5. Soil Water Balance

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Introduction

In the more than 80 references related to banded vegetation patterns, five continents and 12 countries are represented. The early research concerned only the vegetation pattern itself (Clos-Arceduc 1956). Hypotheses regarding ecological functioning were then proposed between 1956 and 1970 and clearly synthesized by White (1971) for seven countries. He defined the minimum common characteristics necessary for the existence of banded vegetation spatial structure. These characteristics are now well known and include a semiarid climate, high-intensity rainfall, and a gentle slope. These characteristics are cited in almost all the publications on banded vegetation. We will not further review them here but focus instead on what they imply: the importance the spatial redistribution of water in the dynamics and the functioning of tiger bush bands. The areas of sealed, substantially bare soils yield a high proportion of runoff. On encountering the thicket bands immediately downslope, the flow rate diminishes and infiltration occurs, thus providing an additional water supply to the thicket. This process is more active in the upslope part of the thicket and progressively decreases to nil on the downslope edge, where many dead trees are observed. The zone located immediately upslope of the thicket is often called the "pioneer front" (Table 5.1) and is a zone of active plant colonization. Recently, a mathematical model based on two hypothesis: (1) competition for water resources along the slope and (2) synergy with lateral neighbors was successful in reproducing a banded structure from an initially random dis-

Table 5.1. Names Used by the Various Authors to Refer to the Functional Zones Forming a Banded Vegetation Unit

	Australia patterned mulga woodland		Mexico two-phase mosaic "mogote"	Niger tiger bush	
Functional zone	Alice Springs	Lake Mere	Mapimi	Banizoumbou	Say
Bare/herbaceous areas					
Upslope bare area			Downhill bare area		
Central bare area	Intergrove	Runoff zone	Bare area (transit zone)	Bare soil	Bare area
Downslope bare area (pioneer zone)		Interception zone	Deposition area (pioneer zone)	Upslope border (pioneer zone)	Grassy open bush
Bushy areas					
Upslope grove			Upslope vegetation (screen of *F. cernua*)		
Central grove	Grove	Mulga grove	Dense bushy area	Thicket core	Closed bush
Downslope grove			Rear edge of dense bush	Downslope border (senescence zone)	Bare open bush

tribution of vegetation (Thiéry, d'Herbès, and Valentin 1995; Dunkerley 1997). The outputs of these modeling exercises underline the overriding influence that differential spatial water availability has on the formation of vegetation bands.

Despite the obvious importance of water redistribution in tiger bush functioning, only a few studies have actually tried to confirm and quantify the processes and outcomes. In this chapter, we review and compare those studies, which are concerned with quantification of soil moisture, runoff, and evapotranspiration patterns at banded vegetation sites. The studies cover three countries, Australia, Mexico, and Niger, located on three continents. We compare the main results obtained and discuss the similarities as well as the differences between the sites.

One issue that can complicate such a comparison is a difference in terminology. Table 5.1 summarizes the names used for various zones in banded vegetation areas in each continent. In a banded vegetation unit, up to six functional zones can be recognized. These zones can be grouped more generally into "bare area" (including bare soil and sparse annual herbaceous cover) and "vegetated area" (composed of shrubs and/or trees). The precise terminology and definitions of the various functional zones are included in the description of each site.

Australia

The arid and semiarid mulga lands of Australia, where mulga (*Acacia aneura* F. Muell.) forms a significant part of the vegetation, comprise an estimated 1.5 million km^2. These mulga lands can exhibit a banded vegetation pattern (Figures 1.12, 1.13a,b, this volume; chapter 1, this volume). Such a pattern has most commonly been reported from woodlands growing on gentle topographic gradients, where wooded bands are essentially parallel to the contour, separated by sparsely grassed treeless areas. *Acacia aneura* banding has been described as "band–interband" patterning in Western Australia (Mabbutt and Fanning 1987), central Australia (Slatyer 1961), and eastern Australia (Tongway and Ludwig 1990; Dunkerley and Brown 1995).

As Dunkerley and Brown (1995) mentioned in their critical bibliographic analysis of patterned chenopod shrubland in Australia, the literature on vegetation patterning contains a wealth of hypotheses but few firm data. This section deals with results of quantitative studies relating to the soil water balance of patterned vegetation areas in Australia. The presentation focuses on two sites near Alice Springs (Northern Territory) and at Lake Mere (New South Wales).

Alice Springs

Description

Slatyer (1961) investigated this site where classical examples of banded vegetation patterning were found: the area was semiarid (250-mm annual rainfall), with a single rainy season (75% of the rain falls during the 6 summer months) characterized by high-intensity rainstorms. The potential evapotranspiration was high compared with rainfall (2,410 mm yr^{-1}). In addition, the average slope was gentle (0.2%). The interbands had a slightly greater slope than the bands. At this site, individual trees of *A. aneura* (mulga woodland) occurred in bands 5 to 50 m wide and 20 to 400 m long. The interband areas were three to five times as wide as the bands. The soils were highly weathered and of low fertility and had crusted surfaces. There was a marked difference in soil permeability between the band and interband areas, and within the band, permeability was higher close to the trees. The experimental site occupied an area of 25 ha and included three complete band–interband units (Slatyer 1961).

Quantitative Results Related to Soil Water Balance

Although the degree of runoff varied with the amount and intensity of the rainfall, as well as with antecedent soil water, substantial runoff from the interband normally took place with rainfall in excess of 15 mm. With heavier rainfall events, infiltration after rain was almost twice as great in the bands as in the interbands. Given the average widths of the bands and interbands, this represented a runoff percentage of about 20% from the interbands. No deep drainage below 200 cm (access tube depth) was found for the 18 access tubes.

Within the band, Slatyer (1961) clearly underlined the importance of trees in creating a heterogeneous soil water distribution. First, part of the rain is intercepted by the foliage and channeled down the branches and trunks. When rainfall intensity was less than 25 mm h^{-1}, the amount of stem flow was approximately 40% of the rainfall expected on an area equivalent to the horizontal projection of the canopy. Second, the infiltration capacity of the soil was higher close to the trees. Marked differences were found in the infiltration rates measured with a positive pressure head. The infiltration rates varied by a factor of 2 between interband (10 mm h^{-1}) and band (22 mm h^{-1}), but also within the bands: from 22 mm h^{-1} at 0.5 m from tree trunk to 15 mm h^{-1} at 2 m from tree.

Slatyer (1961) investigated differences in evapotranspiration by measuring changes in the soil water content. This was possible because there was no deep drainage. The changes in soil water content (equal to the actual evapotranspiration [AET] were divided by the potential evapotranspiration [PET]) and then plotted against available soil water storage (Figure 5.1). Zero soil water storage was the minimum value measured after a summer period of about 3 dry months. It can be seen that the initial values of AET/PET were close to unity in the interband and were lowest (0.6) closest to the trunk, where most shade occurred. In the interband, after an initial rapid loss of water by direct evaporation from the moist surface horizon, there was a sudden drop in evapotranspiration, as the surface soil dried, to a value determined mostly by the transpiration component. Under the bands, these decreases were much more gradual, with no great difference between 0.5 and 2.0 m from the tree trunk. Slatyer (1961) combined these data with changes in soil water profile and concluded that in the band, most evaporation occurred within 2 to 4 days after rain; afterward, transpiration was the main cause of water loss.

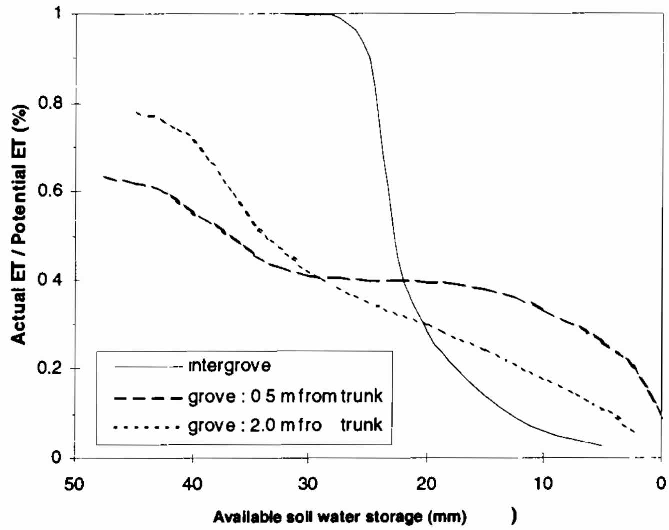

Figure 5.1. Soil water extraction in banded vegetation. Alice Springs (Australia). (Modified from Slatyer 1961.)

The main quantitative soil water balance information from the Alice Springs site is summarized in Table 5.2. From this information, it may be deduced how much extra water the vegetated areas received on average. We know that runoff represented 20% of rainfall events exceeding 15 mm; moreover, 80% of rainfall events are less than 12.5 mm (40% of the total rainfall). Significant runoff was observed for only a few events, typically four rain events of 25 to 33 mm yr^{-1} (or 100 to 132 mm). For these events, ponding and deep soil water penetration were observed in the bands. Thus, about 25 mm or 10% of annual rainfall ran off from the bare areas to the bands. However, as the interbands were three to five times as wide as bands, this translated to an average extra 75- to 125-mm water supply per year, in addition to the 250 mm that fell directly on the vegetated areas. Average annual infiltration in the band areas was thus approximately 140% of rainfall.

Lake Mere

Description

This site located in eastern semiarid Australia was first described by Tongway and Ludwig (1990). This pastoral production zone was selected for its good condition of the *Acacia aneura* vegetation, due to historically low grazing pressure. Average annual rainfall was 308 mm and characterized by large variability both within and between years. Unlike Alice Springs there was no marked rainy season; rain can fall at any time of the year. The overall slope of the site was less than 0.5%.

Table 5.2. Main Characteristics of Studied Sites Related to Soil Water Balance Quantitative Information

	Australia		Mexico	Niger (Africa)	
	Alice Springs	Lake Mere	Mapimi	Banizoumbou	Say
Annual rain (mm yr^{-1})	250	310	270	560	
Coefficient of variation (CV) of rainfall (%)			25	26	
Rainfall events distribution	80% (<12 mm)		80% (<10 mm)	60% (<10 mm)	
Slope (%)	0.2	<0.5	0.6	0.2	<1
Thicket width (m)	5–50		20–70	10–30	10–30
Concentration ratio bare/vegetated areas	3–5	1.3	3.5	2–3 2	
Soil difference bare/vegetated		No	No	No	Yes
Macroporosity in stripes		1 mm	Yes	Yes	6 mm
Runoff (% P) (threshold)					
Central bare	20% (>15mm)	55% (?)	100% (>4mm)	70% (>5 mm)	
Downslope bare				15% (>30 mm)	
Downslope grove				42% (>15 mm)	
Infiltration[a] (%P)					
number of studied events	?	1	16	60	4
Upslope bare	—	—	28%P	—	—
Central bare	80%P	40%P	22%P	20%P	22%P
Downslope bare	—	90%P	82%P	85%P	100–300%P

Upslope grove	—	—	152%P	—	—
Central grove	160%P	140%P	200%P	400%P	200%P
Downslope grove	—	—	123%P	40%P	<P
Annual infiltration[b] (%P)					
Author	Reinterpretation	—	Mauchamp et al. (1994)	Galle et al. (1999)	
Upslope bare	—	—		—	
Central bare	90%P		52%P	46%P	
Downslope bare	—			98%P	
Upslope grove	—	—	283%P	—	
Central grove	140%P		300%P	277%P	
Downslope grove	—	—	137%P	82%P	
Actual evapotranspiration[c]					
Bare			61%P		42%P
Grove			287%P		210%P
					Reinterpretation
Deep drainage	No	No	No	Yes	2–5%P

?, estimated values; —, no data available.
[a]Measured infiltration in the different zones during runoff events
[b]Modeled infiltration over the year (including low rainfall events)
[c]Modeled actual evapotranspiration for average year.

Between band and interband areas, Tongway and Ludwig (1990) described a "grass band" that they called an interception zone (see Table 5.1), associated with the upslope side of bands and occupying 12% of the site. Although noted, such grass bands were not described as an important component of the banded mulga lands of western and central Australia (cf., e.g., Slatyer 1961). Tongway and Ludwig (1990) suggested that this difference could simply be due to differences in livestock grazing pressure, although the Lake Mere site had higher and more reliable rainfall than the other sites reported from Australia. The mulga bands at Lake Mere had only 52% total vegetation cover (12% grass, 40% trees), whereas 20% grass cover was observed in the interception zone and 7% grass cover in the runoff zone. The runoff zone had a stony, strongly crusted surface soil, the interception zone had some cracks, and the runon zone of the mulga bands was covered with litter. Greene (1992) measured infiltration in the field by using a disc permeameter (200-mm diameter) at water supply potentials of –40 and +10 mm. He studied 12 line transects with three replicates in each of the zones.

Quantitative Results Related to Soil Water Balance

Under unsaturated conditions (–40-mm pressure head), there were no significant differences in the sorptivity and infiltration rates between the three zones (Table 5.3). But under saturated conditions (+10-mm pressure head), the soils in the mulga band had five to ten times higher infiltration rate than the soil in the runoff and interception zones (Table 5.3). At negative potential, only the soil matrix was active in conducting water into the profile, and as the soil was of similar textural composition under band and interband, no significant difference was observed in infiltration rate. Under ponding conditions, the presence of macropores allowed rapid infiltration. A positive 10-mm water potential allowed macropores of greater than 0.75-mm diameter to conduct water. Stable macropores (1-mm-diameter pores) were due to faunal activity (ants and termites), plant roots, or cracks were observed in the mulga band and, to a lesser extent, in the interception zone soils but are absent in interband.

Table 5.3. Disc Permeameter Measurements (200-mm diameter) at Supply Potential of +10 and –40 mm on the Three Geomorphic Zones in Lake Mere (Australia)[a,b]

	Supply potential of +10 mm			Supply potential of –40 mm		
	Runoff zone	Interception zone	Mulga grove	Runoff zone	Interception zone	Mulga grove
Sorptivity (mm h–1/2)	13.1	20.5	22.7	16.2	16.6	17.0
Hydraulic conductivity (mm h^{-1})	20	32	245[c]	6	8	6

[a]Each measurement is a mean of 36 replicates
[b]From Greene (1992).
[c]Significant difference between means $p = .05$.

This difference in hydraulic properties resulted in a major redistribution of water between the three zones. After a rain event of 37.5 mm, 16 mm (42%) infiltrated in the runoff zone, 34 mm (90%) in the interception zone, and 52 mm (138%) in the mulga band. Even though water from the runoff zone passed across the interception zone, infiltration there was still less than 100% of the incident rainfall.

The difference in soil physical properties between the three zones were due to a combination of geomorphic processes and the amount of vegetation cover in the different zones. Vegetation had a positive feedback in terms of maintenance of a nutrient cycle and protecting the soil surface from raindrop splash, thus preventing surface sealing. Bioturbation of the soil by fauna such as ants and termites involved in organic matter cycling provides stable biopores for water transport (Tongway, Ludwig, and Whitford 1989). All these factors resulted in the soil under vegetation having improved physical properties such as structural stability and infiltration rate.

The infiltration rates obtained with the disc permeameter on interband areas were later compared with rainfall simulator and runoff plot data (Greene 1993). Infiltration rates for the interband measured by using a rainfall simulator (11 ± 2 mm h^{-1}) were similar to those measured by using a runoff plot during a natural rainfall event of similar intensity (and to those measured with a ring infiltrometer at Alice Springs by Slatyer [1961]). The soil types at Alice Springs and Lake Mere are similar. The infiltration rates measured with the disc permeameter had a higher mean and a wider range (20 ± 12 mm h^{-1}). This is probably due to the smaller area sampled by the permeameter and underlines the spatial variability of infiltration even at fine scale. Although lower than between zones, the intrazone variability of infiltration rate was significant.

Analytical Model

Based in part on the results from Lake Mere, the water and vegetation dynamics of semiarid landscapes were analyzed by Ludwig, Tongway, and Marsden (1994). They proposed a flow- filter model based on the hypothesis of Noy-Meir (1973): given resource limitations, the concentration of natural resources from source areas into sinks result in a level of landscape productivity that is higher per unit area than if resources are uniformly dispersed over the landscape. The vegetation patches act as sinks by filtering and concentrating water and nutrients lost from source areas (i.e., interbands). The aim of the flow-filter model was to determine the area of sink needed to conserve all water within a landscape. In the model, runoff is a function of rainfall input, soil infiltration rate, soil water storage capacity, slope, fetch length, and landscape area. Thus, both the level of water input and the filtering capacity and width of a sink will affect whether any water is lost from the system to the next sink or out of the landscape system.

The simulation model was run using topographic soil and vegetation parameters derived from a range of studies at Lake Mere. They found that for a low rainfall year (160 mm), no water ran out of the bands until they decline to 40 to 60% of the total surface. This closely matched the total area of landscape sinks observed

(43%). However, with 320 mm of annual rain, typical for the site, the system will lose water, even for a completely covered surface. This emphasizes the fact that, although vegetation of semiarid areas has to face high spatial and temporal variability of rain, the system is optimized to survive drought conditions.

Mexico

A two-phase mosaic scrubland, or banded vegetation patterning, in northern Mexico was first described by Cornet, Delhoume, and Montaña (1987). These formations are located in the Mapimi Biosphere Reserve, which forms part of the Chihuahuan Desert (Schmidt 1979). The hydrological functioning of these vegetation formations was investigated experimentally over a 4-year period. The results of these studies are summarized here.

Mapimi

Description

A representative toposequence of the Mapimi Biosphere Reserve was studied that included areas of two-phase mosaic scrubland (Delhoume 1988). The landscape toposequence was 10 km long. It started at a small ridge (cerro) with a maximum height of 1475 m and pronounced slopes (>20%). The elevation and slope decreased over the "bajada" (5% to <1% slope) and finally to the "playa" (slope of <1%). The two-phase mosaics were commonly situated on the gentle slopes of the lower "bajada" (~0.5%). They represented 32% of the 172,000 ha of the Mapimi Biosphere Reserve (Montaña 1992).

The climate was classified as an "arid tropical, continental climate, at medium altitude, with summer rains and cool winters" (Cornet, Delhoume, and Montaña 1988). The average annual potential evapotranspiration calculated by the Penman method was 1800 mm. The average annual rainfall was 279 mm, with a coefficient of variation (CV) of 25% (1978 to 1992). About 70% of rain fell in the 4 months from June to September. Storms were torrential but did not last long: 99% of rainfall events were less than 40 mm and 80% less than 10 mm, representing, respectively, 92% and 37% of total annual precipitation. The rainfall was characterized by strong variability both spatially and temporally (Delhoume 1996).

From a hydrological point of view, the zone formed part of one of the closed (endoreic) basins of the Chihuahuan Desert. The surface runoff occurred as dispersed sheet-flow where the slope was less than 2% and was more concentrated in unchanneled shallow linear depressions or water lanes where the slope exceeds 2% (Breimer 1988).

In aerial photographs (Figure 1.10, this volume), the Mapimi tiger bush appears as a mosaic of dense vegetation bands (or vegetation arcs), alternating with barren zones (Cornet, Delhoume, and Montaña 1988; Cornet et al. 1992). The main axis of every band follows a contour line: lengths of band range from 100 to 300 m and widths from 20 to 70 m. Bare zones were three to four times as wide as the vegetated bands.

Mosaic units at Mapimi were divided into five zones by Cornet, Delhoume, and Montaña (1987). From upslope to downslope, they distinguished (upper part of Figure 5.2)

1. a transit zone with bare ground: the soil surface was covered by erosion and pavement crusts indicating high runoff potential (K_r = 80 to 90% (Casenave and Valentin 1992)
2. a deposition area or pioneer zone covered by sedimentation crusts with polygonal cracks; this pioneer zone was colonized by a sparse low vegetation, essentially characterized by *Tridens pulchellus*
3. an upslope vegetation band densely covered by perennial grass *Hilaria mutica* in 15- to 60-cm-high tufts, under a dense shrub canopy of 1.0 to 1.5 m high, almost exclusively made up of *Flourensia cernua*
4. a floristically more diverse area, consisting of shrubs and a tree species (*Prosopis glandulosa*), from 1.5 to 2.5 m high, followed by open shrubland with fewer species and fading into a rim of old dying tufts of *Hilaria* and a few trees: in this zone, the finely structured soil had a high water permeability, due to the macroporosity caused by mesofaunal activity
5. a zone of bare ground covered by erosion crusts, with a few *Cactaceae* and remnants of dead shrubs

The soil did not show any discontinuities or marked pedological heterogeneity within the two-phase mosaic unit, except for some minor variations in the topsoil (0 to 30 cm) in relation to the plant cover. These variations involved the thickness of the horizons and the organic matter content of the top soil (Delhoume 1988). The slope was irregular and ranged from 0.7 to 0.9% in the transit zone, less than 0.4% in the pioneer zone, and intermediate in the vegetation formation (0.5 to 0.6%). Moreover, the existence of a microrelief (gilgai type) within the vegetation formations differentiated them from the bare zones.

Methods

Soil water content was monitored over a a 4-year period along a transect parallel to the slope and located across one bare area and one vegetation band. Access tubes for a neutron probe were installed to 1.20 m deep in six different locations. These corresponded to the five zones of the vegetation mosaic unit described above, plus an extra one in the rear edge of the dense shrub zone (listed as a separate functional zone in Table 5.1). Measurements were made every 10 days during the rainy season and every month during the dry season. To assess infiltration and runoff more precisely, extra measurements were made before and after 16 storms, which ranged from 7 to 67 mm in size. These data allowed dependable conclusions to be drawn on redistribution of water over the soil surface.

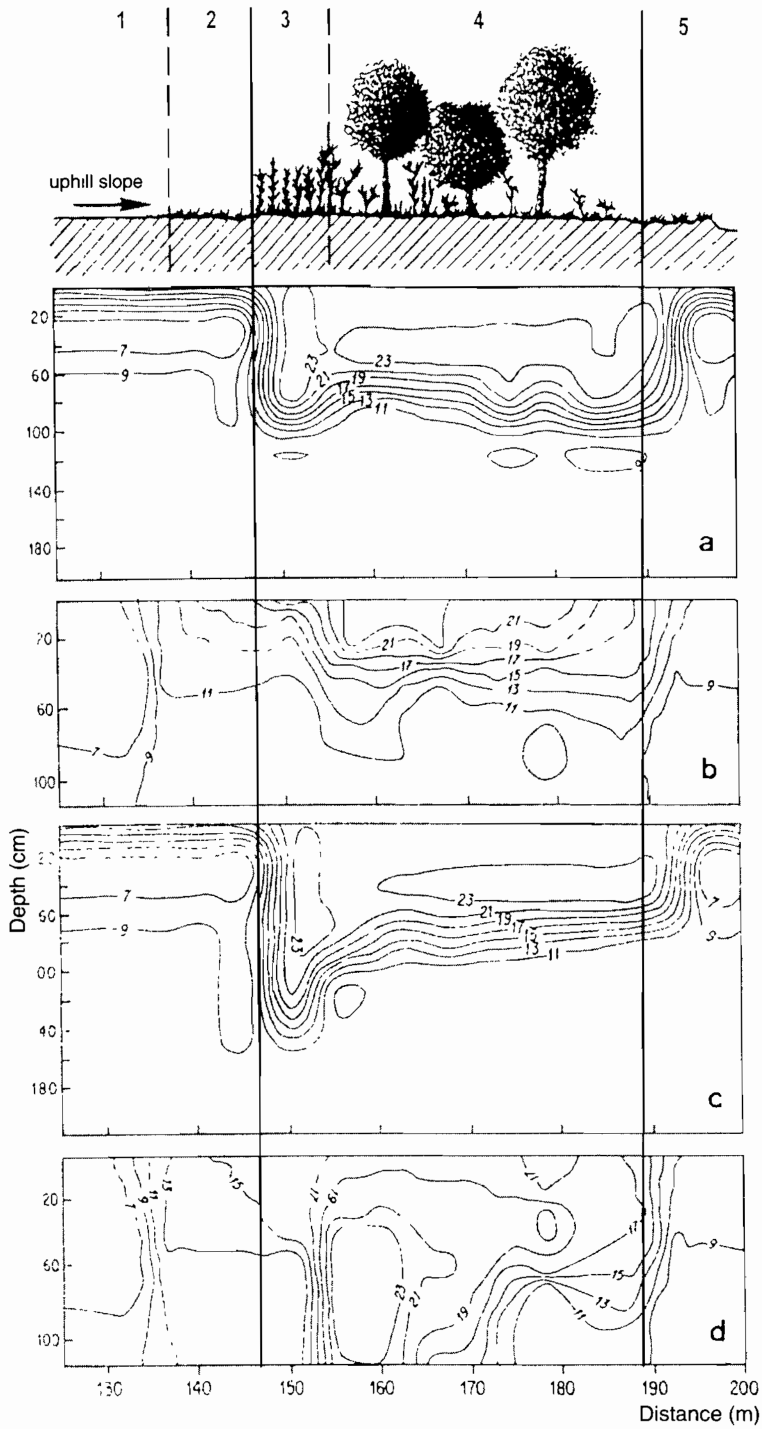

Figure 5.2. Water infiltration in the five zones of tiger bush (Mapimi, Mexico). (Modified from Delhoume 1996.)

Particular attention was paid to neutron moisture meter calibration. The high clay content of the soil (40 to 50%) dominated by smectites, produced cycles of swelling and shrinking. Delhoume (1988) had shown that the bulk density of the soil varied from 1.3 to 1.7 g cm^{-3} as the gravimetric water content varies from 0.32 to 0.05 g g^{-1}.

Quantitative Results Related to Soil Water Balance

The rainfall concentration factor (RCF; change in soil water storage divided by size of rainfall event) was plotted against rainfall for 16 events (Figure 5.3). An RCF of 100% indicates that infiltration equals rainfall. The RCF values of the three "bare" zones (upslope, central, and deposition area) were almost without exception less than 100%. This means that there was almost always net runoff from each of these zones. The two vegetated zones benefited from this additional supply of water and had RCF values of up to 300%. The RCF values were fairly stable for each zone for rainfall events exceeding 7 mm. The mean values of the RCF were 25% for the upslope and central bare area, 80% for the deposit area, 150% for the upslope vegetation zone, and 200% for the dense shrub area. Thus, runoff generated in upslope bare areas (75% of rain) crossed but did not infiltrate in the deposit area. Instead, runoff water infiltrated in the *F. cernua* zone to some extent and even more in the shrub zone. As observed in Australia, and despite its position downslope of the bare area, the deposit zone hardly benefited from the runoff.

This behavior has been simulated in two water-balance models (BIJOU and TLALOC), based on the water-balance equation (Eq. 5.1).

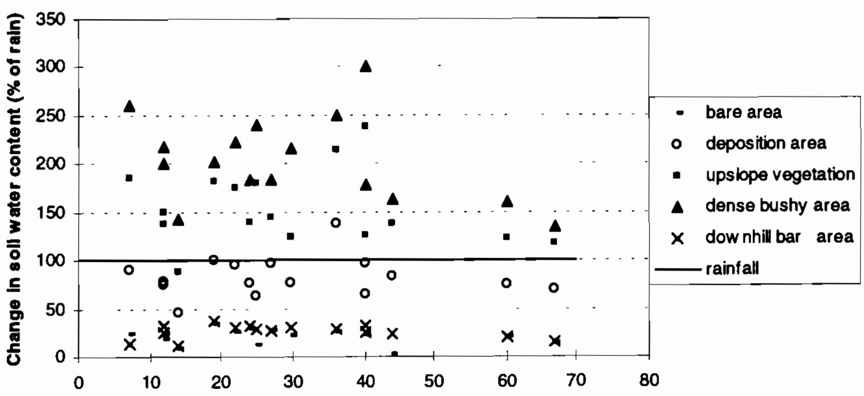

Figure 5.3. Mapimi (Mexico): Section across a vegetation stripe and location of the five functional zones. Associated patterns of soil water content variations after a low-intensity 33-mm rain (a and b) and after a 50-mm storm (c and d). For each rain, the simulated data are presented above the measured ones. (From Mauchamp, Rambal, and Lepart 1994.)

$$\Delta S = P - R - D - AET \tag{5.1}$$

where

ΔS is the change in soil water content
P is the precipitation
R is the runoff (or runon)
D is the loss through drainage
AET is the actual evapotranspiration

This equation expresses conservation of water in each zone during a time-step. In Mapimi, D was assumed to be nil as the wetting front never passed the monitored depth (120 cm).

The BIJOU model (Cornet 1981; Cornet and Rambal 1981) estimates AET from the experimental relationship of Eagleman (1971), which used the PET values of Penman, the vegetation cover, and the relative soil moisture. After calculation of the AET value at each site, the R value was determined step by step so that the resulting water storage matched the measured storage (Cornet et al. 1992). The AET for the bushy area was about three times higher than the rainfall (Table 5.4) and matched its high measured infiltration (Figure 5.4). Moreover, in this zone, vegetation cover reduced losses through soil evaporation, and consequently the ratio of evapotranspiration to water supply was maximized.

The TLALOC model, developed by Mauchamp, Rambal, and Lepart (1994), takes into simultaneous account within-patch dynamics, ecotone dynamics, and the interactions between patches and flows. In each square meter of a transect perpendicular to a band, both functional and dynamic processes were simulated. In this section, we focus on the functional modeling of water balance of the TLALOC model. In this model, AET and R are simulated, and ΔS is the output that is compared with actual measurements. The runoff is assessed in each quadrat (1 m^2) by

Table 5.4. Calculated Values of the Water Budget Components (in mm) during the Period February 8 to September 9, 1985, in Mapimi (Mexico)[a]

		Upper bare zone	Upslope part of vegetation stripe
Rainfall (mm)[b]		227.7	227.7
Potential evapotranspiration (mm)[c]		1353	1353
Initial water storage (mm) 0–120 cm[b]		72.7	106.9
Final water storage (mm) 0–120 cm[b]		75.2	178.2
Actual evapotranspiration (mm)[c]		138.7	654.3
	(%P)	61%	287%
Runoff	(mm)[c]	+86.5	–497.9[d]
	(%P)	38%	219%

[a]From Cornet et al. (1992)
[b]Measured value
[c]Calculated value.
[d]Negative value corresponds to runon.

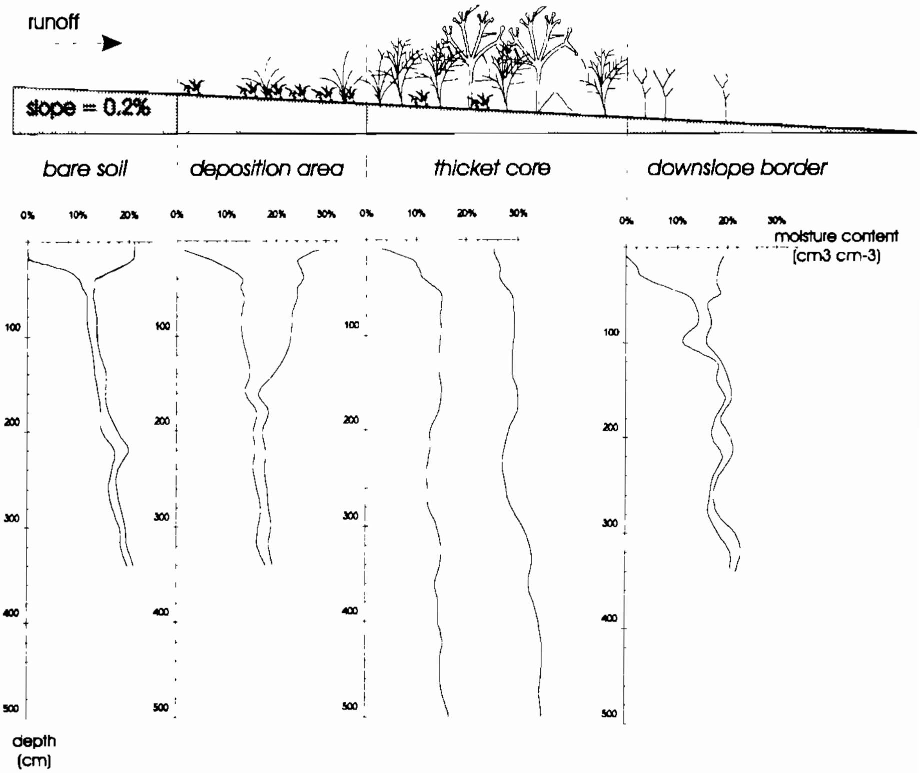

Figure 5.4. Annual range of variation in soil moisture content across a tiger bush unit. (From Galle, Seghieri, and Mounkaila 1997.)

using the USDA Soil Conservation Service method. Compared with the original equations (Boughton 1989), water input (W) is composed of rain plus runoff coming from the upslope quadrat. Only one parameter ($I_{VC(x)}$; a surface water storage or retention factor) is needed to assess the runoff of any quadrat (R_x):

$$R_x = (W_x - 0.2\, I_{VC(x)})^2/(W_x + 0.8\, I_{VC(x)}) \quad \text{for } W_x \geq 0.2\, I_{VC(x)} \qquad (5.2a)$$

$$R_x = 0 \quad \text{for } W_x < 0.2\, I_{VC(x)} \qquad (5.2b)$$

W_x is the water input = $P + R_{x-1}$
R_{x-1} is the runoff coming from the upslope quadrat
$I_{VC(x)}$ is the potential maximum retention of the quadrat, related to its vegetation cover (VC)
x is the quadrat position

Two parameters corresponding to bare soil ($I_{VC=0}$) and complete cover ($I_{VC=1}$) were determined from the infiltration measurements of Delhoume (1996). Any intermediate position was related to the percentage of VC by a sigmoidal curve. This method permits cover to evolve over time but does not assume landscape zonation. However, a realistic model should generate or maintain zonation. The remaining water was redistributed vertically within the profile by using a reservoir model. After rain, the AET consisted of evaporation and transpiration. The ratio of partitioning was linked to the VC. Evaporation was modeled with the Ritchie (1972) equation, transpiration using the function proposed by Feddes, Kowalik, and Zaradny (1978). This function needed a soil water retention curve, which is difficult to estimate, but the maximum depth reached by roots is a more important factor for which field measurements were available. The maximum root depth was 2 m for the trees.

Mauchamp, Rambal, and Lepart (1994) calculated the water budget for 13 years from initial in situ conditions. They found a mean runoff of 55% from bare zones (VC = 0). This percentage was reduced to 25% when a 50-m-wide vegetation band was assumed to be present. The system therefore was not closed for individual mosaic units so that water supply was higher for the bands lower in the landscape. This would explain the observation of Cornet and colleagues (1992) that the broadest bands are to be found in the lower part of the toposequence.

According to the model calculations, the annual soil water budget was stable: little change was observed in the soil water content from one year to another. The AET was found to be equal to infiltration. Modeled infiltration reached 300% of total rainfall in densely vegetated areas, 283% in the upper edge, 137% at the rear front, and only 52% in bare areas (Table 5.4). The average modeled infiltration rates were slightly higher than those measured. This was because the modeling included all rainfall events throughout the season, including those that produced no runoff but infiltrated 100%.

These patterns of rainfall redistribution within a two-phase mosaic unit may vary with the intensity of rainfall and with initial soil moisture content. A pronounced gradient of soil water content was simulated within the band after a heavy storm of 50 mm, but a more homogeneous water content was obtained for low-intensity rain (see Figure 5.2). Even though TLALOC overestimates the infiltration in the *F. cernua* zone, these results were in remarkable agreement with field data. Measured maximum infiltration rates were also found downslope in the dense shrub zone. Overall, it can be concluded that at Mapimi, too, the spatial and temporal water availability determined vegetation productivity and that among perennial vegetation, the shrubs in the central dense shrub zone were more sensitive to the benefits of runon than the grasses in the upslope vegetation.

Niger

Tiger bush patterned vegetation was first described in Niger by Clos-Arceduc (1956) based on aerial observations. This type of vegetation covers one-third of Sahelian Niger (between 400- and 700-mm annual rainfall). It occurs exclusively on plateaus, capped with a thick Pliocene ironpan (Gavaud 1965). The shallow (25 to 85 cm) gravelly soils have low plant nutrient status (Ambouta 1984) and are poorly developed.

Since 1992, hydrological and ecological studies related to tiger bush functioning were undertaken in Niger as part of two international experiments, HAPEX-Sahel[1] (Goutorbe et al. 1994) and GCTE-SALT[2] (Menaut, Saint, and Valentin 1993). Within these larger experiments, the tiger bush was studied intensively at two sites: near Banizoumbou, 50 km east of the capital Niamey, and near Say, 30 km south of Niamey (Figures 1.3a and b and 1.5, this volume). The common aims and soil water monitoring procedures are described by Cuenca and colleagues (1997). The annual potential evaporation is almost 2500 mm. Mean annual rainfall in the Niamey region for the period 1905 to 1989 was 560 mm, with a standard deviation of 140 mm (Lebel, Taupin, and d'Amato 1997). The year can be divided into a dry and a rainy season, with 75% precipitation falling between July and September. At this latitude, rainstorms are mostly convective and display high spatial variability at the event as well as the seasonal scale (annual rain CV = 26%). For example, during 1992 two stations less than 10 km apart recorded annual totals of 510 and 780 mm, respectively (Lebel and Le Barbé 1997).

Banizoumbou

Description

The Banizoumbou plateau is to the northeast of the Niger River and lies at about 250 m above sea level. The general slope of the plateau is about 0.2% (range, 0.06% to 0.5%) (Galle, Ehrmann, and Peugeot 1999). The study site comprised a typical tiger bush pattern with trees covering 25% of the area. Couteron and others (2000) studied the vegetation of this plateau along a 700-m-long transect crossing eight vegetated bands. They found that the average width of the perennial vegetation bands was 10 m (±7 m) and of the bare areas 50 m (± 28 m). The high variation was due to the undulating border of the thickets. The main woody species are *Combretum micranthum* G. Don and *Guiera senegalensis* J.F. Gmel., which average 2.40 m in height. The bands had distinct vegetation composition zones on an upslope-to-downslope gradient.

On a nearby site, Thiéry, d'Herbès, and Valentin (1995) observed that soils in and between vegetation bands showed few morphological differences, apart from those that can be directly accounted for by the influence of the vegetation itself (i.e., higher porosity and rooting within the vegetated bands). These observations are consistent with other soil surveys of Nigerian tiger bush (Ambouta 1984; Barker 1992; Bromley et al. 1997a). Although soil textural properties show few differences, the soil surface presents various types of crusts organised in a predictable succession along the slope, as described at Banizoumbou by Seghieri and co-workers (1996). The basic tiger bush unit was composed of a bare area with erosional crusts, changing to depositional crusts at its downslope edge, which merged into

[1]HAPEX-Sahel: Hydrological and Atmospheric Pilot Experiment in the Sahel.
[2]GCTE-SALT: Global Change Terrestrial Ecosystems—Savane à Long Terme core project.

a shrub zone divided into two zones, the core and the downslope margin. The deposition area, covered by annual grass and sparse shrubs, was considered either as the downslope part of the bare area or an upslope border of the thicket, depending on authors.

Galle, Ehrmann, and Peugeot (1999) studied both water storage to a depth of 5.60 m and runoff on three plots of about 50 m^2. Soil moisture profiles were measured in two transects of neutron probe access tubes. Each transect, installed perpendicularly to a different vegetation band, included at least one access tube in each of the four zones of the tiger bush (Figure 5.4). Soil moisture profiles were monitored at a rain-dependent time-step (1, 2, and 4 days after rainfall). Measurements were progressively decreased to once monthly during the dry season. The observation period covered 4 years, including both relatively poor (–25%) and wet (+21%) rainy seasons.

Quantitative Results Related to Soil Water Balance

The measured infiltration showed sharp variations in the different landscape zones. The infiltration in the core of the band was rapid, and the wetting front passed 5.60 m during the rainy season, whereas it hardly reached 50 cm at the downslope edge of the band (Figure 5.4). Data from the runoff plots showed that on the three different crusted zones, runoff has a classic piecewise linear relationship with rainfall amount: no runoff is observed below a rainfall threshold, but above this value, runoff varies linearly with rain (Table 5.4; Galle, Ehrmann, and Peugeot 1999). There was a different rainfall/runoff threshold for the each of the three runoff generating zones. At the seasonal scale, runoff was 18% of annual rainfall on the downslope of band zone, 54% on bare soil, and 2% on the deposition zone. Galle, Ehrmann, and Peugeot (1999) tested this simple runoff model against soil water storage data. For 60 rainfall events over 4 years, changes in soil water storage, equivalent to infiltration, were compared with the difference between rain and estimated runoff (Figure 5.5). In the core of the band, the measured infiltration was reduced to 16 events, otherwise deep drainage occurred. The deposition area did not benefit from upslope runoff. Whereas in the core of the thicket, measured infiltration corresponded with the sum of the contributions of upslope zones, weighted by their relative lengths. Thus, the downslope border of the vegetated band contributed 10% of the adjacent thicket supply, the bare area 62%, the deposition area only 1%, and direct rain 27%. This means that the average water accumulation in the thicket equaled four times the incident rainfall. These significant additions of water in the thicket core explained the presence of two Sudanian woody species normally found in a more mesic climate (J. Seghieri, pers. comm.). However, as also observed in Mapimi, the water redistribution was not homogeneous within the core of the thicket. At the most favorable location (upper edge of the thicket core), infiltration depth was measured to be about eight times incident rainfall. The important runoff, mainly generated on the impervious bare area, crossed the deposition area without infiltrating to the entire benefit of the thicket core. The infiltration percentage measured in the deposition area was explained by

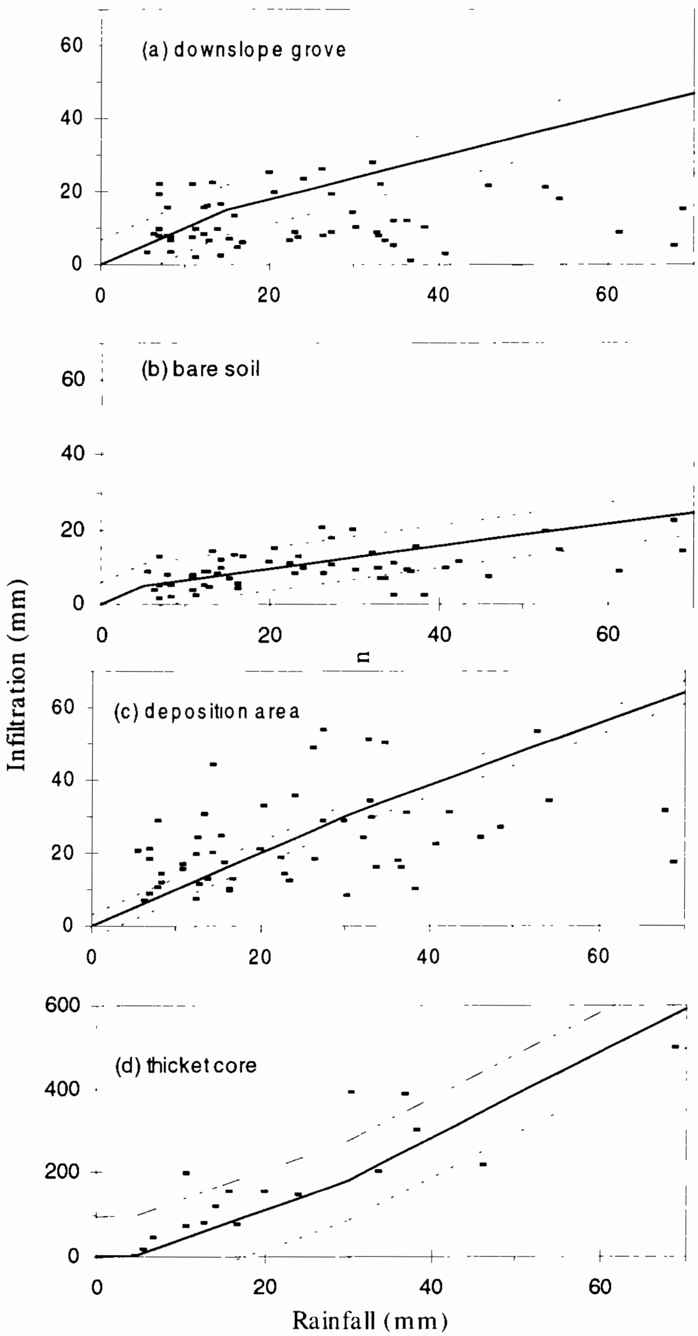

Figure 5.5. Observed and modeled change in soil water storage (infiltration) versus rainfall. (Reprinted from Catena 37, Galle, Ehrmann, and Peugeot, Water balance in a banded vegetation pattern, pp. 197–216, Copyright 1999, with permission from Elsevier Science.)

combination of its low microtopography and its low inherent infiltration rate. The natural obstructions caused by biological activity in the thicket core create a counterslope, so that water ponds upslope in the deposition area where sedimentation crusts were observed. However, infiltration rates in this zone were low (K_s = 1.8 mm h^{-1}) (Vandervaere et al. 1997), and the shallow depressions quickly overflowed into the core of the thicket where macropores permitted rapid infiltration under ponded conditions observed during rain. Little or no runoff was therefore available for the downslope border of the thicket, which was consequently only rain-fed. It should be added that the deposition area was the only zone to exhibit a cyclic seasonal trend in infiltration. By the end of the rainy season, it had enhanced macroporosity, due to annual vegetation growth and termite activity, and was able to infiltrate larger amounts of water from late rains.

To verify the conclusions regarding the importance of runoff for the survival of the bands of vegetation, a wall was built to prevent runon to the vegetation band (Seghieri and Galle 1999). The wall was located at the boundary between the bare soil zone and the upper edge of the deposition area. The difference in infiltration and in plant survival between the treatment and control confirmed that the overall runoff process advantaged only the core of the band during an average rainy season (about 560 mm). However, toward the end of a wetter rainy season (672 mm), the deposition area and downslope edges of the band also received extra water (Galle, Seghieri, and Mounkaila 1997). In the treatment deprived of runon, herbage growth was severely reduced in the deposition area, whereas only a smaller effect was observed in the thicket core. Here, the infiltration capacity was so high that even a reduction in water input (by a factor 8) could not induce a water deficit in the main rooting zone (0 to 1 m). Although strongly stressed, shrub species located in the deposition area survived a 45% reduction in water infiltration. The spatial organization clearly made the whole system resilient in the face of temporal rainfall variations (Seghieri and Galle 1999).

At Banizoumbou, Galle, Ehrmann, and Peugeot (1999) also noted that, although a single tiger bush unit acts as a source-sink system, at the plateau scale hydrological connections between intervening bare areas allowed some runoff from the plateau to take place. However, Peugeot and associates (1997) showed that the runoff over the edge of the plateau mainly comes from the bare border of the plateau.

Say

Description

The Say plateau is located on the southern side of the Niger River. Its vegetation and altitude are comparable with those of the Banizoumbou plateau. The tiger bush units were divided into four classes of vegetation, namely, bare ground, grassy open shrub (deposition area), closed shrub, and bare open shrub. This is similar to landscape zonation at Banizoumbou. Five transects of neutron probe access tubes were installed at right angles to vegetation bands. Tubes were installed to a depth varying from 1 to 6 m. The time interval between the measurements before and af-

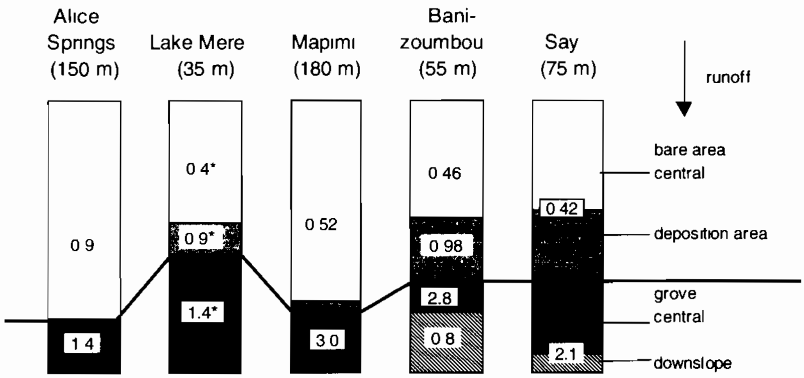

Figure 5.6. Rainfall concentration factor versus vegetation contraction on all studied sites. Lake Mere results (*) refer to a single 37-mm rainfall.

ter rain ranged from 1 to 3 days. Note, however, that relative proportions of each zone may vary with the site (Figure 5.6), which may be due to slight differences in ecological circumstances but also to the difficulty in clearly determining the boundaries of the zones. Most of the hydrological fieldwork was carried out during the 1992 rainy season (Bromley et al. 1997a).

Quantitative Results Related to Soil Water Balance

Observations revealed that runoff from bare areas began within minutes of the start of a rainfall event. The runoff reached the deposition area where the water tended to pond in slight depressions. The overflow from these depressions disappeared into the litter cover associated with the dense bush zone (Bromley et al. 1997a), as also observed at Banizoumbou by Galle, Ehrmann, and Peugeot (1999).

At –40-mm hydraulic potential, infiltrometer measurements showed similar infiltration rates and hydraulic conductivity on the bare soil, the deposition area, and the core of the thicket (Table 5.5). This reflects the similarity of the soil matrix or texture of all the zones of tiger bush. Ponded hydraulic conductivity for the bare ground and the deposition zones were similar to the –40-mm data, but the soil under the core of the thicket had an infiltration rate an order of magnitude higher, as also observed in Australia (see Table 5.2). Examination of the soil profile showed that in the core of the thicket, large pores (≤6 mm) perforate the soil surface. Dye tests revealed the presence of preferential flow along active and inactive root channels and termite tunnels, in addition to matrix flow (Bromley et al. 1997a).

Bromley and colleagues (1997a) calculated the rainfall concentration factor (the ratio of change in water storage to rainfall) for four rainfall events. The values obtained ranged from 22% in the bare zone to 350% in the deposition area. The average rainfall concentration factor was about 200% in the core of the thicket. These results were similar in principle but different in magnitude from those of Galle, Ehrmann, and Peugeot (1999). The differences may be related to the lower number of measurements at Say but also to differences in site organization. The bare

Table 5.5. Measured Surface Saturated Conductivity *K* of Different Surface Type in Say (Niger)[a]

	Matrix potential	
	−40 mm	−5 mm
Bare open bush (downslope grove)	12	9
Bare area (central bare area)	15	14
Grassy open bush (deposition area)	8	7
Closed bush (central grove)	6	37

[a]Modified from Bromley et al. (1997a).

zone–to–vegetation zone ratio was only 2 at Say, for instance, whereas it was 2 to 3 at Banizoumbou. Moreover, the drainage component was unknown at Say and may be important. It was not in Banizoumbou where such rain events were excluded. One cannot exclude also some geological differences between the two sites located on either side of the Niger River.

Culf and assoicates (1993) presented some measurements of the total evapotranspiration from the same tiger bush as Bromley and colleagues (1997a), including both bare and vegetated zones. When the soil was wet, Culf and associates (1993) measured maximum area average evapotranspiration rates of 5 mmd^{-1}. The total evapotranspiration of the 1990 season (428 mm) was estimated to be 97% of the rain ±10%, leaving little for runoff or recharge. Culf and colleagues noted the need to separately determine the evaporation from the bare soil bands. On the same site, Wallace and Holwill (1997) used the Bowen ratio energy budget approach to measure soil evaporation, placing the sensors close to the soil surface. They measured that the evaporation from bare areas decreased from 4 mmd^{-1} on the day following a rainstorm to 0.5 mmd^{-1} 3 days later (cf. results from Alice Springs in Figure 5.1). They calibrated the Ritchie (1972) approach with these data and simulated soil evaporation over an 11-year period. Annual evaporation came to 42% of rainfall when rainfall was close to the average of the area (560 mm) and markedly increased in drier years. For 1984, when rainfall was only 260 mm, they calculated that 79% of the rainfall evaporated. They estimated that bare soil runoff tends to zero when rainfall decreases to less than 200 mm yr^{-1}.

Conclusions

The studied sites show some common characteristics with respect to the soil water balance despite obvious site differences (see Table 5.2). First, all sites have a semiarid to arid climate, with potential evaporation much higher than annual rainfall. However, the total annual rainfall differed greatly from 250 mm in Alice Springs to 560 mm in Niger. All sites have some heavy rainstorms, but they are not necessarily restricted to a particular season: at Lake Mere, they can occur at any time of year. A significant part of the seasonal rainfall at all sites comes in small events: typically, 80% of annual total is in rainfall events of less than 10 mm. Thus, only a few rain events (four to eight per year) generate runoff and consequent water redistribution.

Slopes everywhere are gentle and never exceed 1%; thus, sheet runoff is the dominant process. The soil texture is not greatly different between band and interband at all sites, but soil surface crusting, porosity, and organic matter content vary markedly with cover.

For each zone at each site, the major results concerning infiltration for a mean year are summarized in Figure 5.6. On bare crusted soil zones, there is a threshold rainfall quantum varying from 4 to 15 mm (see Table 5.3) after which a large proportion of the rainfall runs off, except at Alice Springs, where only 20% runs off. This runoff transits the downslope bare area or deposition zone with no significant infiltration compared with the huge volumes of incoming water, which is composed of direct rainfall plus runoff from upslope. In Niger and Mexico at least, the downslope bare area is covered with sedimentation crusts, which result from deposition in standing water. The water tends to pond in slight depressions where fine particles deposit and the resulting infiltration rates are low (2 mm h^{-1} measured in Niger). Sedimentation crusts are rarely seen in Australia, where raindrop-induced crusts are common (D. Tongway, pers. comm.). Annual grasses and herbs and colonizing shrubs are found in this zone in Mexico and Niger. The overflow from these depressions disappears into the litter cover of the core of the band. Here, in contrast to bare crusted soils, there are macropores resulting from roots or bioturbation (observations from Lake Mere in Australia, Mexico, and Niger). Macroporosity plays a major role in water redistribution within the tiger bush unit as it facilitates rapid infiltration under ponded conditions, generally observed during rain. It has been shown in each continent that the soils have comparable infiltration rates on bare soil and vegetated bands for negative pressure head, when the soil matrix governs infiltration, but huge differences are observed under ponded conditions. The macroporosity of the shrub bands results in infiltration rates of four to 10 times greater than the bare/herbaceous areas. Within the vegetation band, infiltration rates are not homogeneous. Slatyer (1961) emphasized the role of roots or distance to a trunk. In Burkina Faso, Ouedraogo (1997) reported that infiltration rate was related to the distance from an active termite mound, with a maximum value observed for the maximum harvest activity of *Macrotermes* (5 to 10 m).

These hydrodynamic characteristics lead to marked contrasts in soil water storage within banded vegetation units. The rainfall concentration factor in the thicket core (infiltration in the vegetated band divided by rain) varied with the studied sites and was linked to the ratio of total to vegetated area (Figure 5.7). However, this was not the only factor. At Lake Mere in Australia and in Say and Banizoumbou in Niger, maximum use was made of rainfall (rainfall concentration equals vegetation concentration), whereas at Alice Springs, much water apparently is not used by the local vegetation. The low runoff coefficient of the bare soil in Alice Springs (20%) did not contribute a lot of water to the band, and there may have been a considerable amount of deep drainage under the bare areas.

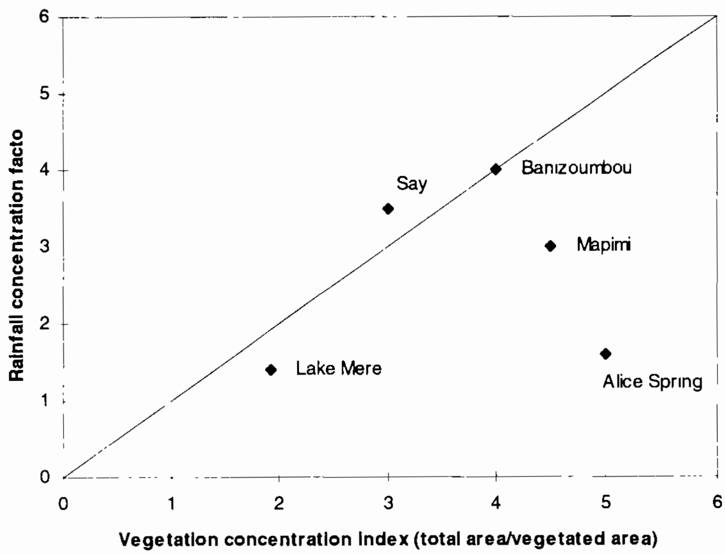

Figure 5.7. Percentage of each functional zone in a banded vegetation unit, for the five studied sites. Total length of a unit is noted in brackets. Total infiltration for average year (%P) is mentioned when available.

However, if the system is able to maintain all water resources within the banded vegetation unit, it should be well adapted to the climate. There have been some attempts to answer this question. At Lake Mere in Australia, Ludwig, Tongway, and Marsden (1994) showed that runoff from the system depends on the amount of annual rain. For a low-rainfall year, the bands retained all the incoming runoff water, but for years with mean rainfall, water left the system via runoff. In Niger, rain stayed in the source-sink unit, but deep drainage was observed in the soil profile, even during average years (Bromley et al. 1997a; Galle, Seghieri, and Mounkaila 1997). Wallace and Holwill (1997) estimated the recharge from modeled evapotranspiration measurements and arrived at an average figure for the site at Say of 3% of the average annual rainfall of 560 mm ±10%. This is equivalent to an average of 15 to 19 mm yr^{-1}. Bromley and colleagues (1997b) analyzed a 70-m-deep chloride concentration profile on the edge of a slight depression in a tiger bush area only 10 km from the site at Say described above. They found a mean recharge rate of 13 mm yr^{-1} (range, 10 to 19 mm or 2 to 3% of annual rainfall). For the total upland landscape in southwest Niger, including the valleys that separate different plateaus with tiger bush vegetation, regional recharge of the water table mainly takes place below gullies and pools and is about 10% of annual rain (Leduc, Bromley, and Schroeter 1997). In Mexico, although there was high runoff generated from the bare soil (75% of precipitation [%P]), the Mapimi site is clearly below the 1/1 curve (Figure 5.7). Mauchamp, Rambal, and Lepart (1994) calculated that 25% of runoff left the system, which was supported by field observations, in that the bands are wider in the downslope areas of the landscape, which receive the runoff. In summary, Nigerien tiger bush is about optimum for the actual climate: the hydrological contrast between vegetation and bare soil is high, with no runoff out of the system and little deep drainage (3%P). In Mexico and Australia, results are not so clear-cut because water does leave the system. However, the efficiency of the system cannot be reduced to simply the behavior in an average year, as high interseasonal rainfall variability (CV = 25%) is a characteristic of semiarid climates.

All reviewed studies of banded vegetation showed important changes in soil water balance of banded vegetation landscapes with the amount of annual rainfall. Continuing complementary studies (chapter 8, this volume) are using the functional TLALOC model (Mauchamp, Rambal, and Lepart 1994) to study a long time series including contrasting rainy seasons. This model, designed in Mexico, has also been tested on another site (Banizoumbou, Niger). The model accurately predicted the water redistribution in the different zones after the runoff module was slightly modified to take account of measured observations (Ehrmann 1999). The weakest point of the model is in the downslope bare area simulation, where infiltration and hence vegetation development are overestimated. The model could be improved by taking into account not only the overall amount of water but also runoff rate in relation to infiltration capacity of each quadrat of the tiger bush unit.

Global climate changes may affect the runoff/runon balance of the banded vegetation types discussed in this book. As an example, Culf and associates (1993) estimated that the Nigerien banded system could not function below 200 mm rainfall yr^{-1}. Increasing anthropogenic pressure could also modify the ecosystem function. Each reported study used as natural and undisturbed a site as possible. Scenarios of degradation or desertification have not been factored into the models yet. However, even low-density sheep grazing may significantly modify the functioning of banded vegetation as noted by Tongway and Ludwig (1990). In Niger, an additional fast-increasing pressure is the exploitation of tiger bush wood for domestic use (Peltier et al. 1995). Obviously, total wood exploitation would eventually generate high runoff (70% of rain exceeding 5 mm) through destruction of the sink areas, leading in time to disastrous erosion in the footslopes, as already seen in the Filingué region. Conversely, the maintenance of the bare areas in tiger bush is essential for the survival and productivity of woody vegetation as they bring 30 to 60% of the thicket water supply. Planting the bare zone with trees, as previously attempted in revegetation projects in Niger and elsewhere in West Africa, must be avoided.

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