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The impact of land use change on soil water holding capacity and river flow modelling in the Nakambe River, Burkina-Faso

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Abstract

The annual hydrological regime of the Nakambe River shows substantial changes during the period 1955–1998 with a shift occurring around 1970. From 1970 to the mid-1990s, despite a reduction in rainfall and an increase in the number of dams in the basin, average runoff and maximum daily discharges increased. This paper reviews the hydrological behaviour of the Nakambe River from 1955 to 1998 and examines the potential role of land use change on soil water holding capacity (WHC) in producing the counter-intuitive change in runoff observed after 1970. We compare the results of two monthly hydrological models using different rainfall, potential evapotranspiration and WHC data sets. Model simulations with soil WHC values modified over time based upon historical maps of land use, are compared against simulations with a constant value for WHC. The extent of natural vegetation declined from 43 to 13% of the total basin area between 1965 and 1995, whilst the cultivated areas increased from 53 to 76% and the area of bare soil nearly tripled from 4 to 11%. The total reduction in WHC is estimated to range from 33 to 62% depending on the method used, either considering that the WHC values given by the FAO stand for the environmental situation in 1965 or before. There is a marked improvement in river flow simulation using the time-varying values of soil WHC. The paper ends with a discussion of the role of other factors such as surface runoff processes and groundwater trends in explaining the hydrological behaviour of the Nakambe River.

Keywords: Land use; Soil water holding capacity; Hydrological modelling; Nakambe River; Burkina-Faso

1. Introduction

Many studies have demonstrated that the rainfall decline across the Sahel since 1970 has had a significant impact on runoff in the region. In most cases, river flows have declined (Bricquet et al., 1997; Mahé et al., 2000) but in a few cases flows have increased (Pouyaud, 1987), depending on the nature of drainage network and geology. Empirical process studies have also shown that the type of land use has a significant impact on runoff generation in parts of the Sahel (Roose, 1977; Fournier et al., 2000). Ouedraogo et al. (2001) obtained good simulations of river flows in West Africa using a monthly water balance model

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(WBM). However, they found that north of about the 1000 mm isohyet, the model was less efficient in simulating observed flows and hypothesised that this may have been due to a greater impact of land use change on runoff generation in drier (Sahelian) areas than in more humid areas, as suggested by Casenave and Valentin (1988).

The Nakambe is an ephemeral river in a semi-arid region with annual rainfall of about 645 mm with a rather flat basin of 20,800 km^2. This paper reviews the hydrological behaviour of the Nakambe River from 1955 to 1998 and examines a counter-intuitive change in runoff regime that occurred around 1970: from 1970 to the mid-1990s, despite a reduction in rainfall and an increase in the number of dams in the basin, average runoff and maximum daily discharges increased. The paper tests the hypothesis that changes in land use, through their impact on soil water holding capacity (WHC) have partially offset the expected decrease in runoff that might have occurred as a result of rainfall decline and increased reservoir storage in the basin. This is done by modelling the monthly hydrological regime of the Nakambe River basin (Fig. 1) and incorporating the impact of changing soil WHC on the flow regime. The high level of human disturbance to land surface characteristics in the basin, including the construction of dams, and intensification and expansion of agricultural practices, are considered as explanatory factors for the observed hydrological behaviour of the Nakambe River.

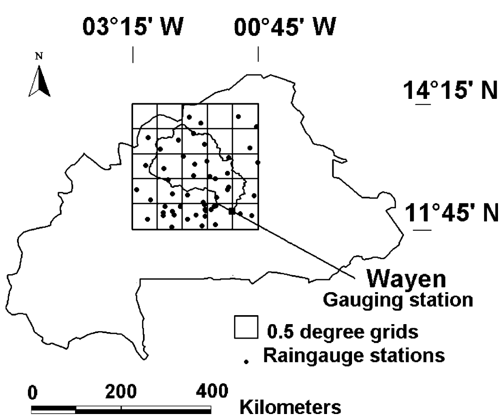


Fig. 1. Location of the Nakambe River basin at Wayen in Burkina-Faso West Africa.

2. The data sets

The approach utilises sub-sets of data from global data sets of rainfall, potential evapotranspiration (PE) and soil WHC at 0.5° latitude and longitude resolution. Two monthly time series of rainfall from 1950 to 1995 were used: New et al. (2000), hereafter called Climatic Research Unit (CRU), and a modified version of this data set (IRD) with additional rainfall data from the Institut de Recherche pour le Dévelopement (Mahé et al., 2001). PE time series were constructed using monthly time series of temperature (t_{min} and t_{max}), vapour pressure, and sunshine hours from New et al. (2000), according to the standard Penman formula.

Three data sets were used to derive three separate estimates of WHC in the basin. All of them are based on FAO (1981) digital soil map of the world in which WHC is determined to a depth of 1 m, or to an impermeable layer which ever is shallower. WHC is determined independently of the prevailing climate and takes no account of vegetation rooting characteristics. FAO (1981) gives a range of values for WHC, which are not associated with particular vegetation types but based upon the soil depth and texture, the influence of parent material, seasonal flooding conditions, top soil texture and other minor correcting factors. A set of WHC values were computed by Ouedraogo et al. (2001) for the basin according to the average value of WHC, ranging from 92 to 159 mm with an overall average for the basin of 129 mm. These estimates are used here and referred to as *FAOavg*. An additional set of values called *FAOmax* was computed for this study, based on the maximum value of WHC derived from FAO (1981). Dunne and Willmott (1996) also generated soil WHC at 0.5° resolution, hereafter *D&W*, which values range from 44 to 106 mm with an overall average of 56 mm for the basin, considerably lower than *FAO* estimates. They used the FAO soil map of the world with two additional criteria: soil organic matter, estimated from climatic data, and plant rooting depths and ground coverages obtained from a vegetation characteristic data set.

Daily runoff data were obtained from the National Hydrological Service (DGIRH) of Burkina-Faso. Observations began in 1955 but were followed by nearly 10 years without continuous observations,

Table 1
Maximum daily flows and total annual flows at Wayen

	$Q_{j,\max}$ ($m^3 s^{-1}$)	Volume (km^3)		$Q_{j,\max}$ ($m^3 s^{-1}$)	Volume (km^3)		$Q_{j,\max}$ ($m^3 s^{-1}$)	Volume (km^3)		$Q_{j,\max}$ ($m^3 s^{-1}$)	Volume (km^3)
1965	159	0.34	1974	256	0.66	1983	153	0.45	1992	419	0.49
1966	34	0.07	1975	262	0.39	1984	56	0.15	1993	77	0.22
1967	116	0.22	1976	34	0.13	1985	116	0.44	1994	384	1.06
1968	14	0.07	1977	47	0.16	1986	144	0.41	1995	24	0.09
1969	35	0.12	1978	174	0.36	1987	30	0.15	1996	94	0.29
1970	42	0.11	1979	180	0.30	1988	357	1.01	1997	51	0.17
1971	No data		1980	130	0.32	1989	190	0.40	1998	171	0.57
1972	16	0.05	1981	166	0.60	1990	29	0.10			
1973	150	0.23	1982	50	0.19	1991	147	0.45	Mean	130	0.31

which re-started in 1965, with only 1 year missing until 1998 (1971). The monthly values presented here refer to the years 1955 and then from 1965 to 1998. Annual values were reconstructed by Moniod et al. (1977) for the years 1956–1964, by using temporarily measures, data from close river basins and rainfall–runoff relationships. Except for the above period, the discharges at Wayen (Fig. 2, Table 1) are only the measured values and not a reconstruction of values taking into account the impacts of the numerous dams.

The groundwater data come from the DGIRH. For each station, there are several wells, from which we selected only one, which was indicated to be far from villages and also far from river beds, hypothesising that it would then better reflect the natural interannual climatic impact on groundwater level.

3. Factors affecting hydrological variability in the Nakambe River

3.1. Rainfall, PE and river flows

There is only one major flood peak (Fig. 3). The base flow contributes a minor part of the runoff as the hydrograph falls rapidly after flood peaks. Mean annual runoff up to 1970 was about 7.2 $m^3 s^{-1}$ (and 5 $m^3 s^{-1}$ over the period without reconstructed flows 1965–1970). Flows began decreasing slowly from the end of the 1960s up to 1972, like most other West African rivers (Mahé and Olivry, 1999). From 1973 onwards, however, flows increase even though basin-wide rainfall decreased (Fig. 2). Runoff actually increased by 60% from 7.2 to 11.6 $m^3 s^{-1}$ between 1955–1970 and 1972–1998 and the mean daily maximum flows also increased from 67 to 145 $m^3 s^{-1}$ (Table 1). The monthly flows shown in Figs. 3 and 4 highlight large increases during July, August and September from 1973 onwards, while discharges of October and November have not changed. The flood peak now occurs mainly in August, while it mainly occurred in September before the 1970s. Hubert's test (Hubert et al., 1989), which separates statistically different populations of points in a time series, highlights decreases in May to August rainfall from the 1950s to 1988. Rainfall in September increased slightly since 1985, and more significantly in August from 1988 (Fig. 5). Over the period 1955–1998, Hubert's test shows a discontinuity in the time series in 1969/1970, which separates the earlier higher rainfall period (average 742 mm per year) and the following drier period (595 mm). Hubert's test shows no discontinuity in the PE annual time series in the centre of the basin (not shown here), and only a slight increase in the south (5%) since 1978, following an increase of minimum temperatures.

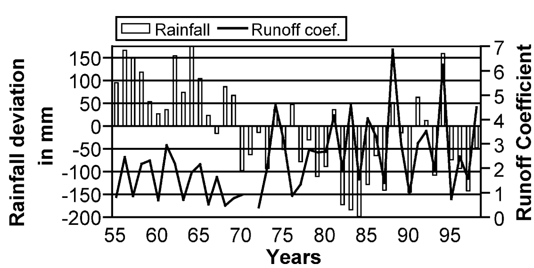


Fig. 2. Runoff coefficients, from observed measures, and rainfall indexes over the period 1955–1995 for the Nakambe River at Wayen.

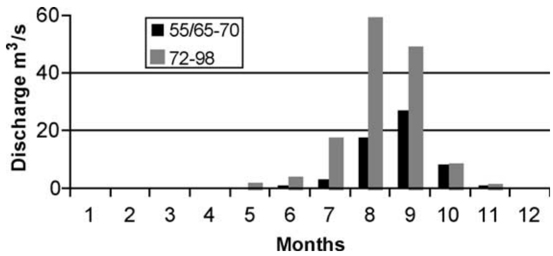


Fig. 3. Monthly discharges over the periods 1955/1965–1970 and 1972–1998.

As a result of the opposing rainfall and river flow changes the average standardised runoff coefficient is twice as high after 1973 (confirmed by Hubert's test): increasing from 1.4 to 3.0 during a period when the rainfall exhibited a prolonged decline with slight recovery in some months towards the end of the period (Fig. 2). Poppel and Lekkerkerker (1991) found that in the less inhabited southern parts of the basin (protected forest), the runoff coefficient did not increase suggesting that the influence of human activity (land use change) on soil characteristics may have had a major impact upon runoff generation.

3.2. Baseflows and groundwater

Leduc et al. (2000) found that the water table has been increasing over the last 50 years around small endoreic ponds near Niamey, in the SW Niger Republic, due to an increase in the surface runoff coefficients, which they linked to an intensification of agricultural activities.

To investigate the potential role of groundwater in explaining the observed behaviour of the Nakambe flows, we compared the surface and groundwater level data for the whole Nakambe River. Although the number of wells regularly observed by the DGIRH is very small, we found eight wells on the surface of the Nakambe basin, which are located far from urban areas or villages and from the river beds, and with time series of at least monthly resolution, with some periods with weekly and even daily observations. For each year, we determine the highest level reached by the ground water at each well. We then calculate the time series of ground water level differences between 2 years, for each well, in standardised values, which we average to obtain one standard value per year for the whole basin. We assume that this index only reflects the basin-wide climatic impact on groundwater levels, and can be related to the rainfall over the basin, which should be largely responsible for the annual recharge of the basin groundwater. The variability of groundwater levels of local aquifers (Fig. 6) generally follows that of rainfall over the whole Nakambe River basin and do not show any long-term positive trend like in SW

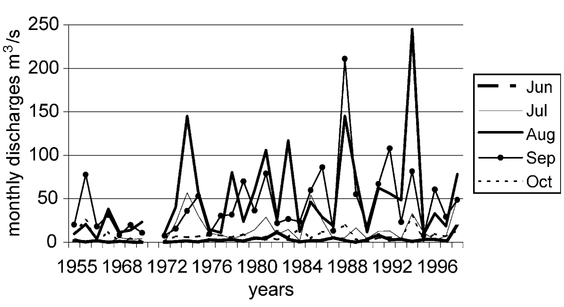


Fig. 4. Nakambe monthly discharges 1955, and 1965–1998.

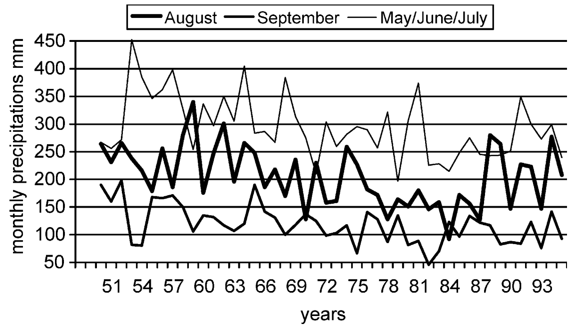


Fig. 5. Monthly precipitations over the Nakambe River basin from 1950 to 1995.

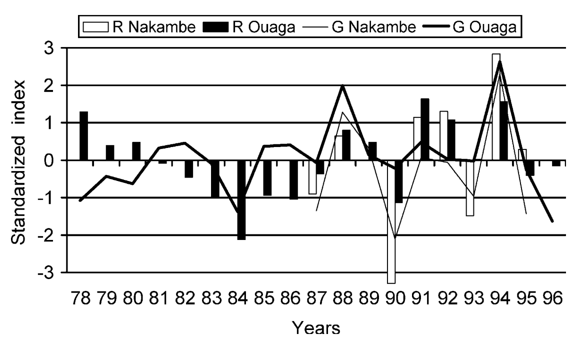


Fig. 6. Rainfall (R) and Groundwater (G) variability over the Nakambe basin compared to the Ouagadougou station, south of the basin.

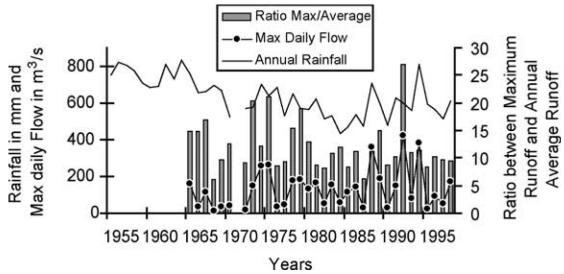


Fig. 7. Maximum daily flows, ratio between maximum daily flow and annual average runoff, and annual rainfall.

Niger. This means that the increase in runoff in the Nakambe is not due to an increase of the groundwater levels. This differs from the situation in SW Niger, where the drainage systems collect runoff within endoreic areas which fill small ponds, which in turn contribute directly to groundwater recharge.

Finally, the ratio between maximum daily runoff and annual average runoff of the Nakambe River (Fig. 7) does not show any systematic changes over the study period. This means that the increase of runoff is not due to an increase in just extreme events, which would have caused exceptional flood peaks, but that both the average and the peak flows have increased since the 1970s.

3.3. The impact of dams

There are 242 dams in the basin, out of 1456 in the whole of Burkina-Faso. The volume of water stored in dams within the basin was about 55 million m^3 in 1965. This volume rose continuously up to 170 million m^3 by 1994, which are partly emptied and refilled every year, compared with 315 million m^3 mean annual river flow. Most of the stored water can be considered as consumptive losses because of abstractions and evaporation.

The discharge time series at Wayen includes the gradual increase in storage water and therefore artificial losses. Nevertheless, measured river flows show an increase, and the flood peak now occurs approximately 1 month earlier. The net effect of dams in the basin should be to reduce the runoff through increased evaporative losses from reservoir surfaces and abstractions. This process is not included in this modelling exercise, but should be developed in a further study as a source of possible improvement.

3.4. Land use change in the basin

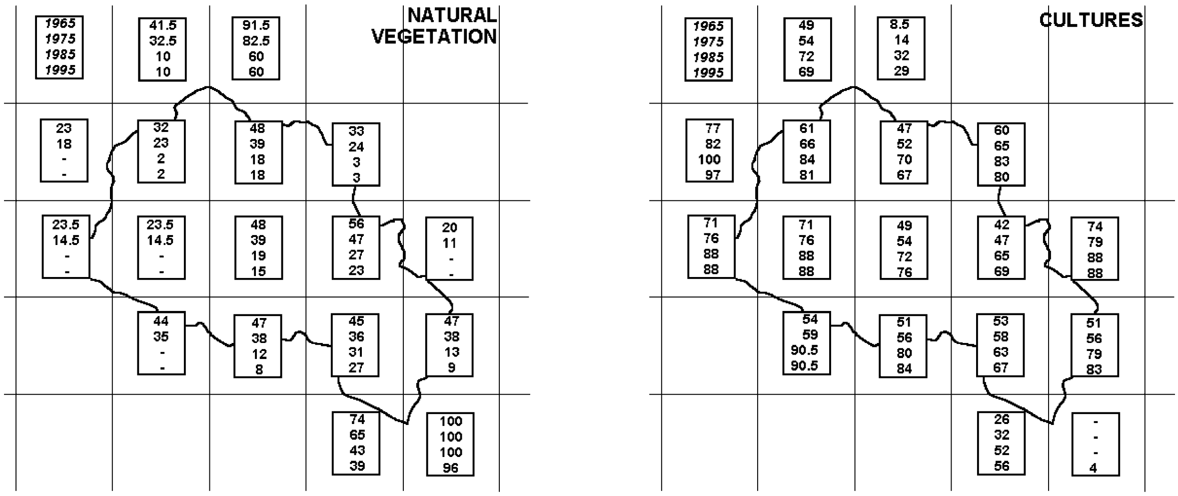
We generated a set of four different land use maps for the basin for the years 1965, 1975, 1985 and 1995 by comparing local studies with larger areal surveys Three classes of land-cover were identified: natural vegetation (which includes fallow areas, assumed to behave like natural vegetation), cultivated areas and bare soil (Fig. 8).

The changes in ratios between the three classes are translated into modifications of the WHC in each grid cell, by referring to runoff coefficient values published by Fournier et al. (2000). They studied runoff from small surfaces in Western Burkina-Faso, in a climatic area corresponding to the South of the Nakambe basin, and observed a reduction of the infiltration proportional to the increase of the runoff coefficient. They published average values of runoff coefficients based on several rainy seasons for different land types: natural vegetation and fallow areas 13%, cultivated land 20%, and bare soil 50%. These figures are slightly lower than what is observed in North-Sahelian basins in Burkina-Faso (Yacouba et al., 2002; Karambiri et al., 2003).

4. Monthly river flow modelling

4.1. The models

We use two models to simulate monthly flows: GR2M (Ambroise, 1999) and a standard monthly WBM (Conway, 1997; Conway and Mahé, 2004). Both models use a simple soil moisture accounting procedure where rainfall excess over potential evaporation (PE) fills a soil moisture reservoir (taken as the WHC). When the soil reservoir is full any remaining excess is added to a linear storage reservoir. Both models GR2M and WBM have only two parameters, representing direct and lagged runoff, although the WBM has seasonally varying values. Runoff and storage are calculated for 0.5° grid cells within the catchment (Fig. 1) without any flow routing between grid cells. Runoff from all full and partial cells within the basin is then summed to produce an overall monthly flow. The flood time transfer along the whole catchment is short (a few days), which allows a monthly calculation without taking into account any transfer time.



Year	Natural Vegetation	Cultivated	Bare Soil	WHC reduction
Initial values	100%	0%	0%	0%
1965	43 %	53 %	4 %	21 %
1975	34 %	58 %	8 %	25 %
1985	15 %	75 %	10 %	32 %
1995	13 %	76 %	11 %	33 %

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

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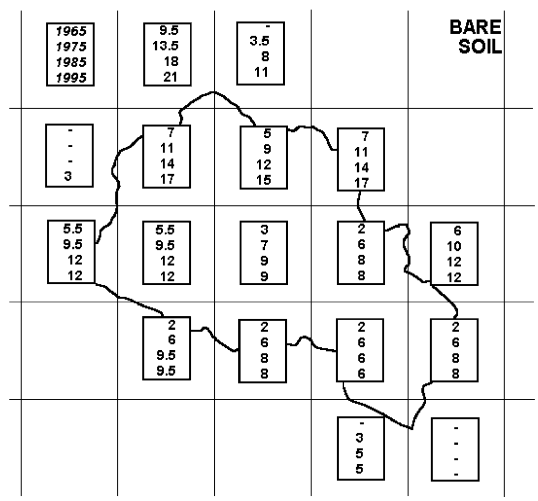


Fig. 8. Soil classification and evolution in per cent of land use in each grid cell in 1965, 1975, 1985 and 1995, percentage reduction by 1995 compared to initial values (*D&W* or *FAOavg* and *FAOmax*). The table indicates the decadal change in three land use classes expressed as percentage areas within the Nakambe River basin and the resulting impact on WHC. Two cases: initial conditions prior to 1965 (A top); initial conditions = 1965 (A bottom).

4.2. Impact of land use change on the water level in the model's reservoir

We consider the hypothesis that changes in land use/cover in the basin may have contributed to the observed increase in runoff. We use estimates of land use change over time coupled with some simple assumptions about their impact on the WHC of soils under a range of land use types. Reducing the soil WHC suggests that it cannot hold as much moisture, because either the soil is eroding and therefore thinner, or the organic matter or texture is changing or degrading, or both of these assumptions.

We generated four WHC grids for 1965, 1975, 1985, 1995 as follows. The unadjusted values of the *FAOavg*, *FAOmax* and *D&W* WHC files were used to provide the initial soil WHC, which are assumed to represent the theoretical natural vegetation prior to human activities. We used two hypotheses for estimating the impact of land-use change on WHC.

In the first—low impact—(Fig. 8, A top) we consider that the soil maps given by the FAO correspond to a 'theoretical' state of 100% natural vegetation, which could have been observed prior to the human settlement. Thus, in 1965, due to the past human impact, the 'initial' WHC must be reduced prior to river modelling. The impact of the land-use change is then lower, as the starting value is already reduced by 21%. The final reduction is 33%, which means that during the 30 years of river modelling, the WHC reduction is only of 12%. In the second hypothesis—high impact—(Fig. 8, A bottom), we assume that the soil maps given by the FAO correspond to a natural/human equilibrium, and thus that the human impact is already taken into account in the WHC values given by the FAO. The starting values of WHC are thus not reduced and correspond to the land-use state in 1965. The total reduction over 30 years of river modelling is then of 62%.

From 1965 onwards, we modified these initial values according to the change in percentage area of different land use classes during each decade. Annual grids were generated between each decade using a linear interpolation of the change.

The percentage change between the initial WHC values and WHC values in 1995 are shown in Fig. 8. The decadal change in each vegetation class is given in Fig. 8. The area of natural vegetation is 3.5 times smaller in 1995 than in 1965, the area of bare soil is 3 times larger, and the cultivated area increased by more than 40%.

4.3. Modelling results

We run both models for 12 sets of data: 1 PE, 2 rainfall, 3 fixed WHC and 3 time-varying WHC data sets.

$$\text{NASH Index (\%)} = 100\left[1 - \frac{\sum_i (Q_o^i - Q_c^i)^2}{\sum_i (Q_o^i - Q_m)^2}\right]$$

For this study, we used the Nash index as performance criteria with Q_o^i and Q_c^i observed and simulated runoff, respectively; and Q_m the average observed runoff over the whole observation period. The Nash index increases to 100 for perfect simulation.

Table 2
Results of the river flow modelling: Nash performance criteria for calibration and validation, for fixed and time-varying WHC data

Data Precip.	File source WHC	Fixed WHC		Time varying WHC	
		Calib. (%)	Val. (%)	Calib. (%)	Val. (%)
Model GR2M					
CRU	FAO avg	50.6	37.0	+16.7	+26.2
	FAO max	61.5	47.5	+5.7	+15.8
	D&W	64.5	47.7	+4.7	+10.6
IRD	FAO avg	52.3	36.8	+20.2	+26.9
	FAO max	66.7	50.0	+5.7	+13.9
	D&W	67.7	48.9	+4.5	+9.3
Model WBM					
CRU	FAO avg	70.8	−4.3	+4.2	+17.1
	FAO max	51.6	36.3	+26.5	−30.6
	D&W	61.1	39.4	+0.8	+4.7
IRD	FAO avg	67.0	41.6	+5.6	−7.7
	FAO max	77.5	70.3	−7.2	−4.8
	D&W	63.5	40.4	+3.3	−2.2

Table 2 gives the results of the river flow modelling. With both models, when using the time-varying WHC data set the performance criteria is markedly increased. We only present the results with the second hypothesis (high impact), which are better. For all but one combination the Nash index increases (up to 26%) (period 1965–1975) for model calibration, and higher values with WBM. For model validation (period 1976–1995), there is a strong increase with GR2M, but the results are not robust with WBM: increase with the CRU rainfall file, and decrease with the IRD rainfall file. The GR2M model produces higher values for the time-varying WHC with the IRD rainfall file, and always gives higher values in validation (+17% in average). The IRD rainfall series produces slightly better results than the IRD file (+3–4%). Results are better with the *FAOavg* or *FAOmax* WHC data than with the *D&W* values. Finally, as a sensitivity test both models were run with a set of optimized parameters with the initial WHC values reduced by 75% to test the impact of a global reduction in WHC compared to the spatially and temporally variant data set: this resulted in lower values of Nash index than when using the time-varying WHC.

5. Discussion

Since the 1960s the River Nakambe's hydrological regime has been affected by the construction of numerous dams, a change in the rainfall regime and extensive land use change within its basin. Since 1970 rainfall decreased by 20%, runoff increased by 60%, and runoff coefficients by more than 100%.

To assess the impact of land use change on soil WHC we use two monthly time step hydrological models with six WHC data sets, three with spatially and temporally varying values and three with constant values throughout the simulation, at a half-degree square scale. The time-varying WHC data were realised by using field experiments results of runoff coefficient change on different land-cover types. These land-cover types have been selected to be representative of the different kinds of land-cover found on the basin. The first assumption we made is that the results of these hydrological studies are usable for the whole Nakambe basin. For this matter, we made comparisons with results of other studies in the area, which prove to be in the same range of values. But we must note that there are not enough recent studies of rainfall–runoff relationships in the Sahelian area, in regard to the impact that climate change might have had on surface hydrology processes.

Due to the size of the basin, 20,800 km^2, it is not possible to delineate accurately the contours of each type of land-cover, e.g. natural vegetation, cultivated areas and bare soils, over the whole surface of the basin. The second assumption is that we must assume that the resolution of the satellite imagery, coupled with some ground validating data, is sufficient for estimating the variability in space and time of the surface occupied by each of these land-cover types over the whole basin.

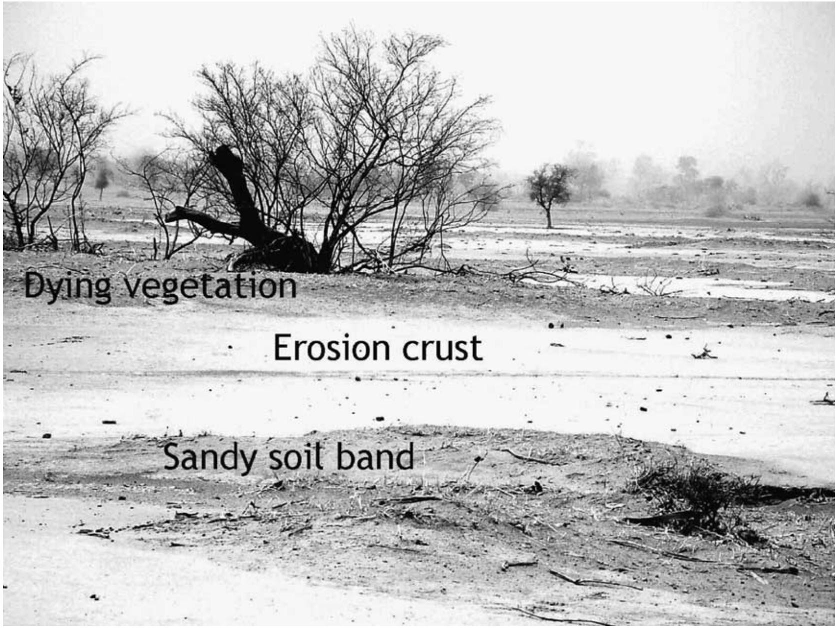
As a result of this study, the simulation of monthly river flows of the Nakambe River was improved markedly by using the time-varying WHC values. This shows that model performance is sensitive to a change in catchment characteristics over time, such as varying soil WHC due to land-cover change, and that our kind of approach mixing local and large-scale data, is useful, in a context of scarcity of data.

The best results are obtained with the higher WHC values, from the *FAOmax* data, which does not specifically take into account the vegetation types.

GR2M and WBM are conceptual models which loss functions are empirical ones. Ardoin et al. (2001) had very good results of daily river flow modelling in Northern Ivory-Coast, by using a loss function not using the PE values but rather an actual evaporation value related to the soil moisture availability. The two models we use in this study are not very sensitive to PE formula used for calculating PE, as confirmed by recent results by Paturel et al. (2003). It is not easy to imagine how runoff would increase due to an effect of PE, in a context of increasing world air temperature and therefore of PE.

Karambiri et al. (2003) studied runoff in the very degraded areas of the North of Burkina-Faso, near to the North of the Nakambe basin. In this area, the vegetation is composed by little trees, shrubs and patches of grass, developed over narrow bands of sandy soil, which thickness do not exceed some tenths of centimetres (Picture 1). Between these bands of soil appears the erosion crust. The overall porosity of these soils is very low, because the fauna and flora are only scarcely developed, and offers very few possibilities for water to penetrate through the crust. The runoff coefficient, of Hortonian type on the erosion crust, can reach nearly 100%. The WHC in the narrow sandy soil bands is very limited, the soil is very rapidly saturated. Thus, when rainfall reach the soil surface, missing bare soil, sandy bands and others, surface runoff is dominant and nearly immediate, the infiltration in the first centimetres of the soil, even on the erosion crust, exists but is very limited, even if not negligible, and finally the amount of water available for a delayed evapotranspiration is low, largely exceeded by the runoff. During the rainy season, when the vegetation grows, the runoff coefficient decreases, due to the higher evapotranspiration demand of plants, except on the crust, where no vegetation grows. Even during the rainy season, Karambiri et al. (2003) noted that, due to the very weak thickness of the soil bands, runoff of Hortonian type was rapidly observed.

Runoff coefficients on bare soils might be largely under-estimated, because the runoff coefficient's data we used come from river basins located too much southward within the basin. Scarce data from the very northern part of the basin show runoff coefficients sometimes up to 100% (Karambiri et al., 2003). This could explain why the total WHC reduction we



Picture 1. North Sahelian landscape in Burkina-Faso, Nakambe River basin. Erosion crust and sandy soil bands.

calculate is not sufficient to explain the increase of 108% of the runoff coefficient.

There are other examples of river flows increasing in the Sahelo-Sudanian area during the recent period of rainfall reduction. Amani and Nguetora (2002) showed an increase of the summer flood of the Niger river at Niamey in 1984, 1988, 1994 and 1998, above the level of the winter main flood, coming from the upper Niger river basin. This kind of modification of the hydrological regime of the Niger river at Niamey has never been observed in the past series beginning in 1928. The author associates this increase in local runoff to the degradation of land-cover. Leduc et al. (2000) give a similar conclusions for explaining the increase of the water table level in SW Niger Republic. Mahé et al. (2003) also show a runoff increase within the whole Sahelian area of Burkina-Faso and West Niger since 1970.

In areas which are less inhabited and which land-cover is consequently less degraded, the runoff increase is lowered. This is the case of the Dargol upper basin in the North of Burkina-Faso (Mahé et al., 2003).

6. Conclusions

Since the 1960s land use has changed in the North of Burkina-Faso: increase of agricultural areas and of the number of dams. A climate shift also occurred in West Africa since around 1970, with two major impacts in the northern, Sahelian, part of Burkina-Faso: a reduction in annual rainfall and a change of land-cover. Despite the reduction of rainfall and the increase of the number of dams, average runoff and maximum daily discharges increased. The impact of land use change on soil WHC during this period is tested through monthly river flow modelling, and show a marked improvement in flow simulation using the time-varying values of soil WHC. The natural vegetation reduces from 43 to 13% of the basin surface area between 1965 and 1995, and the cultivated areas increase from 53 to 76% at the same time, while bare soil areas are nearly tripled from 4 to 11%. Groundwater levels in the basin seem to be inferred to the rainfall interannual variability, and cannot be responsible for the runoff increase.

Further improvements in monthly river flow conceptual models, could be certainly reached by improving the quality of the WHC data, by taking into account a temporal variability as done in our study.

A better simulation of the river flows in this Sudano-Sahelian climatic area might proof very useful. For example, the 12 years old Bagre Dam, constructed downstream of the Wayen's gauging station in Burkina-Faso, faces unpredicted high flood peaks since its opening: the design flood has been already exceeded, with disastrous consequences. Expensive works are now forecasted to design new spillways for this dam.

Finally, too few measurements have been done up to now over small Sahelian catchments with very degraded land-surfaces. We would need such knowledge to improve the efficiency of the monthly river flow modelling, and we encourage National Hydrological Services to promote measurement campaign on such basins.

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