ELSEVIER

Catena 37 (1999) 197–216

CATENA

# Water balance in a banded vegetation pattern A case study of tiger bush in western Niger

S. Galle [a,*], M. Ehrmann [b], C. Peugeot [c]

[a] LTHE, BP 53, 38041 Grenoble, Cedex 9, France
[b] ORSTOM, Niamey, Niger
[c] ORSTOM, Montpellier, France

Received 19 September 1996; received in revised form 10 October 1997; accepted 10 February 1998

**Abstract**

The tiger bush is a patterned woodland with alternating bare area and vegetated stripes. In Niger, it covers one third of the Sahelian zone. These natural forests are of considerable economical interest since they are the main source of livestock forage and domestic energy. Its sustainable exploitation needs improved understanding of its dynamics. The redistribution of water between thicket and intervening bare areas is decisive for the water supply of the vegetation. Tiger bush patterning replicates an elementary unit composed of a bare area, the upslope border, the core and the downslope margin of the thicket. (Each zone of tiger bush is characterised by specific soil crusting associated with vegetation). Both water storage and runoff have been monitored after each rain, over a period of 4 yr, including contrasting rainy seasons, on the different zones composing the tiger bush. On the three crusted zones, runoff has a piecewise linear relationship with rain: on closed plots, runoff yield vs. annual rainfall ratio reaches 54% on bare soil, 2% on upslope border and 18% on downslope border. The measured infiltration confirms these rates on independent plots. In the core of the thicket, measured infiltration corresponds with the sum of the contributions of upslope zones, weighted by their relative lengths. This model predicts that bare area contributes up to 62% of the thicket supply, while direct rain is 27%, the senescence zone is 10% and the upslope border contribution is negligible (1%). The average water infiltration in the thicket is equal to 4 × the incident rainfall, but water redistribution is not homogeneous within the core of the thicket. By the most favourable location, infiltration depth is measured to be about 8 × the rainfall. The important runoff, mainly generated on the impervious bare area crosses the upslope border of the thicket without infiltrating, and entirely benefit to the core. Nothing is left to

* Corresponding author. Tel.: +33-4-76-82-70-12; fax: +33-4-76-82-52-86; e-mail: sylvie.galle@hmg.inpg.fr.


PII: S0341-8162(98)00060-5

the downslope border, only rainfed. The upslope border, often described as favourable location for young plants is only rainfed most part of the year. By the end of the season, its increasing porosity, due to vegetation and termite activity let it benefit of the last rains. The simple water balance model based on runoff measurement is satisfactorily validated by independent observed infiltration. 

*Keywords:* Water balance; Tiger bush; Sahel; Soil moisture storage; Runoff yield

## 1. Introduction

In Niger, tiger bush woodlands supply the major part of domestic energy (Peltier et al., 1995) and contribute to livestock forage. As the anthropogen pressure increases, so too does the risk of damage to the ecosystem. The need for sustainable exploitation implies an understanding of tiger bush dynamics. Tiger bush is a patterned woodland made up of alternating bare areas and vegetated stripes. It occurs in arid or semi-arid climates, where water availability is limited, relative to vegetation needs. Similar patterned vegetation has been reported in many parts of the world: in Sahelian Africa (from Mauritania to Somali), in Australia, Mexico, and in the USA. Since the first description in Niger by Clos-Arceduc (1956), Boaler and Hodges (1964) postulated the importance of the superficial water dynamics in the maintenance of the spatial structure: sheet runoff is generated on the bare ground area which benefits the downslope vegetation stripe. Although numerous studies have been undertaken describing similar ecosystems all over the world, very few of them have actually measured runoff or soil moisture distribution over bare and vegetated areas to validate water dynamics hypotheses. Moreover, these studies concern different continents: Slatyer (1961) and Greene (1992) worked in Australia; Cornet et al. (1992) and Mauchamp et al. (1994) in Mexico. Since 1992, hydrological and ecological studies related to tiger bush functioning have been undertaken in Niger as part of two international experiments HAPEX-Sahel [1] (Goutorbe et al., 1994) and GCTE-SALT [2] (Menaut et al., 1993).

Peugeot et al. (1997) measured high runoff generation on tiger bush bare surface. But at the plateau scale, the contribution to the foothill runoff is limited to the bare border of the plateau. This difference must be due to the sink role of the vegetated stripes. Seghieri et al. (1997) studied the relationship between surface soil water dynamics and herbaceous plant development on the upslope part of the thicket. The present paper aims to calculate water balance of an entire tiger bush unit, including bare and vegetated areas, to validate a rain redistribution hypothesis. We monitored measurements of runoff and soil moisture content in each zone composing a tiger bush unit in Niger during a period of 4 yr, including contrasting rainy seasons. The data were monitored at a rain dependent time step.

[1] HAPEX-Sahel: Hydrological and Atmospheric Pilot Experiment in the Sahel.

[2] GCTE-SALT: Global Change Terrestrial Ecosystems-Savane à Long Terme core project.

## 2. The study area

Tiger bush covers 22 000 $km^2$, or one-third of the Sahelian Niger, between 13° and 15°N (Ambouta, 1984). The year is divided into two seasons, 90% of the annual rain fall in three months (from July to September), the remaining part of the year is a dry season. Within these latitudes, rainstorms are mostly convective, and annual rainfall varies from 400 mm in the north to 700 mm in the south. Tiger bush forest occurs exclusively on plateau, capped with a thick Pliocene iron pan (Gavaud, 1966). The shallow gravelly soils (25 to 85 cm) have very low nutrient reserves (Ambouta, 1984) and are poorly developed.

The tiger bush study site is located on a plateau near the Banizoumbou village, 70 km northeast from Niamey (13°32′N, 2°42′E). Its elevation is 250 m, and the general slope of the plateau is about 0.2%, ranging from 0.06% to 0.5%. Mean annual rainfall for that region is 560 mm for the period of 1905 to 1989 (Lebel and Le Barbé, 1997). The study site presents typical tiger bush facies with trees covering 25% of the area shown on the aerial photograph (Fig. 1).

Seghieri (pers. comm.) has studied the vegetation of this plateau on a 700 m long transect crossing eight vegetated stripes. She found that the average width of the perennial vegetation stripes was 10 m ($\pm 7$ SD), and 50 m ($\pm 28$ SD) for the bare areas. The high standard deviation is due to the undulating border of the thickets. The main woody species are *Combretum micranthum* G. Don and *Guiera senegalensis* J.F. Gmel. averaging 2.40 m in height. Vegetation zonation is observed, based on slope orientation.

On another site nearby, Thiéry et al. (1995) observed that soils in and between vegetation bands showed few morphological differences, apart from those which can be directly accounted for by the influence of the vegetation itself (i.e., higher porosity and rooting within the band). These observations are consistent with other soil surveys of Nigerien tiger bush (Ambouta, 1984, and Barker, 1992). Though soil textural properties show few differences, the soil surface, on the contrary, presents various types of crusts organised in a typical succession as described on our site by Seghieri et al. (1997).

These observations led us to divide the tiger bush into four discrete zones based on vegetation and soil crust type. The crustal type and characteristics presented here refer to the Sahelian surface crust classification proposed by Casenave and Valentin (1992). The runoff ratio, $K_r$, is defined by the ratio of the runoff depth to the rainfall depth for a given rainstorm. Casenave and Valentin (1992) measured $K_r$ for each crust type with a rainfall simulator. The four zones of the tiger bush are described from upslope to downslope, starting with the runoff generating areas: (1) The downslope border of the thicket, often called 'senescence' zone considering it contains a majority of dead stumps with a few mature trees. It is covered mainly by structural crusts indicating intensive sheet flow ($K_r = 75$–$85\%$). Structural crusts are composed of different layers (coarse sandy layer at the top, finer particles at the bottom) and result from a granulometric sieving impacted by rain drops. (2) The bare area covered by erosion and gravel crusts, with the highest runoff potential ($K_r = 80$–$90\%$). Erosion crusts consist of a smooth surface made up of a single seal of fine cemented particles more or less colonised by algae, while gravel crusts are composed of fine particles including coarse fragments. (3) The upslope border zone with predominant sedimentation crusts resulting from sedi-

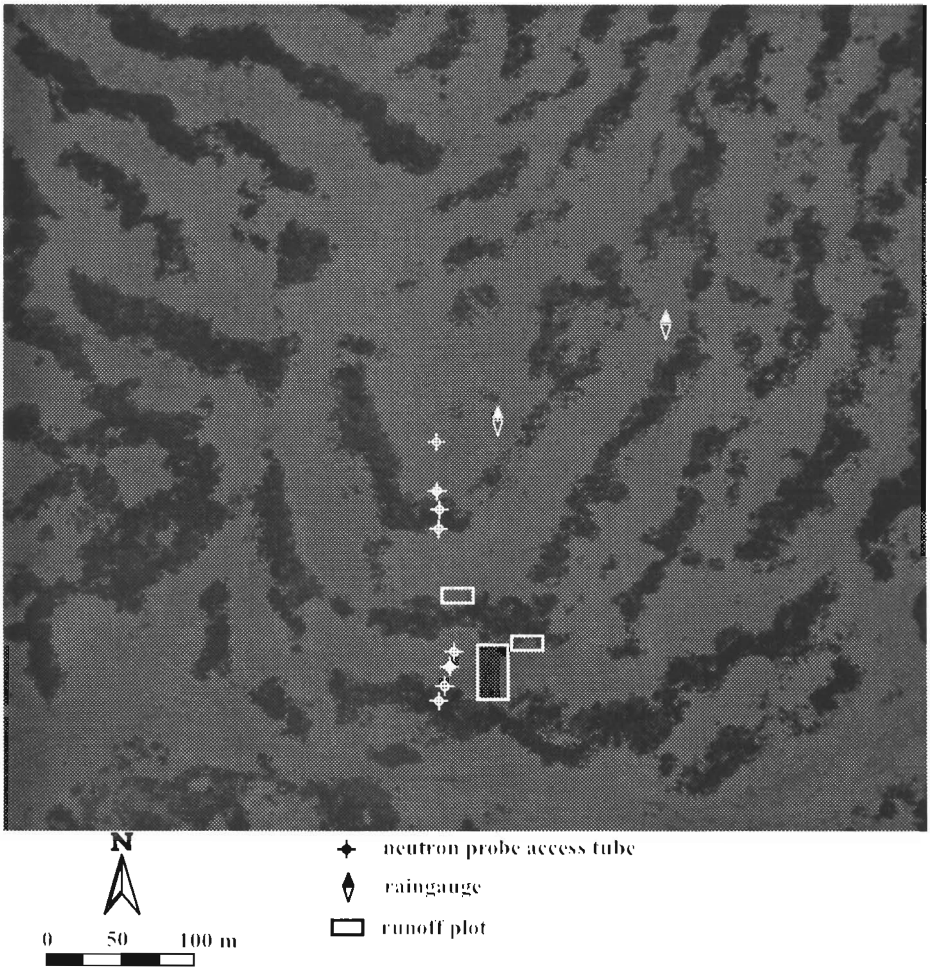


Fig. 1. Aerial photograph of the Banizoumbou plateau.

ments deposits, evidence of ponding processes ($K_r$ = 45–55%). Its vegetation is composed of annual species, woody seedlings, and a few mature trees. (4) The body of the thicket contains mature trees which prevent an herbaceous layer developing. Here the soil is covered by litter and dead branches characterising high biological activity, high root density, high permeability, and the absence of surface crusting.

This simplified description of variability along the axis of maximum slope does not take into account lateral variation of the thicket showing bays and capes (Fig. 1). Given the field observations of plant species and crustal types, the following hypothesis proposed by Thiéry et al. (1995) describing functioning of the system can be assessed. This hypothesis states that the bare area, with a high runoff capability, feeds the downslope vegetation strip which in turn benefits from the water supply. Pioneer species at the front and dead trees at the rear of the thicket suggest that the pioneer front is always favoured with respect to water feeding.

## 3. Methods

The study area, including three vegetation arcs, covers an area of $200 \times 200$ m$^2$ and is shown in Fig. 1. The hydrological fieldwork was carried out from January, 1992 to December, 1995 including four rainy seasons and three dry seasons. Rainfall amount and intensity were measured at the event time step using raingauge recorders forming part of the EPSAT-Niger [3] rainfall monitoring network described in Lebel et al. (1992).

### 3.1. Runoff

Three runoff plots were set up to provide discharge measurements on bare zone, upslope border and downslope border. As it is closed, a runoff plot is designed to measure runoff generated on a selected area. The total runoff crossing an open area will be higher if it receives water from the upward zone. This plot arrangement did not measure runoff generated on the body of the thicket, as it is assumed to be null. This assumption is based on observation of both absence of soil crusting and high macroporosity due to termite activity.

A runoff plot consists of a rectangular area of natural soil surrounded by an iron border driven 10 cm into the soil and equipped downstream with a collector feeding a 1 m$^3$ tank for water volume measurements. A by-ten divider is mounted on the bare zone plot to supply excess volume to a second tank. Water volume in the tanks were measured after each rainstorm. Each plot is assumed to be representative of the hydrologic behaviour of the surface crust enclosed. The three plots have the same width, but their length varies to include the total length of each zone of tiger bush. The plot areas are $26 \times 5$ m$^2$, $13 \times 5$ m$^2$, and $12.4 \times 5$ m$^2$, for bare, pioneer and downslope borders, respectively. The bare soil plot has been monitored from early July, 1992 to the end of the 1993 rainy season, whereas only the 1995 rainy season data set is available for the two other plots.

### 3.2. Soil water content

Soil moisture profiles were measured in two lines of neutron probe access tubes. Each line, installed perpendicularly to a different vegetation strip, included at least one access tube in each of the four zones of the tiger bush. On this lateritic plateau, the access tubes were installed using a motorised hammer drill. The drilling rod and the access tubes had the same diameter to ensure tight contact with the surrounding soil. A narrow 5-cm diameter seal of cement was settled around the tube on the soil surface, to prevent downward leakage of water. On the first line, four access tubes were placed to a

[3] EPSAT: Estimating Precipitation using SATellite.

depth ranging from 0.90 m to 1.20 m. On the second line, eight access tubes were placed to a depth of 3.40 m, and one, in the center of the thicket, to a depth of 5.40 m. Soil water measurements were made using a Solo25s neutron probe (Nardeux, France). For calibration, two soil samples of 500 g were used. The first consists of sandy clay loam (56% sand, 26% clay) from the 0–250 cm soil layer. The second, taken from the 250–550 cm layer, was more loamy and homogeneous. These samples were analysed using the nuclear absorption desorption technique described by Couchat et al. (1975). The resulting calibration equation is a function of the dry bulk density. It was measured with a gamma-ray probe (Nardeux Solo40), with values ranging from 1.65 g $cm^{-3}$ in the 0–20 cm top layer, to 1.8 g $cm^{-3}$ at deeper layers. Further details on the calibration technique used on tiger bush can be found in Cuenca et al. (1997).

Soil moisture profiles were monitored at a rain-dependent time step. Measurements of soil water content were made as soon as possible after each rainstorm. Typically, rainfall occurred during the night, and measurements were made 12 h later. Measurements were taken 1, 2 and 4 days later if no rain occurred. After that, the frequency was progressively decreased to once weekly during the rainy season or to once monthly during the dry season.

## 4. Results

### 4.1. Rainfall

The four observed years correspond to different amounts and temporal distributions of rainfall. The average (530 mm) was close to the climatic mean (560 mm, Lebel and Le Barbé, 1997) but a wide range of variation was observed (250 mm). During the driest year (425 mm in 1992), once the rains started, no gap occurred in the distribution of the 10-days rainfalls (Fig. 2). In 1993, the total amount was greater (490 mm) but a dry period covering 20 days occurred at the beginning of the season. This long dry period

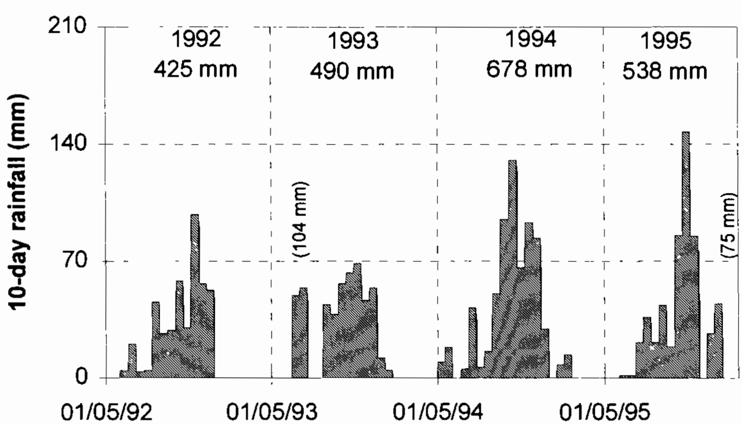


Fig 2. 10-days rainfall distribution on tiger bush site (Banizoumbou) for the four studied years and annual total.

dried out the soil. The following year, 1994, had both a high total (678 mm) and a continuous distribution, except for 25 mm before and after the season. The last year showed a 10-days period without rain before the last rains of the season. The total amount (538 mm) was close to the long term average.

### 4.2. Runoff

For each one of the three plots, the relationship between rainfall depth and runoff depth showed the same behaviour (Fig. 3). Whenever rain is lower than a threshold ($P_T$), no runoff occurs, and for higher rainfall, runoff increases linearly with the amount precipitated ($P$) within the observed range of rain. The resulting broken line is a particular piecewise linear model where the origin and slope of the first line are null. The only parameters to determine are the precipitation threshold and the slope of the second line. They are estimated by simple linear regression, the fitting quality being characterised by the determination coefficient ($r^2$). The model is formulated:

$$\mathrm{Roff} = 0 \qquad \text{if } P < P_T \tag{1a}$$

$$\mathrm{Roff} = \alpha (P - P_T) \qquad \text{if } P \geq P_T \tag{1b}$$

where $P_T$ is the rainfall threshold and $\alpha$ the slope. The parameters of the model for the three plots, summarised in Table 1, were computed from the 1992 to 1993 data set for the bare soil plot, and from the 1995 data set for the two other plots. The 95% confidence interval is shown on Fig. 3. Due to tanks overflowing, some data are missing in these data sets. Except for upslope border, no data are available for rain higher than 45 mm.

The slope $\alpha$, or runoff ratio, increases from the upslope border (15%), to the senescence zone (42%), and the bare zone (70%) which is enhanced by the decrease of the associated rain threshold (from 30 to 5 mm). This order agrees with those of Casenave and Valentin (1992), but the slope ($\alpha$) is lower than $K_r$ on upper and lower border of the thicket, and similar on bare soil.

These three piecewise linear models were applied to simulate runoff at the event time step, on each plot, for the four rainy seasons. Cumulative runoff yield over one season on one plot, given in Table 2 together with the ratio of annual runoff yield over annual rainfall depth, allow the inter-annual comparison of the behaviour of the plots. The averaged total amount of estimated runoff is about 270 mm (or 51% of annual rain) in the bare zone, three times lower (16% of rain) for the senescence zone, and very low (2% of rain) for the upslope border. These ratios are lower than the slope of the model because of the threshold effect. The percentage varies with year according to the proportion of low-rain events to the annual amount of rainfall.

### 4.3. Soil water content

The minimum soil water content, corresponding to the driest moisture profile, measured by the end of the dry season (May) depends on the location but remains steady over years (Fig. 4). Whatever the previous rainy season, the dry profile remained the same. During the prolonged 7 months of dry season, drainage and evapotranspiration

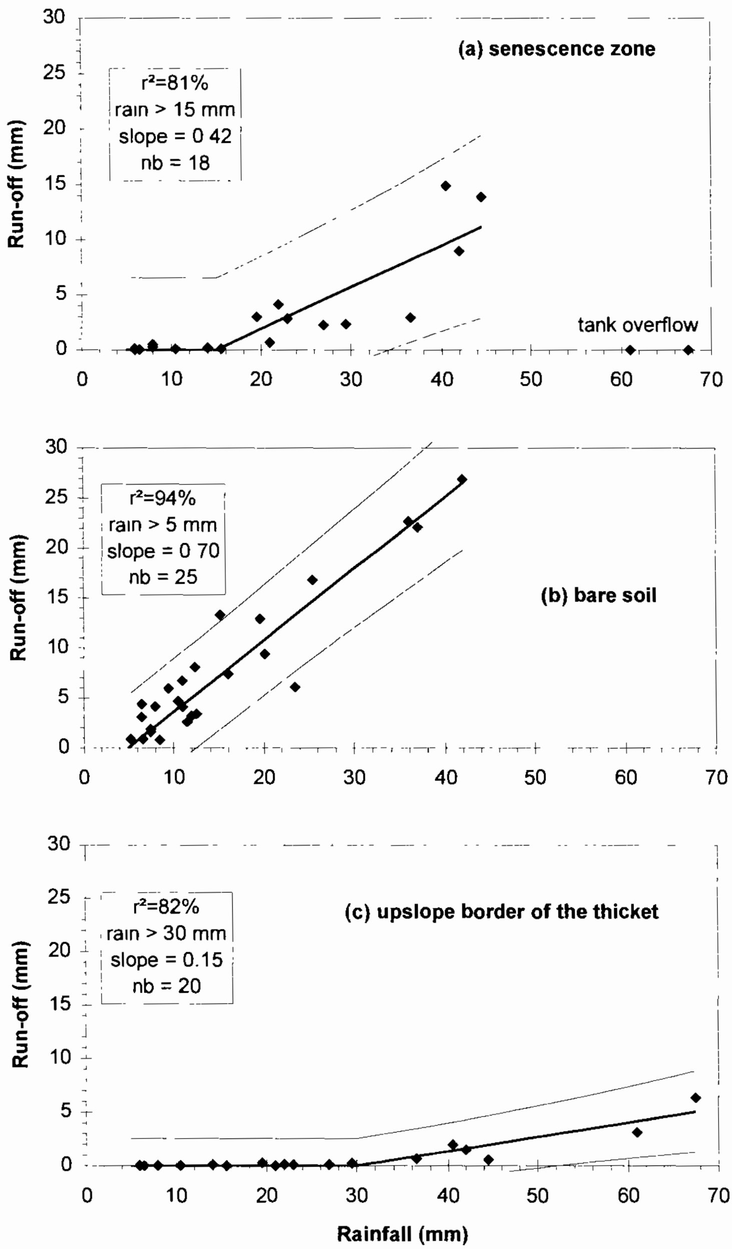


Fig 3. Observed and fitted runoff vs. rainfall. (a) Senescence zone, (b) bare zone, (c) upslope border.

exhaust the profile. The remaining water is tightly bound to the soil and becomes unavailable for plants or redistribution. Besides, the maximum water profile depends on

Table 1
Regression parameters (and associated error) between runoff and rainfall

| | Senescence zone | Bare zone | Upslope border |
|---|---|---|---|
| $r^2$ | 81% | 94% | 82% |
| Rain limit (mm) | 15 (4) | 5 (1) | 30 (10) |
| Slope | 0.42 (0.06) | 0.70 (0.04) | 0.15 (0.03) |
| Sample | 18 | 25 | 20 |

the rainy season. The annual range of variation of soil water content characterises the infiltration processes of each year and each zone (Fig. 4).

From upslope to downslope we find: (1) the senescence zone with low available water, but higher than in the bare zone, that is significantly increased during 1992 and 1994; (2) the bare zone with a low available soil water where the infiltration front does not progress deeper than 50 cm, whatever the year. The high rainfall in 1994 generated deeper infiltration compared with other seasons, with still a weak storage, however; (3) the upslope border of the thicket had a higher storage than the two upslope zones. The total volume of stored water varies considerably with annual rain: the wet front reached 80 cm in 1993, and down to 2.40 m in 1994; (4) the body of the thicket stores a huge amount of water. Whatever the year, the maximum measured profile remained the same, i.e., close to field capacity, in the 0–5.40 m layer of soil (not seen on graph because of the scale). Despite its depth (5.40 m), the infiltration front crosses the bottom of the access tube and deep drainage occurs. The annual amount of infiltrated water cannot be measured in this zone.

These results are summarised in Table 3, where the maximum available water is the difference between maximum and minimum profile of each year. A high infiltration corresponds to a rainy year showing a high rainfall amount, but also a regular distribution of rain. Although 1993 and 1995 had higher rainfall than 1992, the dry periods occurring during these years were unfavourable for deep infiltration.

Taking duration into consideration, the noticeable difference in soil water content among the four zones composing the tiger bush is further strengthened. For example, one can observe the monthly evolution of soil water storage during the 1994 rainy season (Fig. 5). The body of the thicket rapidly increased its water storage to reach a maximum on the 6th August, maintaining this level for the ensuing 2 months. On the other hand, the upslope border had to wait until the 2nd September to skip to a higher water content corresponding to one less month of high water storage. The same

Table 2
Estimated runoff using the fitted piecewise linear model

| | Senescence zone | | Bare zone | | Upslope border | |
|---|---|---|---|---|---|---|
| | (mm) | (% Rain) | (mm) | (% Rain) | (mm) | (% Rain) |
| 1992 | 56 | 13% | 204 | 48% | 7 | 2% |
| 1993 | 77 | 16% | 254 | 52% | 9 | 2% |
| 1994 | 111 | 16% | 345 | 51% | 15 | 2% |
| 1995 | 102 | 19% | 286 | 53% | 17 | 3% |

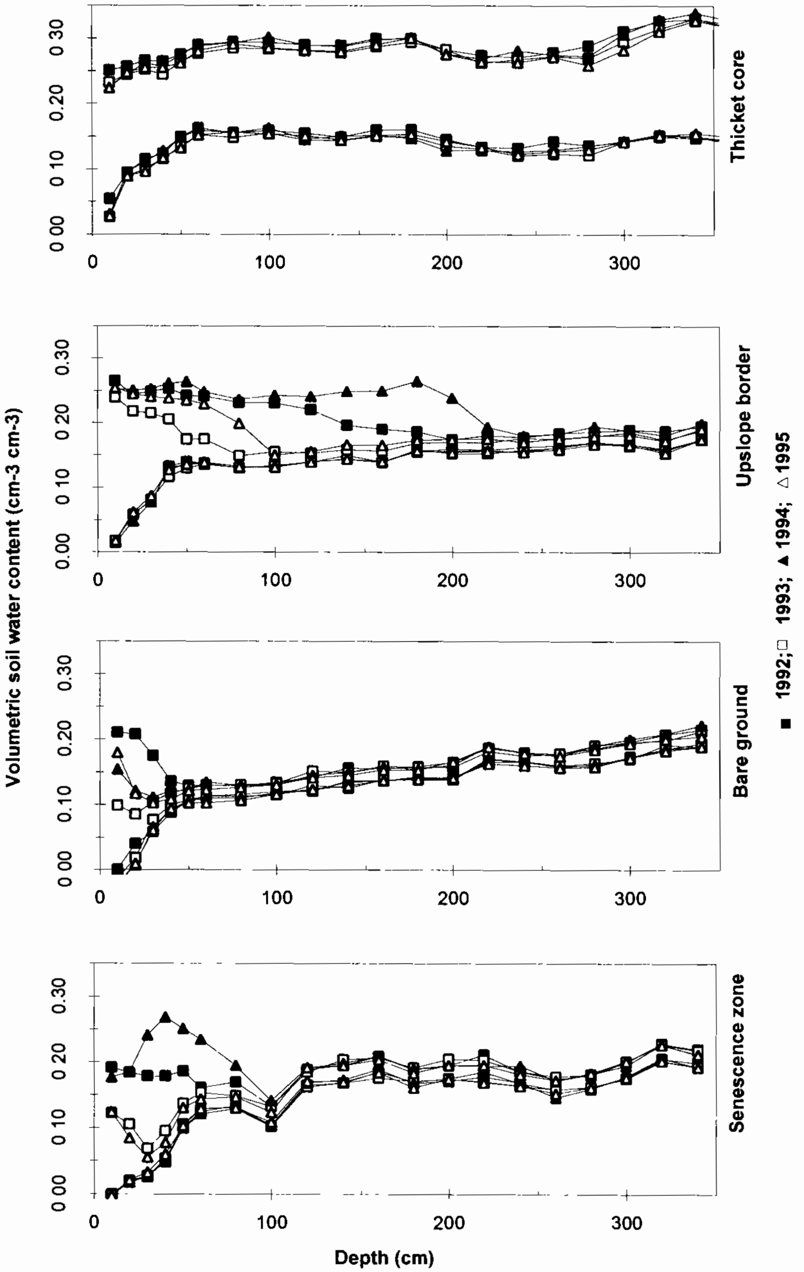


Fig. 4. Annual range of soil moisture content (1 May–1 November) for the four zones and the four monitored years.

noticeable increase was observed by the end of the rainy season (10th October, or 6 days before the last rain), for the upslope border of this zone, and never in the bare area. A

Table 3
Observed infiltration in the four zones of the tiger bush: maximum available water in 0–3.40 m soil layer, and maximum depth of the wetting front

| | Senescence zone | | Bare zone | | Upslope border | | Thicket core | |
|---|---|---|---|---|---|---|---|---|
| | water (mm) | depth (m) | water (mm) | depth (m) | water (mm) | depth (m) | water (mm) | depth (m) |
| 1992 | 140 | 1.00 | 111 | 0.50 | 221 | 2.00 | 503(*) | > 5.40 |
| 1993 | 108 | 0.40 | 81 | 0.40 | 113 | 0.80 | 498(*) | > 5.40 |
| 1994 | 176 | 1.00 | 97 | 0.40 | 279 | 2.20 | 510(*) | > 5.40 |
| 1995 | 86 | 0.40 | 94 | 0.40 | 147 | 1.00 | 485(*) | > 5.40 |

(*): Drainage is observed.

lower increase in soil water content was also observed for the senescence zone. A delay in fully charging the upslope border of the thicket, compared to its core was also observed during the three other years (1992, 1993 and 1995).

### 4.4. Water balance

Establishing the soil water balance on each tiger bush area allows the functioning hypothesis detailed earlier to be validated. Considering a rain event, soil water balance can be expressed as follows:

$$\text{Infiltration} = \text{Rain} + \text{Runon} - \text{Runoff} \quad (2)$$

Where Runon and runoff respectively refer to water volumes reaching and leaving a given area, by surface movement.

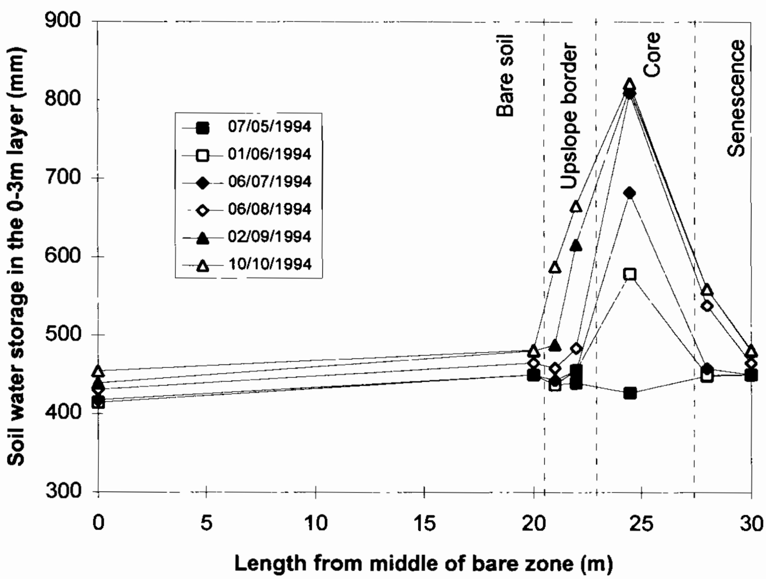


Fig. 5. Increase in soil water storage (0–3 m) on a transect perpendicular to a tiger bush elementary unit, during 1994 rainy season.

Two elements of the soil water balance equation (Eq. (2)) were directly measured on the site (rain and runoff). The infiltration occurring during a rain event equals the change in soil water storage before and after the event plus deep drainage and evapotranspiration (Eq. (3)).

$$\text{Infiltration} = \Delta S + D + \text{ETR} \qquad (3)$$

where $\Delta S$ is the change in soil water storage in the monitored soil layer, $D$ is the deep drainage beyond this level, ETR is the real evapotranspiration.

The change in soil water storage is measured using neutron probe. As soil physical properties of the soil are not known, drainage flux cannot be assessed. So we consider only those events when no deep drainage occurs ($D = 0$), i.e., the wetting front has not crossed the bottom of the tube. This limit does not affect bare soil, upslope and downslope border of the thicket as seen on Fig. 4. Furthermore, infiltration in the thicket core is only accessible during the beginning of the season. As soil water measurements are not exactly synchronised with rain, evapotranspiration occurring in the meantime has to be assessed and added to the measured change in water storage to obtain the actual amount infiltrated during a rainstorm.

Evapotranspiration is estimated using methodology developed by Monteny et al. (1997). They worked on the evaporation of a savannah located nearby (1 km), mainly covered by the same woody species *G. senegalensis*. They showed that soil moisture depletion affects the evapotranspiration rate through an increase in the local large-scale surface resistance. When nearly 40% of the total soil water is depleted in the root zone, soil water content controls the evaporative regime of the Sahelian land surface. This relation can be expressed as follows:

$$\begin{aligned} \text{ETR}/\text{ETP} &= (1/0.6) * S/S_{max} && \text{if } 0 < S/S_{max} \leq 0.6 \\ \text{ETR}/\text{ETP} &= 1 && \text{if } 0.6 < S/S_{max} \leq 1 \end{aligned} \qquad (4)$$

where *ETR* is the real evapotranspiration, *ETP* is the potential evapotranspiration, $S/S_{max}$ is the fraction of available water in the considered depth of soil.

Potential evapotranspiration was measured at the Banizoumbou weather station situated 2 km from our plateau. Estimated evaporation agreed with that recorded by Culf et al. (1993), and also by Wallace and Holwill (1997) on another tiger bush site in Niger. They found evaporation from bare areas decreased from 4 mm day$^{-1}$ on the day following a rainstorm to 0.5 mm day$^{-1}$ 3 days later.

The remaining unknown in Eq. (2) was runon. Three assumptions were made from our understanding of the water dynamics suggested by experimental data: (i) all generated runoff is transmitted to the downward zone, i.e., no lateral flux of water exists; (ii) runoff from the thicket body is negligible; and (iii) all generated runoff benefits the core of the thicket. The third assumption is the strongest but it highly simplifies the functioning by considering that upslope generated runon simply crosses bare soil and upslope border of the thicket without infiltration benefit. Given the amount of runoff generated on upslope zones, a particular attention must be given to the water balance of the upslope border of the thicket. All assumptions were tested by comparing estimated and actual infiltration.

Following assumption (i), the contribution of each upslope zone (z) to runon in the thicket core is proportional to its relative area. For a transect of unit width, only the length ($L_z$) of each zone is required. These lengths were measured on our tiger bush site (Table 4). A simple infiltration model derived from Eq. (2) can then be developed using two different expressions for source or sink area.

For source areas (senescence zone, bare soil and upslope border):

$$\text{Infiltration}(z) = \text{Rain} - \text{Runoff}(z) \tag{2.1}$$

where runoff in the z zone is estimated using the piecewise linear models.

For sink area (core of the thicket):

$$\begin{aligned}\text{Infiltration} &= \text{Rain} + \text{Runon} \\ &= \text{Rain} + \Sigma_z(L_z/L_{\text{core}} \times \text{Runoff}(z))\end{aligned} \tag{2.2}$$

where $L_z$ is the length of the zth source area.

Using this model, infiltration can be estimated for any incident rainfall on each of the four zones of our tiger bush. In Fig. 6, the infiltration model based on rainfall (thick line) and its 95% confidence interval (dotted lines) is compared with the measured change in water storage corrected by the evapotranspiration (Eq. (3)). The 95% confidence interval of the model equal to the confidence interval of the piecewise runoff model. If the model satisfactorily represents reality, most of observed infiltration depths should remain in the 95% interval. The error associated with change in soil moisture is the sum of instrumental error, calibration error and integration error. Vandervaere et al. (1994) presented an error analysis for estimating the variance of volumetric water content and soil water storage. The error increases with the soil storage. On our site, maximum limits of error on change in soil moisture are 2.3 mm, 1.7 mm, 5.6 mm and 12.3 mm for senescence, bare soil, upslope and core of the thicket, respectively. The error associated with rainfall measurements is about 2 mm (Lebel pers. comm., 1996).

In the senescence zone (Fig. 6a), the model overestimates the infiltration for high rainfalls. This should not be the case if additional runon feeds this zone. Hypothesis (ii) implies that no water runs off the core of the thicket is fulfilled. When rain exceeds 45 mm (highest runoff measurement), the linear extension of the model should overestimate the infiltration. It is likely that the runoff is no longer a linear response to rain. To

Table 4
Length of each zone comprising the tiger bush study site

| | Length | |
|---|---|---|
| | (m) | (%) |
| Downslope border | 12 | 22 |
| Bare soil | 23 | 43 |
| Pioneer front | 13 | 24 |
| Thicket body | 6 | 11 |
| Total | 54 | 100 |

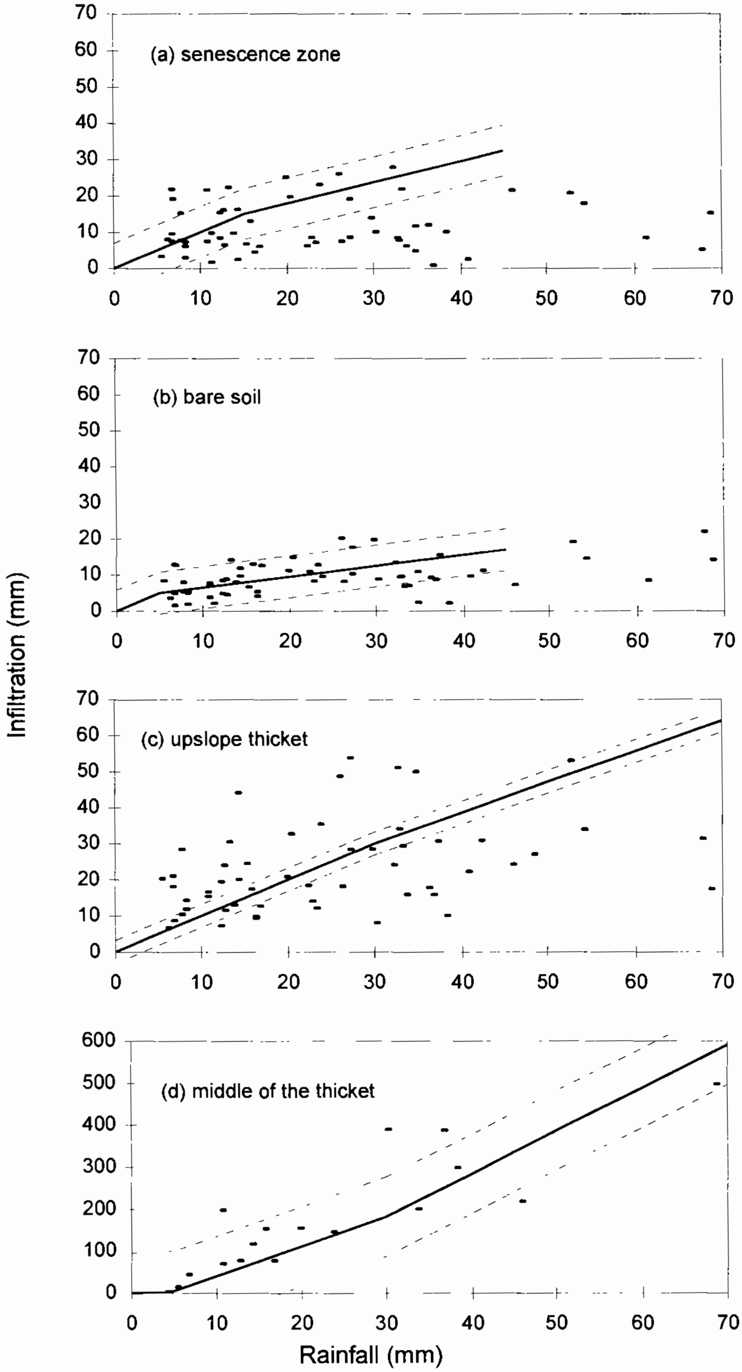


Fig. 6. Observed and modelled change in soil water storage (infiltration) vs. rainfall: (a) senescence zone, (b) bare zone, (c) upslope border, (d) middle of the thicket.

understand the difference between estimated and actual infiltration for lower rainfalls, one must remember that the neutron probe access tubes are not located in the runoff plots and that the soil crusts are spatially variable. Our access tubes are surrounded by erosion crusts, while the senescence runoff plot is mainly covered by structural crusts with a lower runoff coefficient (Peugeot et al., 1997). The overestimation of infiltration in our access tubes may be partially explained by variations of soil properties encountered when generalising from a point measurement to the areal estimate.

For the bare soil zone (Fig. 6b), model estimates fit satisfactorily with actual measurements. This result is important as it is the main source area of runoff, due both to its high runoff coefficient and also its area (43% of a tiger bush unit).

For the upslope border of the thicket (Fig. 6c), the model does not globally over- or under-estimate infiltration. Yet the scattering of the points implies that not only rainfall amount are involved in the determination of infiltration depth in this zone. For instance, initial soil moisture, rain intensity or vegetation development may play a role.

In the core of the thicket, the weighted sum of the upslope runoff (Eq. (2.2)) is compared with the measured infiltration. In this particular area, huge water content variations are observed from border to center, and location of the tube within the thicket must be taken into account. In Mexico, Mauchamp et al. (1994) showed that infiltration is higher in the upslope part of the thicket and then decreases to senescence zone. In Niger, an asymmetric triangle has been used to roughly approximate distribution shape (Fig. 5). Our two access tubes are located in the upper part of the thicket, corresponding to the maximum infiltration potential, or to the summit of the triangle. Given the geometry, the observed water in this location is equal to twice the average core water content. Model output fits fairly well with observed data, the infiltrated water is about 8 × the rainfall volume when rain exceeds 5 mm (Fig. 6). A maximum infiltration of 500 mm (about the annual rainfall depth) has been recorded for a single rainy event 70 mm rain. Globally, the core of the thicket infiltrates about 4 × the rain corresponding to direct rainfall plus incoming runon. The relative contributions of the upslope areas are 10% for senescence, 62% for bare soil and only 1% for upslope border in the beginning of the rainy season (Table 5).

For each source area, error terms (modelled minus observed infiltration) have been correlated with antecedent soil moisture. The stored water has been considered for the

Table 5
Water balance of an elementary tiger bush unit over a period of 4 yr

| | Estimated runoff (% of rain) | Contribution of each component to thicket supply (%) |
|---|---|---|
| Rain | – | 27% |
| Downslope border | 18% | 10% |
| Bare soil | 54% | 62% |
| Pioneer front | 2% | 1% |
| Thicket body | −277%(*) | – |

(*): Negative runoff is infiltration.
Only rains exceeding 5 mm are considered.

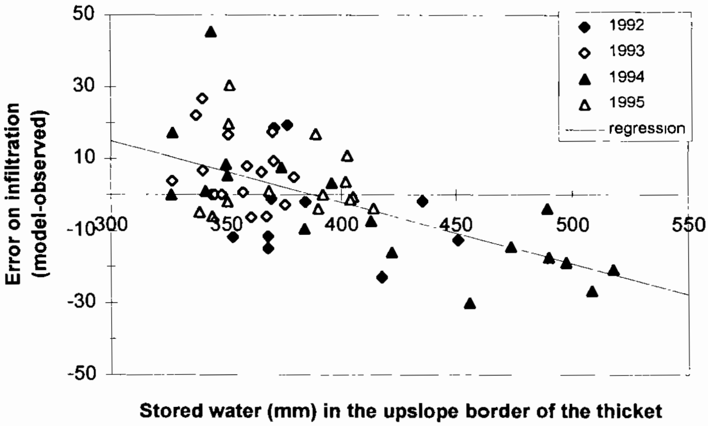


Fig. 7. Error on infiltration in the upslope border of the thicket vs. total stored water in this zone.

0–30 cm surface soil layer and the 0–340 cm total storage. As the determination coefficients between superficial soil water and error of the model are lower than 11% on every zone, they are not significant for our sample. It is the same for the 0–340 cm layer, except for the upslope border. In this case, $r^2 = 34\%$ and the error terms are inversely proportional to soil moisture (Fig. 7). Higher measured water content implies underestimation of the infiltration by the model.

## 5. Discussion

The data set from the tiger bush study site allowed us to verify a simple water balance model at rain event time step. The results of the water balance confirm and quantify the hypothesis on water redistribution among the different zones constituting a tiger bush unit, first developed by Clos-Arceduc (1956). Yet some process must be further identified.

The runoff potential of a tiger bush zone can be described as a function of its surface soil crusts (Thiéry et al., 1995). Our results show good agreement in relative classification but measured runoff ratio is systematically lower than the reference data of Casenave and Valentin (1992). These differences could be explained by the difference in scale of the study areas. We work on large runoff plots (about 80 $m^2$) when they simulate runoff on 1 $m^2$ closed plots. Additionally, natural rainfall intensities may be different than simulated ones.

The bare zone, covered by erosion and gravel crusts, generate large amount of runoff: more than half of annual rain becomes runoff. The infiltration measurements confirm these values, and wetting fronts were never observed to pass 50 cm. The thicket zone, including core and border, receive this runon and redistribute it in a heterogeneous manner.

The upslope border, hardly benefit from this extra supply of water. As a low runoff coefficient was measured on closed runoff plot (only 2% of annual rain produces runoff), a good infiltration potential should be expected. Measured infiltration on open area where all upslope runon arrives is not higher than rain height. The model expresses it by considering runon equal to zero. This result may seem paradoxical, it is due to infiltration dynamics. Vandervaere et al. (1997) measured a saturated hydraulic conductivity of 5.2 E-04 mm $s^{-1}$ for sedimentation crusts of the upslope border, lower than for structural crusts covering downslope border (8.3 E-04 mm $s^{-1}$), yet the latter produce higher runoff. The low runoff height measured in the upslope border of the thicket is not due to high hydraulic conductivity but to the microtopography. The natural obstacles (roots, leaves) create local zones where water is temporarily stored (up to 30 mm) allowing longer time for surface storage infiltration. However, the major part goes through and reaches the body of the thicket. There, the macroporosity (due to microfauna) allows rapid infiltration under the ponded conditions found after rain. Chase and Boudouresque (1989) have shown that a single 0.8 cm diameter termite channel had sufficient capacity to drain 0.6 l $min^{-1}$ during a 30 min test. Therefore, despite receiving important runon, only water stored in the ripples appears to infiltrate in the upslope thicket.

In the upslope border of the thicket, the mean infiltration rate is reproduced, however, our simple piecewise linear model shows a wide scattering when compared with actual measurements. Error analysis shows a correlation between total stored water and error. Whether this relation was due to hydrodynamic properties, i.e., an increase in infiltration capacity with soil water content, the correlation should also be significant with surface soil water. As stored water increase with time, the measured correlation may be due to the joint progress of the rainy season and annual plant development. Moreover, the correlation with stored water is not significant on the other tiger bush zones where very little annual vegetation develops. By the end of the season, annual plants have finished their growth and cover upslope zone of tiger bush (Seghieri et al., 1997). The stems slow down the runon from upslope areas, and the roots brake surface soil crusts. Saturated hydraulic conductivity increases in the subsoil 6-fold compared with the sedimentation crust (Vandervaere et al., 1997). Thus, the plant roots reduce the impeding effect of the sedimentation crusts, allowing more infiltration in the upslope zone compared with the beginning of the season. Termite activity linked to vegetation development should reinforce this trend, as they generate macropores for their harvesting activity. As seen in Fig. 7, the highest values of soil water storage, implying noticeable correction of the modelled infiltration (up to 30 mm) is mainly observed by the end of two long rainy years (1992 and 1994). In 1995, when the model is calibrated with the runoff data, the rainy season did not last long enough for water storage to reach high values. Because of the high variability of Sahelian rainy season (total amount and temporal distribution), a single year monitoring may lead to miss some behaviour pattern. Although limited, this seasonal increase in infiltration potential may be important for vegetation dynamics (wetting front progress from 80 cm to 2 m deep).

The core of the vegetation receives all upslope generated runon, except by the very end of rainy season as discussed above. Our model has not been tested during the end of the season due to lack of measurements. However by this time, infiltration in the core should be reduced due to higher infiltration in the upslope border. Since the observed maximum increase during the four monitored years is about 30 mm in the upslope border, the relative length of the two zones implies a maximum 70 mm decrease of infiltration in the thicket core. This correction is low compared with measured amounts, and close to the model confidence interval (100 mm) at this location. During the first part of the rainy season, the measured infiltration height is indeed striking, reaching 8 × the incident rain recorded in the most favoured location of the thicket and an average of 4 × the rain received over its total length. These significant amounts of available water in the thicket core explain why two Sudanian woody species (*Gardenia sokotensis* and *Combretum nigricans*: Seghieri et al., 1997) are observed there, beyond their climatic optimum. The concentration ratio is high compared to other studied sites: Cornet et al. (1992) measured a concentration ratio of 3.5 at Mapimi (Mexico) and Tongway and Ludwig (1990) report a ratio of 2 for one rain event at Lake Mere (Australia). The concentration ratio varies with surface ratio (bare plus thicket area divided by thicket area) equal to 5 in our site, 4.5 in Mapimi and 2 in Lake Mere. In Niger, surface ratio is shown to be also related to annual rain (Valentin and d'Herbes, 1998).

Macroporosity is a key factor regulating rainfall redistribution among tiger bush. The rapidity of water infiltration in the core of the thicket explains the significant gradient between the core and its borders. All incoming runon is infiltrated in the core, leaving nothing for the downslope border. The downstream zone has an infiltration ratio much lower than one, equal or slightly lower than the modelled infiltration considering runon equal to zero. This observation confirms the conclusion of Galle et al. (1997) which compared two thickets with and without runon contribution. They found that the bare zone contributed mainly to total infiltration in the core, a lesser extent to the upslope border, and a negligible amount in the downslope area. The water deficit in that area, strengthened when annual rainfall is low, explains why most trees are dead in this «senescence» zone. However, water can cross the thicket on special occasions or by some temporary gullies created by human or animal paths. Though rare, these occasions may be important for Sahelian vegetation which is able to benefit from episodic water supply.

## 6. Conclusion

Tiger bush patterning replicates an elementary unit composed of a bare area, the upslope border of a thicket, the body or core of the thicket and its downslope margin or senescence zone. These terms refer to vegetation dynamics, and they reflect different water storage capacities induced by rain redistribution. By measuring both runoff and infiltration, hypotheses on water redistribution can be validated by comparing model estimates with actual measurements. Water balance determined at rain time steps confirms the generally supposed redistribution of rain: three zones generate runoff, with runon benefiting the thicket. However, the results show that despite its favourable location, the crusted upslope part of the thicket does not benefit much from additional water supply. The thicket comprises three zones possessing large differences in available water over a short distance (about 10 m). This sharp gradient is due mainly to changes in macroporosity that allow for extremely rapid infiltration in some zones under ponded conditions. The core of the thicket acts as a sink.

Locally, a tiger bush unit act as source–sink system (Ludwig et al., 1998) but at the plateau scale, the connections of intervening bare areas allow runoff circulation. Numerous gullies rise in the plateau covered by tiger bush, and Peugeot et al. (1997) show that the plateau contributes runoff to the foothills. Obviously, total wood exploitation would lead to very high runoff generation (70% of rain exceeding 5 mm), through destruction of the sink areas leading in term to disastrous erosion in the foothills, as seen on the Filingué region where road allows easy access for wood exploitation. Conversely, some intervening bare areas are essential to the development of the woody vegetation as they bring 62% of the thicket water supply. Planting them with trees must be avoided.

## Acknowledgements

The rain measurements were kindly provided by the EPSAT team. The authors are also grateful to Eric Elguero for his help in the statistical analysis of the data, and to Professeur Baxter Vieux for his advice and help with English. This research was partially supported by Savannah on the Long Term (SALT), core project of the Global Change Terrestrial Ecosystems project and the Hydrological and Atmospheric pilot Experiment in the Sahel (HAPEX-Sahel).

## References

Ambouta, K., 1984. Contribution à l'édaphologie de la brousse tigrée de l'Ouest Nigérien. Thèse Docteur Ingénieur. Univ. Nancy I, 1–116 pp.

Barker T., 1992. Vegetation pattern in the Nigerien tiger bush. Mémoire, Bachelor of Science Dept. Geography, Coventry Polytechnic, 91 pp.

Boaler, S.B., Hodges, C.A.H., 1964. Observations on vegetation arcs in the northern region Somali Republic. J. Ecol. 52, 511–544.

Casenave, A., Valentin, C., 1992. A runoff capability classification system based on surface features criteria in semi-arid areas of West Africa. J. Hydrol. 130, 231–249.

Chase, R.G., Boudouresque, E., 1989. A study of method for revegetation of barren crusted Sahelian forest soils. ICRISAT proceeding of workshop, pp. 125–135.

Clos-Arceduc, M., 1956. Etude sur photographies aériennes d'une formation végétale sahélienne: la brousse tigrée. Bull IFAN, XVIII, Sér. A (3), 677–684.

Cornet, A., Montana, C., Delhoume, J.-P., Lopez-Portillo, J., 1992. Water flows and the dynamics of desert vegetation stripes. In Hansen, A.J., di Castri, F. (Eds.), Springer-Verlag, Coll. Ecological studies, pp. 327–345.

Couchat, P., Carre, C., Marcesse, J., Ho, J., 1975. The measurement of thermal neutron constants of the soil: application to the calibration of neutron moisture gauges and to the pedological study of the soilo. In: Schrack, R.A., Bowman, C.D. (Eds.), Nuclear cross sections and technology. US Dept. of Congress, pp. 516–579.

Cuenca, R.H., Brouwer, J., Chanzy, A., Droogers, P., Galle, S., Gaze, S.R., Sicot, M., Stricker, H., Angulo-Jaramillo, R., Boyle, S.A., Bromley, J., Chebhouni, A.G., Cooper, J.D., Dixon, A.J., Fies, J.-C., Gandah, M., Gaudu, J.-C., Laguerre, L., Soet, M., Steward, H.J., Vandervaere, J.-P., Vauclin, M., 1997. Variability of profile and surface soil moisture content and physical property measurement during HAPEX-Sahel intensive observation period. J. Hydrol. HAPEX-Sahel Special Issue 188–189, 226–268.

Culf, A.D., Allen, S.J., Gash, J.H.C., Lloyd, C.R., Wallace, J.S., 1993. Energy and water budgets of an area of patterned woodland in the Sahel. Agric For. Meteorol. 66, 65–80.

Galle, S., Seghieri, J., Mounkaila, H., 1997. Fonctionnement hydrologique et biologique à l'échelle locale. Cas d'une brousse tigrée au Niger. In: d'Herbès, J.-M., Ambouta, J.M K., Peltier, R. (Eds.), Fonctionnement et gestion des écosystèmes forestiers contractés Sahéliens. Ed. John Libbey, Paris, pp. 105–118

Gavaud, M.,1966. Etude pédologique du Niger occidental ORSTOM ed , Paris, pp. 109–116.

Goutorbe, J.-P., Lebel, T , Tinga, A., Bessemoulin, P., Brouwer, J., Dolman, A.J., Engman, E.T., Gash, J.H.C., Hoepffner, M., Kabat, P., Kerr, Y.H., Monteny, B.A., Prince, S., Saïd, F., Sellers, P., Wallace, J.S , 1994. HAPEX-Sahel: a large scale study of land–atmosphere interactions in the semi-arid tropics. Ann. Geophys. 12, 53–64.

Greene, R.S.B., 1992. Soil physical properties of three geomorphologic zones in a semi-arid mulga woodland. Aust. J. Soil Res. 30, 55–69.

Lebel, T., Le Barbé, L , 1997. Rainfall climatology of the central Sahel during the years 1950–1990. J. Hydrol HAPEX-Sahel Special Issue 188–189, 44–74.

Lebel, T., Sauvageot, H , Hoepffner, M., Desbois, M., Guillot, M., Hubert, P., 1992. Rainfall estimation in the Sahel: the EPSAT-Niger experiment. Hydrol. Sci. J. 37 (3), 201–215

Ludwig, J , Tongway, DE., 1998. Mardsen S. Stripes, strands or stripples: modelling the influence of three landscape banding patterns on resource capture and productivity in semi-arid woodlands, Australia. Catena, this issue.

Mauchamp, A., Rambal, S., Lepart, J., 1994 Simulating the dynamics of a vegetation mosaic a spatialised functional model. Ecol Modelling 71, 107–130.

Menaut, J.-C., Saint, G., Valentin, C., 1993. SALT, les Savanes à Long Terme. Analyse de la dynamique des savanes d'Afrique de l'Ouest: mécanismes sous-jacents et spatialisation des processus. Lettre du Programme Environnement, CNRS 10, 34–36.

Monteny, B.A., Lhomme, J.-P., Chehbouni, A., Troufleau, D , Amadou, M., Sicot, M , Verhoef, A., Galle, S., Said, F., Lloyd, C.R., 1997. The role of the Sahelian biosphere on the water and the $CO_2$ cycle during the HAPEX-Sahel Experiment J. Hydrol. HAPEX-Sahel Special Issue 188–189, 507–525.

Peltier, R., Bertrand, A., Lawali, M., Madon, G., Montagne, P , 1995. Marchés ruraux de bois-énergie au Sahel Bois forêts tropiques 245, 75–89.

Peugeot, C., Esteves, M., Rajot, J.-L., Vandervaere, J -P., Galle, S , 1997 Runoff generation processes: results and analysis of field data collected at the East Central Supersirte of the HAPEX-Sahel experiment. J. Hydrol. HAPEX-Sahel Special Issue 188–189, 181–204

Seghieri, J., Galle, S., Rajot, J.-L., Ehrmann, M , 1997 Relationships between the soil moisture regime and the growth of the herbaceous plants in a natural vegetation mosaic in Niger. J. Arid Environ. 36, 87–102.

Slatyer, R.O., 1961. Methodology of a water balance study conducted on a desert woodland (*Acacia aneura* F. Muell.) community in central Australia. UNESCO, Paris, Coll. Arid Zone Research, pp 15–25.

Thiéry, J M., Valentin, C., d'Herbès, J.M., 1995. A model simulating the genesis of banding patterns in Niger. J. Ecol. 83, 497–507.

Tongway, D.J., Ludwig, J.A., 1990. Vegetation and soil patterning in semi-arid mulga lands of Eastern Australia Aust J. Ecol. 15, 23–34.

Valentin, C., d'Herbes, J.M.. 1998 The Nigerien tiger bush as a natural water harvesting system. Catena, this issue.

Vandervaere, J.-P., Vauclin, M., Haverkamp, R., Cuenca, R.H., 1994. Error analysis in estimating the soil water balance of irrigated fields during the EFEDA experiment: 1. Local standpoint J Hydrol. 156, 351–370.

Vandervaere, J.-P , Peugeot, C., Vauclin, M., Angulo-Jaramillo, R., Lebel, T., 1997. Estimating hydraulic conductivity of crusted soils using disc infiltrometers and minitensiometers J. Hydrol. Hapex-Sahel Special Issue 188–189, 205–225.

Wallace, J.S , Holwill, C.J., 1997. Soil evaporation from tiger bush in southwest Niger. J. Hydrol 188–189, 415–431.