FRIEND 2002—Regional Hydrology: Bridging the Gap between Research and Practice (Proceedings of the Fourth International FRIEND Conference held at Cape Town, South Africa, March 2002). IAHS Publ. no. 274, 2002.

Climatic and anthropogenic impacts on the flow regime of the Nakambe River in Burkina Faso

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Abstract The annual hydrological regime of the Nakambe River shows substantial changes during the period 1955 to 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, runoff increased, including maximum daily discharges, and a delay of several weeks in the timing of peak flows occurred. To assess the impact of land-use change on soil water holding capacity (WHC) during this period we compare the results of two monthly hydrological models using several different rainfall, potential evapotranspiration (PE) and WHC data sets. Soil WHC values are modified over time using historical maps of land use, and compared with a constant value for WHC over time. There is a moderate improvement in flow simulation using the varying values of soil WHC.

Key words land use; soil water holding capacity; hydrological modelling; Sahel; Burkina Faso

INTRODUCTION

Many studies show that the rainfall decline since 1970 across the Sahel had a significant impact on runoff in the region in most cases by reducing flows (Bricquet *et al.*, 1997; Mahé *et al.*, 2000) and in a few cases by increasing flows (Pouyaud, 1987) depending on the nature of the drainage network and the geology. Other studies have shown that the type of land use has a great impact on runoff generation (Roose, 1977; Fournier *et al.*, 2000). Using a monthly water balance model, Ouedraogo (2001) obtained good simulations of monthly river flows in West Africa, although, roughly north of the 1000 mm isohyet, the model was less efficient in reconstructing observed flows. This may be due to a greater impact of land-use change on runoff generation in Sahelian areas than in more humid regions (Casenave & Valentin, 1988). In this study the monthly hydrological regime of the 20 800-km^2 Nakambe River basin (Fig. 1) (Moniod *et al.*, 1977) is simulated to assess the impact of changing soil water holding capacity (WHC) and other anthropogenic factors on the flow regime. Particular emphasis is given to the change in flow regime which occurred in the Sahel during the

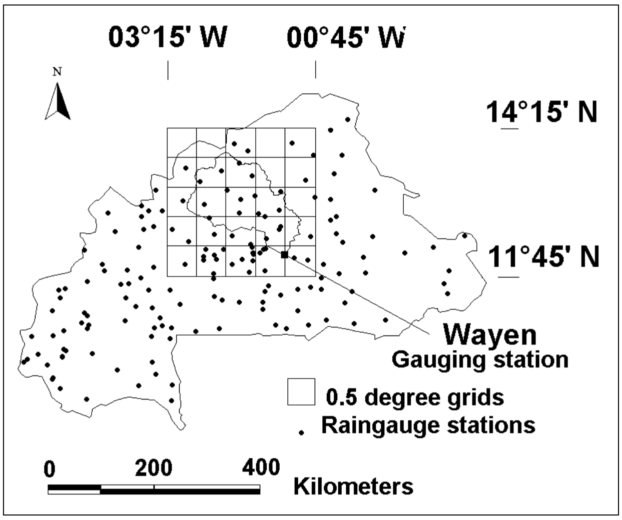

Fig. 1 Location of the Nakambe River basin at Wayen in Burkina Faso, West Africa.

early 1970s and to consideration of the high level of human activity in the basin, including the construction of dams, intensive agriculture, and changes in land use.

THE MODELS

We use two models to simulate monthly flows: GR2M (Makhlouf, 1994) and a standard monthly water balance (MWB) model (Conway, 1997). Both models use a simple soil moisture accounting procedure where rainfall excess over potential evaporation (PE) fills a soil moisture reservoir (taken as the water holding capacity). When the soil reservoir is full any remaining excess is added to a linear storage reservoir. Both the GR2M and the WBM models 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 basin (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.

DATA SETS

The approach utilizes global data sets of rainfall, PE and soil available water capacity at 0.5° latitude and longitude resolution. Two monthly time series of rainfall from 1950 to 1995 were used: that from New *et al.* (2000), hereafter called CRU (Climatic Research Unit), and an expanded data set called CRU-IRD with the addition of Institut de Recherche pour le Développement (IRD) rainfall data (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). A 0.5° resolution data set of plant-extractable water capacity from Dunne & Willmott (1996) were used to provide soil WHC, hereafter D&W. Values of plant-extractable water range from about 44 to 106 mm (average 56 mm). A second set of values was computed by Ouedraogo (2001) from the FAO (1981) soil data with higher values ranging from about 92 to 159 mm (average 129 mm). Daily runoff data were obtained from the National Hydrological Service (DIRH) of Burkina Faso.

ASSESSMENT OF THE IMPACT OF POTENTIAL FACTORS ON RIVER REGIME

Rainfall and runoff variability

Mean annual runoff up to 1970 was about 7 $m^3 s^{-1}$. Flows began decreasing slowly from the end of the 1960s up to 1972, similar to the trend found for most other West African rivers. From 1973 however there are higher flows even though from this period onwards basinwide rainfall decreased (Fig. 2). Indeed, runoff increased by 60% from 4.90 $m^3 s^{-1}$ to 11.6 $m^3 s^{-1}$ between 1965–1970 and 1971–1998 and the mean daily maximum flows also increased between the same two periods from 67.0 to 145 $m^3 s^{-1}$ (Table 1). The Hubert test for discontinuities in times series (Hubert *et al.*, 1989), which separate statistically different populations of points, highlights decreases in May–August rainfall from the 1950s to 1988. September rainfall increased slightly from 1985, and more significantly in August from 1988. The PE series for August and September show a positive trend between 1972 and 1983, followed by a short decline between 1984 and 1988. The average standardized runoff coefficient is twice as high after 1973: increasing from 1.4 to 3.0 during a period when the rainfall decreased (Fig. 2). Poppel & Lekkerkerker (1991) found that in the less inhabited (protected

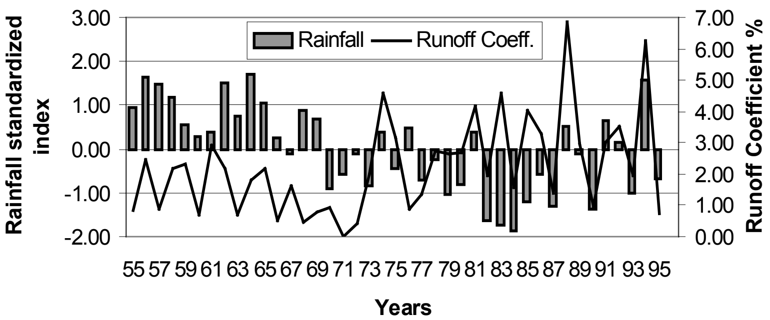

Fig. 2 Runoff coefficients and rainfall indexes over the period 1955–1995 for the Nakambe River at Wayen.

Table 1 Maximum daily flows and total annual flows at Wayen.

Year	*Qj*max ($m^3 s^{-1}$)	Volume (km^3)	Year	*Qj*max ($m^3 s^{-1}$)	Volume (km^3)	Year	*Qj*max ($m^3 s^{-1}$)	Volume (km^3)	Year	*Qj*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

forest) southern parts of the basin, 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.

Increasing the number 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 10^6 m^3 in 1965. This

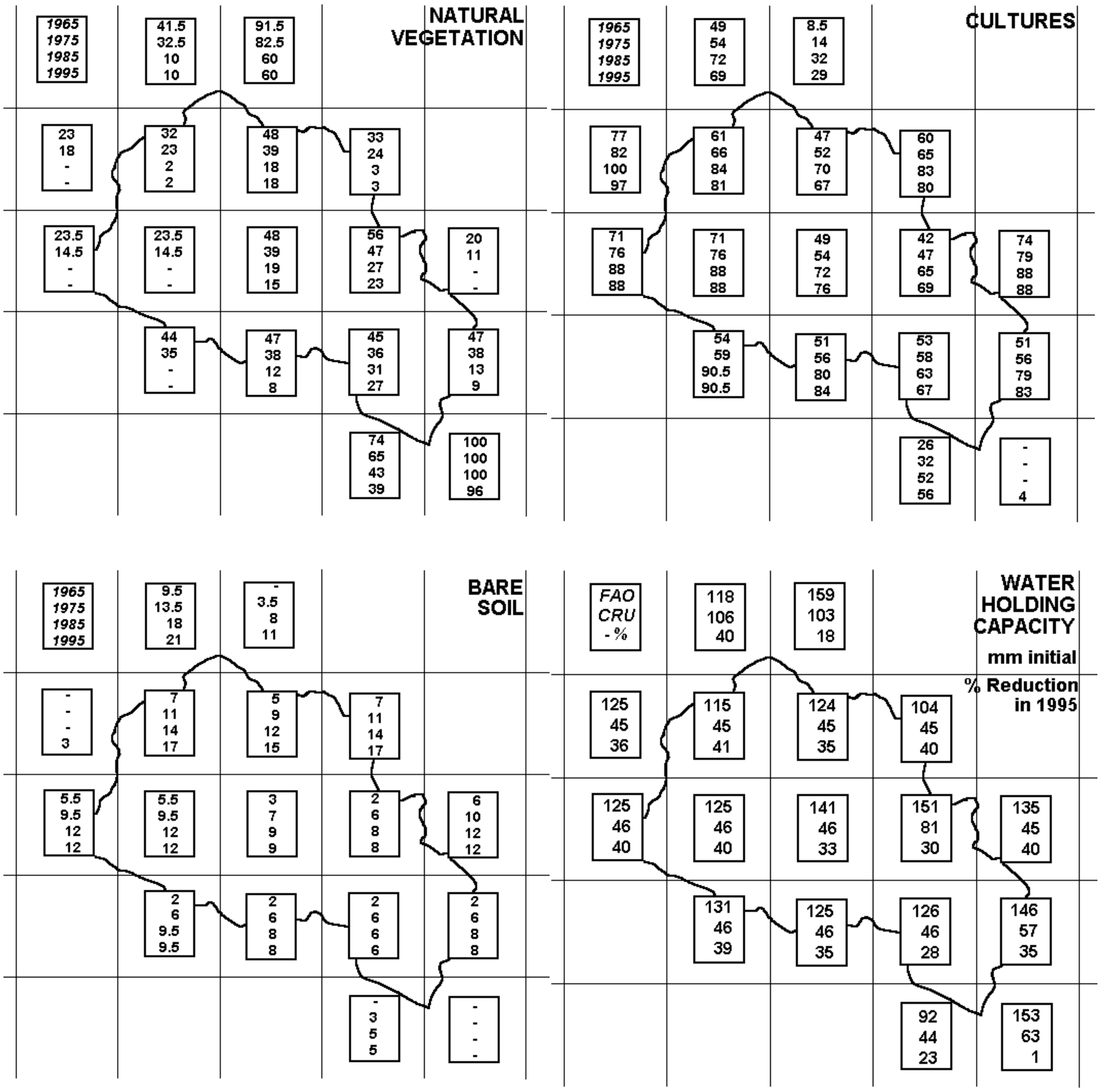

Fig. 3 Soil classification and evolution in per cent of land use in each grid cell in 1965, 1975, 1985 and 1995, percentage reduction by 1995 compared to initial values (D&W or FAO).

volume rose continuously to 170 10^6 m^3 by 1994, compared with 315 10^6 m^3 mean annual river flow. Most of the stored water can be considered as consumptive losses. From 1974 to 1987 the maximum daily runoff was delayed by several weeks (Fig. 3), from early August to early September most likely as a consequence of the increase in storage reservoirs in the basin. There has not been a change in rainfall regime likely to have caused such a shift. Despite the increase in storage and decline in rainfall since the 1970s, river flows, which have been accurately checked, have actually increased.

Land-use change and soil characteristics: modifying the WHC

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 impacts on the WHC of soils under a range of land-use types. Most studies are derived from satellite imagery or aerial photographs. Dray (2001) generated a set of four different land-use maps for the years 1965, 1975, 1985 and 1995 by comparing local studies with larger areal surveys. Three classes were identified: natural vegetation (which includes fallow areas, assumed to behave like natural vegetation), cultivated areas and bare soil (Fig. 3). The changes in ratios between the three classes are translated into modifications of the water-holding capacity in each grid cell, by referring to Fournier *et al.* (2000). They observed a reduction of the infiltration proportional to the increase of the runoff coefficient: natural vegetation and fallow areas 13%, cultivated land 20%, bare soil 50%. We generated four WHC grids for 1965, 1975, 1985, 1995 as follows. The unadjusted values of the FAO and D&W WHC files were used to provide the initial soil WHC. 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. 3. The decadal change in each vegetation class is given in Table 2. In 1995 the area of natural vegetation reduced to 25% of the area in 1965, cultivated areas

Table 2 Decadal change (%) in three land-use classes expressed as percentage areas within the Nakambe River basin and the resulting impact on the WHC.

Year	Natural vegetation	Cultivated	Bare soil	WHC reduction
Initial values	100%	0%	0%	0%
1965	43	53	4	21
1975	34	58	8	25.1
1985	15	75	10	32.2
1995	13	76	11	33.1

increased by more than 40%, and bare soil increased by a factor of about 3. The impact on the average WHC in the basin is a reduction by one third of the WHC in 30 years, according to the ratios we used.

Table 3 Results of the river flow modelling: Nash performance criteria for calibration and validation, for modified and unmodified WHC data.

	File source	Fixed WHC		Modified WHC	
Model GR2M					
Precipitation	WHC	Calib. (%)	Val. (%)	Calib. (%)	Sim. (%)
CRU	FAO	57.7	40.0	59.9	45.6
	D&W	59.8	40.1	61.5	44.2
CRU-IRD	FAO	61.1	49.6	63.3	55.3
	D&W	64.0	50.1	65.6	53.9
Model WBM					
Precipitation	WHC	Calib. (%)	Sim. (%)	Calib. (%)	Sim. (%)
CRU	FAO	59.4	19.9	58.5	28.1
	D&W	55.8	28.0	55.3	28.5
CRU-IRD	FAO	56.9	32.1	61.8	43.1
	D&W	61.3	40.3	63.6	42.8

Modelling results

For this study we used the Nash index as performance criteria:

$$\text{Nash index (\%)} = 100\left[1 - \frac{\sum_i \left(Q_\text{o}^i - Q_\text{c}^i\right)^2}{\sum_i \left(Q_\text{o}^i - Q_\text{m}\right)^2}\right] \tag{1}$$

where Q_o^i and Q_c^i are 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 3 gives the results of the river flow modelling. Using the modified WHC data set the performance criteria are increased moderately. The Nash index increases from 2 to 7% (period 1965–1975) for model calibration and from 2 to 14% (period 1976–1995) for the validation, depending on to which model is used. The GR2M model produces slightly higher values in all but one case. The calibration results are similar for the two models and the validation results are better with GR2M. The CRU-IRD rainfall series produces slightly better results than the CRU file, and results are better with the D&W WHC data than with the FAO data.

CONCLUSIONS

Since the 1960s the hydrological regime of the River Nakambe has been affected by the construction of numerous dams, a change in the rainfall regime and extensive land-use change within its basin. To assess the impact of land-use change on soil WHC we use two monthly time step hydrological models with two WHC data sets, one with spatially and temporally varying values and one with constant values throughout the simulation. The simulation of monthly river flows was improved moderately with the varying WHC values. This shows that model performance is sensitive to a change in basin characteristics over time, such as varying soil WHC due to land-cover change.

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