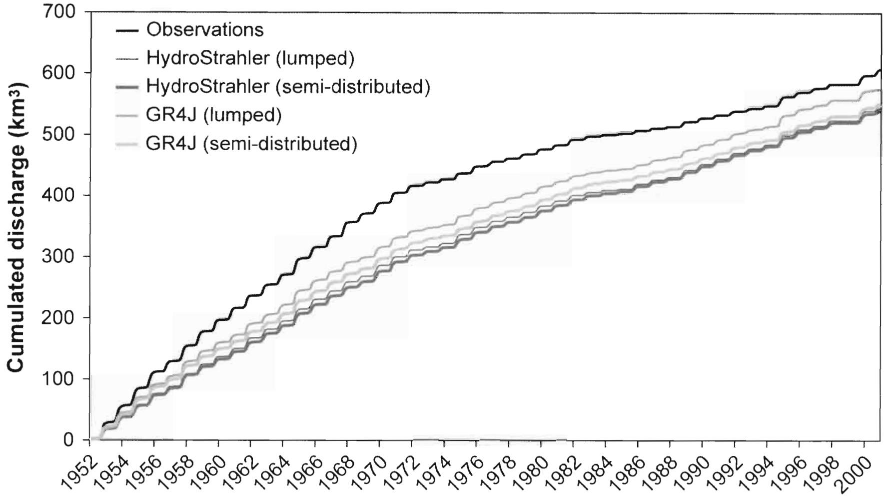

Fig. 6 Comparison of the cumulated discharge obtained at the Douna station from lumped and semi-distributed simulations with HydroStrahler and GR4J.

indicate that the downstream Sahelian part of the catchment has undergone drastic cropland expansion and deforestation since the 1960s. Those changes in vegetation cover may have had an impact on soil water-holding capacity and runoff because of alterations to surface features (see e.g. D'Herbès & Valentin, 1997). Nonetheless, in the most productive sub-basins (in the upstream part), relatively small land cover changes have been observed because of weaker demographic pressure and a greater capacity of the natural environment to regenerate (Ruelland *et al.*, 2010a). Then, if land cover changes in the Bani catchment were taken into account in the models it probably would not dramatically improve the hydrological simulations. In contrast, hydrological functioning could be disrupted by the profusion of dams that have been built in western Africa since the successive drought years of the 1970–1980s (see e.g. Cecchi *et al.*, 2009). Therefore, improvements need to be made in order to take these dams into account when making estimates about long-term water balance. These improvements are essential so that the models can be used to forecast the impacts of global changes in the region and overcome major obstacles to agricultural production/management based development due to water scarcity.

Acknowledgements This work was carried out as part of an internal HydroSciences Lab project and of the ANR RESSAC program (vulnerability of surface water resources to anthropogenic and climate changes in Sahel).

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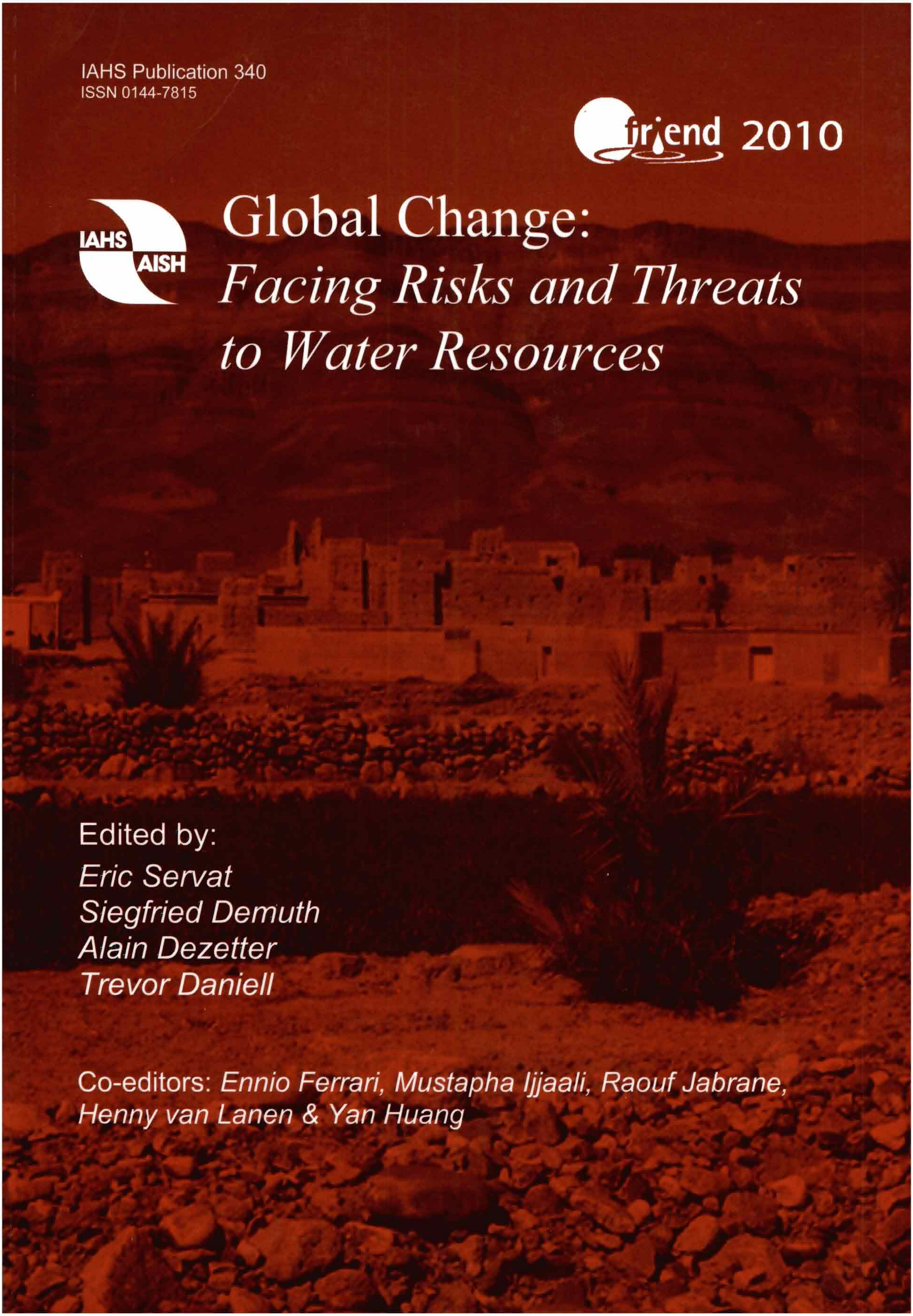

IAHS Publication 340
ISSN 0144-7815

friend 2010

Global Change:
Facing Risks and Threats to Water Resources

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Proceedings of the Sixth World FRIEND Conference, Fez, Morocco,
25–29 October 2010.

IAHS Publication 340
in the IAHS Series of Proceedings and Reports

Published by the International Association of Hydrological Sciences 2010

IAHS Publication 340

ISBN 978-1-907161-13-1

British Library Cataloguing-in-Publication Data.
A catalogue record for this book is available from the British Library.

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IAHS is indebted to the employers of the Editors for the invaluable support and services provided that enabled them to carry out their task effectively and efficiently.

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Printed by Information Press

Cover picture: Southern Morocco by Eric Servat