ELSEVIER

Journal of Hydrology 198 (1997) 1–29

Journal of Hydrology

The role of surface water redistribution in an area of patterned vegetation in a semi-arid environment, south-west Niger

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Received 1 July 1996; revised 13 November 1996; accepted 14 November 1996

Abstract

The surface hydrology of a semi-arid area of patterned vegetation in south-west Niger is described. In this region alternating bands of vegetation and bare ground aligned along the contours of a gently sloping terrain give rise to a phenomenon known as 'brousse tigrée' (tiger bush). At the selected study site the vegetation bands are 10–30 m wide, separated by 50–100-m-wide bands of bare ground. Five species of shrub dominate, *Guiera senegalensis*, *Combretum micranthum*, *C. nigricans*, *Acacia ataxacantha* and *A. macrostachya*. Herbaceous vegetation is generally limited to the upslope edges of vegetation bands.

A comprehensive field programme was undertaken to investigate the hydrology. Topographic, vegetation and surface feature surveys were carried out in conjunction with the measurement of rainfall, surface and subsurface hydraulic conductivity, particle size and soil moisture content.

Four types of vegetation class are recognised, each tending to occupy a constant position relative to the others and to the regional slope. In a downslope direction the classes are: bare ground, grassy open bush, closed bush, bare open bush, bare ground etc. The nature of the ground surface is closely linked to the vegetation class. Over the bare, bare open and grassy open classes various types of surface crust are present with each type of crust tending to occupy a constant position on the regional slope relative to the vegetation class and other crust types. Below closed bush crusts are generally absent. The typical downslope sequence from the downslope boundary of a vegetation band is: structural (sieving) crust → erosion crust → (gravel crust) → sedimentation crust → microphytic sedimentation crust → no crust → sieving crust, etc. It is also shown that these crust types are dynamic and evolve from one to the other as hydrological conditions change.

Hydraulic conductivities of surface crusts are low, typically falling within the range 10^{-6}–10^{-7} m s^{-1}. The presence of large expanses of crust over bare regions tends to generate run-off, which moves

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PII S0022-1694(96)03322-7

down the regional slope to be intercepted and pond within and just upslope of vegetated areas. Such run-off concentrates rainfall by a factor of up to 3.7 below vegetated areas. This concentration combined with an absence of crust development in closed bush areas promotes rapid infiltration below and just upslope of vegetation bands. In this way the hydrology of the area operates to ensure that the bulk of the rain which falls is directed as quickly as possible to the areas where it is most needed to support the existing vegetation.

1. Introduction

1.1. The phenomenon of patterned vegetation

Patterned vegetation types occur at many localities in semi-arid environments. The patterns consist of alternating areas of vegetation and bare ground, aligned along the contours of virtually flat to gently sloping terrain. The exact form of pattern varies from place to place. Sometimes the vegetated areas are linear and give rise to a regular banded appearance. More commonly they form arcs, whorls or oval patches, producing elaborate and striking configurations. The vegetation itself can consist of grasses, shrubs or trees or any combination of these groups.

The phenomenon was first reported from Somalia by MacFadyen (1950), using aerial photographs. Since then numerous examples have been described from Australia, (Slatyer, 1961; Mabbut and Fanning, 1987), Somalia (Boaler and Hodge, 1962; 1964; Hemming, 1965), Mexico (Cornet et al., 1988), Jordan (White, 1969; 1971), Sudan (Worral, 1959; Wickens and Collier, 1971), Mauritania (Audry and Rossetti, 1962), Mali (Leprun, 1979) and Niger (White, 1970; Ambouta, 1984; Wallace et al., 1994; Thiéry et al., 1995).

Though widespread, the regions within which patterned vegetation types occur share a number of characteristics (Table 1). These include: (1) a tropical to semi-tropical climate, with an average annual rainfall of 50–750 mm, typically occurring as high intensity summer storms; (2) gentle slopes of 1:50 to 1:500, sufficient to generate sheet flow, but not to form channels; (3) a homogeneous, horizontally isotropic geological substrate; (4) a tendency to develop low permeability surface crusts.

Various theories have been proposed to explain how these vegetation patterns are formed. One explanation is that they are a primary response to the formation of local geomorphological conditions (White, 1969; Greig-Smith, 1979; Cornet et al., 1988). This theory holds that the development of vegetation stripes are a consequence of the slow geomorphological evolution of slopes initially occupied by a complex vegetation. A second explanation is that they have developed from a once complete cover of vegetation, with intervening bare stripes having formed from the creation and fusion of bare patches caused by processes such as overgrazing, fire damage or the spread of termite mounds (Clos-Arceduc, 1956; Boaler and Hodge, 1964). In other cases it is suggested that in bare or thinly vegetated regions, fallen twigs, branches or other obstacles trap wind-blown sand or sediment transported by sheetwash, thus initiating the development of patterned growth (Audry and Rossetti, 1962; White, 1971).

Table 1

Characteristics of patterned vegetation sites in semi-arid environments taken from selected references

Author, country	Slope	Rainfall (mm/year^{-1})	Vegetation width (m), vegetation length (m), bare ground width (m), ratio bare:vegetation	Vegetation type and *main species*	Geology (soil depth and type)
White (1969), Jordan	?	50–100	5 wide, 300–800 long, 25–100 wide, 5:1 to 20:1	Shrubs/grass, *Artemisia*, *Schismus*, *Anabasis*	Saline and alluvial flats (1 m + ; silt, loam)
Cornet et al. (1988), Mexico	?	260	20–70 wide, 100–300 long, 60–200 wide, 3:1	Bushes/grass *Larea*, *Prosopis*, *Hilarea*	Limestone, marls, alluvium, colluvium (1.6 m + ; regosols, lithosols, yermosols)
Slatyer (1961), Australia	1:500	250	5–50 wide, 20–400 long, 15–250 wide, 3:1 to 5:1	Trees/grass, *Acacia*, *Eragrostis*	Basement complex (0.6 m + ; red earth soils)
Boaler and Hodge (1964), Somalia	1:100–1:450	125–300	15–70 wide, up to 1600 long, 30–200 wide, 2:1 to 1:1	Perennial grasses, *Andropogon*, *Chrysopgon*	Limestone (0–0.25 m loam or clay loam; 0.25–2.5 m clay)
Hemming (1965), Somalia	1:166	150	?	Perennial grasses, *Andropogon*, *Chrysopogon*	Limestone (0.25 m + ; calcareous gritty clay soil)
Worral (1959), Sudan	1:121–1:300	100–400	1–20 wide, –, 2–40 wide, 1:1 to 4:1	Perennial grasses, *Aristida*, *Cymbopogon*	Basement complex (0.04 m loam; 0.4–1.8 m clay loam)
Wickens and Collier (1971), Sudan	Up to 1:200	200–500	Various	Various	Nubian Sandstone Pliocene sediments and basement complex (red/brown sandy loam; clay and sandy clay)
Mabbut and Fanning (1987), Australia	1:50–1:500	200–250	10–40 wide, –, 20–250 wide, 1:1 to 2:1	Trees/shrubs, *Acacia*, *Solanum*	Basement complex with laterite (0.15–2 m sandy clay, clay loam: ‘red earths’)
White (1970), Niger	< 1:100	400–750	20–40 wide, –, 50–150 wide, 1:1 to 2:1	Trees/grass, *Acacia*, *Combretum*, *Ctenium*	Tertiary sandstone with laterite (0.15–1 m; sandy loam, sandy clay loam)

In some regions the bands of vegetation are believed to be dynamic and to migrate slowly up the prevailing slope. For example, the vegetation arcs of Northern Somalia (Hemming, 1965) are thought to migrate upslope at 20–30 cm year^{-1}, while the grass arcs of Sudan (Worral, 1959) are also considered to be mobile. In contrast, the banding described by Mabbut and Fanning (1987) in Australia, Wickens and Collier (1971) in the Sudan and White (1969) in Jordan, appear to be stable.

1.2. Patterned vegetation in Niger

Large areas of south-west Niger are covered by a type of patterned woodland vegetation, to which Clos-Arceduc (1956) gave the name ‘brousse tigrée’ (tiger bush), because the pattern from the air resembles the stripes on a tiger skin (Plate 1). The vegetation type is found between 12°30′ and 15°N. At these latitudes average annual rainfall varies from around 200 mm in the north to 750 mm in the south, mostly falling during the summer months (July–September). Within the region the occurrence of tiger bush is restricted mainly to laterite-capped plateaux, where a combination of gentle slopes and thin, silty, stony soils provides ideal conditions for the formation of patterned vegetation. The laterite forms part of the Continental Terminal Series, a terrestrial sedimentary sequence of Tertiary age (Greigert, 1966; Greigert and Pougnet, 1967).

The vegetation patterns in south-west Niger vary with latitude, as described by Ambouta (1984). They take on the characteristic tiger stripe appearance between latitudes

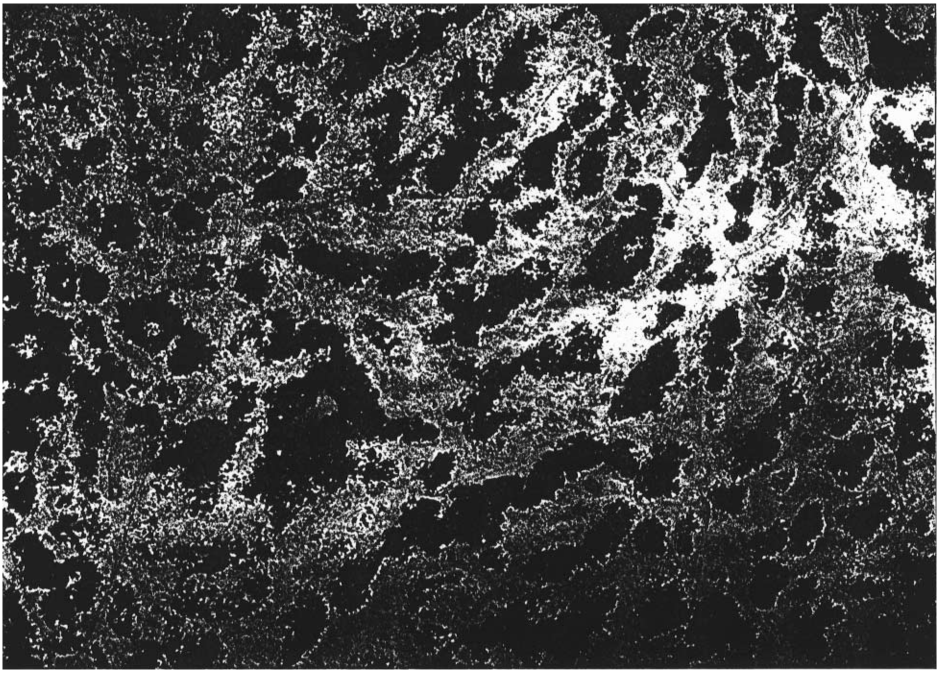

Plate 1.

13° and 14°30′N where the width of both woodland and bare ground varies between 10 and 100 m, and the lines of vegetation have average lengths of 100–200 m. Toward the south, however, wetter conditions are associated with a decreased percentage of bare area and the presence of discontinuous circular patches of vegetation rather than distinct bands. Bare patches disappear completely to the south of the 750-mm isohyet, where the vegetation cover becomes homogeneous. North of the 14th parallel drier conditions lead to a reduction of the percentage of vegetation cover, with stripes being reduced to short lengths separated by 100–200 m of bare ground (Ambouta, 1984).

This paper examines the factors that affect the movement of water within a tiger bush area in south-west Niger. In particular, answers to the following questions have been sought:

1. Does run-off from bare areas contribute to, and thus help sustain, the vegetated areas?
2. If it does, how is such run-off generated?
3. What implications does such run-off have for the water balance of both bare and vegetated areas?

This work forms part of two ongoing studies: HAPEX-Sahel (Hydrology Atmosphere Pilot EXperiment, Sahel), an international project designed to improve the parameterisation of global circulation models (Goutorbe et al., 1994); and SAGRE (Semi Arid Groundwater REcharge), a study to quantify groundwater recharge (Bromley et al., 1995).

2. The study area

The tiger bush area selected for study lies 45 km to the south of Niamey, the capital of Niger (Fig. 1). Situated between latitudes 13°10′ and 13°15′N, the area forms part of the Say plateau. The plateau rises in its western part to 100 m above the Niger river, attaining a maximum altitude of 275 m. Rainfall in the area is very variable in both time and space. The 80-year mean annual rainfall total at Niamey is 562 mm, with a standard deviation of 137 mm (Sivakumar, 1986). About 75% of the rain falls during July–September, generally as high intensity localised storms. Lebel et al. (1996) report that within the 100 × 100 km covered by the HAPEX-Sahel experiment, half the annual rainfall total falls at rates in excess of 35 mm h^{-1} and a third at rates above 50 mm h^{-1}. Intensities exceeding 100 mm h^{-1} in the Sahel are not uncommon (Hoogmoed and Stroosnijder, 1984). Such high intensities ensure the generation of run-off, even on sandy soils, where surface crusting can provide a low permeability barrier to infiltration (van der Watt and Valentin, 1992). Spatially, rainfall during such storms can vary by a factor of 2 (or >30 mm) over a distance of only a few kilometres (Lebel et al., 1992; Wallace et al., 1994). Annual potential evaporation is almost 2500 mm and exceeds rainfall in every month except August (Sivakumar, 1986).

Surface hydrology and vegetation studies have been concentrated within an irregularly shaped area of typical tiger bush, about 3 km across, close to the village of Damari (Fig. 1). Details of the site are shown in Fig. 2. Highest elevations are along the central part of the southern border. From here the ground surface slopes gently away in a radial fashion. The gradient of the slope is somewhat variable, but generally no steeper than 1 in 100. Ground

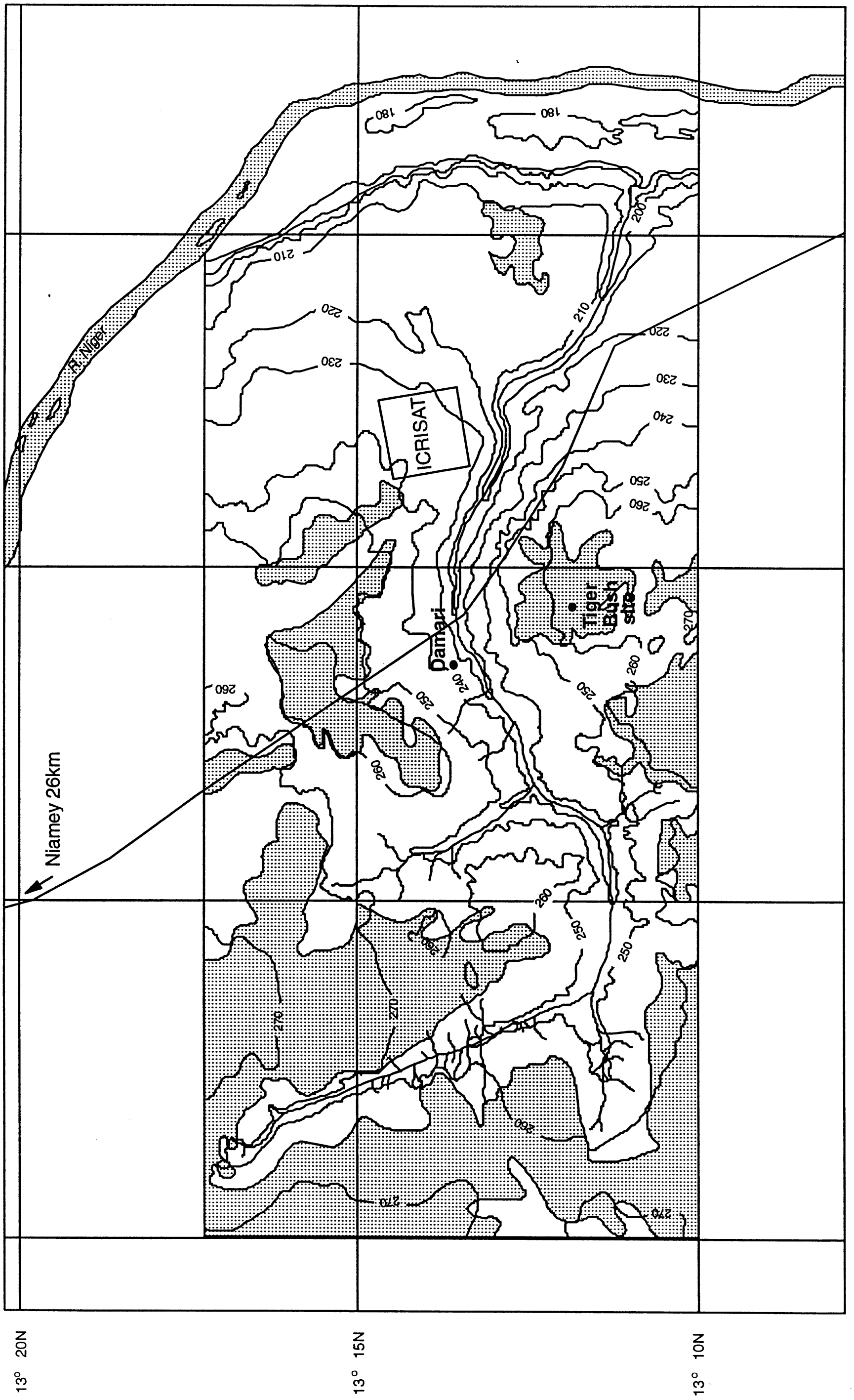

Fig. 1. Map showing the location of the study area and the distribution of tiger bush in the HAPEX-Sahel southern super-site.

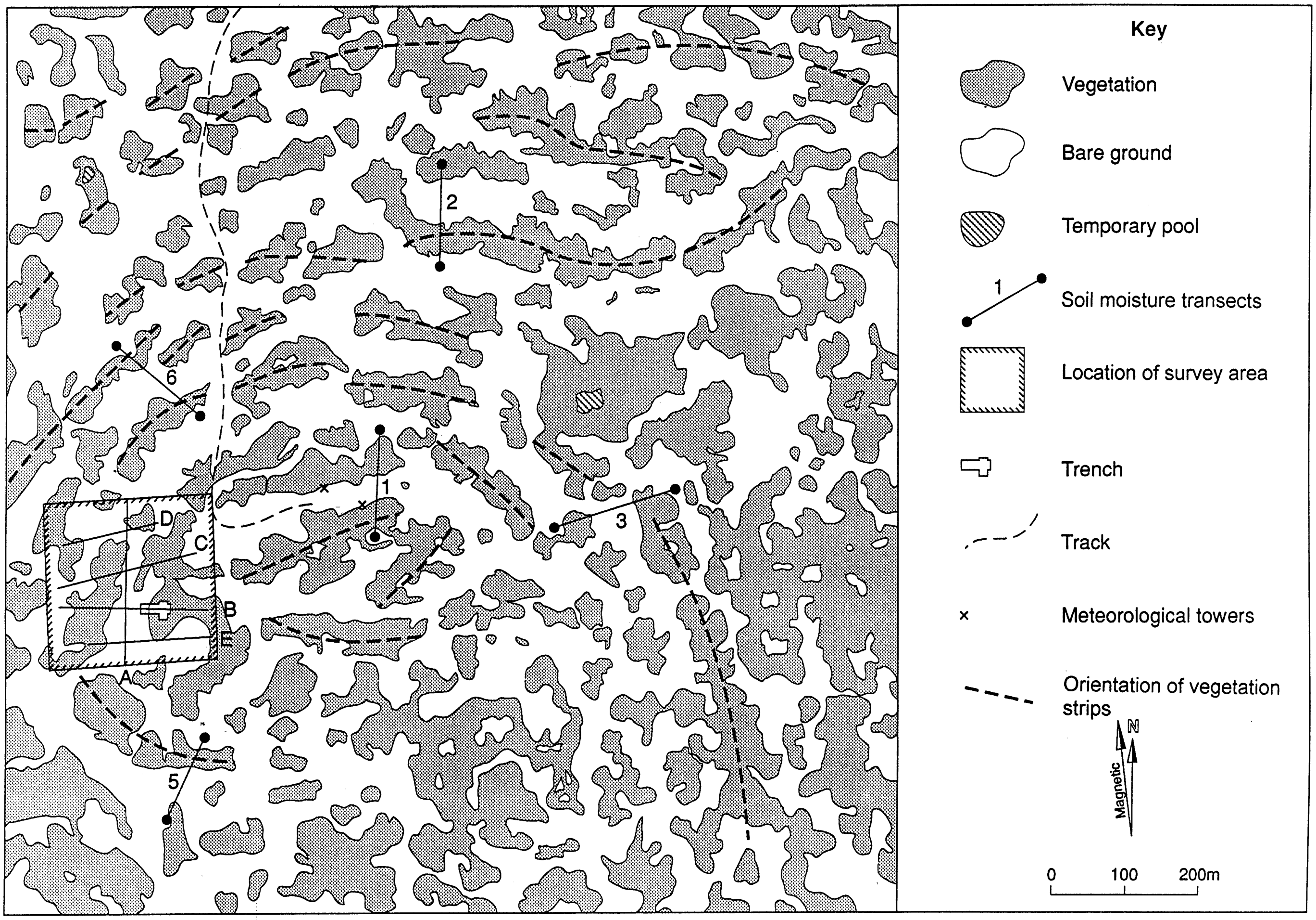

Fig. 2. Detailed site map showing the morphology of the tiger bush pattern, the location of the detailed survey area and of the access tube profiles.

contours can be inferred from the lines of vegetation, which are generally aligned at right angles to the maximum slope (Fig. 2).

Vegetation covers 33% of the site and is concentrated in strips 10–30 m wide and 100–300 m in length, separated by 50–100-m-wide areas of bare ground (Wallace et al., 1994). Five species of shrub dominate, *Guiera senegalensis*, *Combretum micranthum*, *C. nigricans*, *Acacia ataxacantha* and *A. macrostachya*. *C. nigricans* also occurs as a tree. Herbaceous vegetation is generally limited to the upslope edges of vegetation stripes.

The soils mostly consist of 0.1–0.5 m of gravelly sandy loam or gravelly loam overlying weathered laterite, with solid laterite starting at 0.2–0.9 m depth. Under bare areas the soils are classified as Lithic or Typic Torriorthents, under vegetation as Lithic or Aridic Ustorthents (Soil Survey Staff, 1975). Both types of soil are prone to surface crusting, the degree and extent of which is related to particle size distribution, topography, vegetation cover and termite activity.

The underlying laterite layer is up to 3 m thick and, although hard, is by no means impermeable. It exhibits several features that offer potential routes for the percolation of water: horizontal and vertical fissures and joints; many old and some not-so-old termite tunnels; tree and shrub root channels and stringers of softer more porous material forming a network surrounding blocks of harder, less permeable laterite.

3. Methods

3.1. Survey areas

The field site covers an area of 1250 × 1250 m and is shown in Fig. 2. Detailed mapping was restricted to a smaller 190 × 200-m area on the western side of the larger site. Point measurements were carried out along Line 1, and along five transects (A–E) within the smaller survey area (Fig. 2). Most of the hydrological fieldwork was carried out during the 1992 rainy season.

Fieldwork concentrated on factors thought to exert the strongest influence on the hydrology: rainfall; the type of vegetation; the permeability of the soil, particularly of its surface layer, and the topography at the regional, meso- and micro-scale. The work programme carried out is described under two headings: surveys and hydrological measurements.

3.2. Surveys

3.2.1. Vegetation survey

A detailed vegetation map of the smaller survey area was made. Initial classification of vegetation units was based on the work of Ambouta (1984).

3.2.2. Surface features survey

A second map was made to show the various types of soil surface within the survey area. The distribution and type of soil surface, particularly the presence or absence of surface crusting, plays a crucial role in the surface hydrology. The mapping units were based on those devised by Casenave and Valentin (1992), and are described either as a crust type, or where absent as litter cover. Percentages of the mapped area covered by the respective soil surface types were estimated by superimposing a 15 × 16-line square grid on the map, and counting the number of grid nodes falling within each mapping unit.

3.2.3. Topographic survey

A key factor controlling the hydrology of patterned vegetation areas is the topography. To investigate this feature five topographic transects (A–E), from 150 to 200 m in length, were surveyed within the small survey area (Fig. 2). Four transects were at right angles to the vegetation strips; a fifth was oriented along the length of a bare area. Relative ground surface elevations were surveyed along each transect at 1-m intervals, unless rapid changes of slope demanded closer spacing. Pits were dug at intervals to establish the type and depth of soil in relation to the nature of vegetation cover. Surveys along each transect also included species composition, shrub density, shrub height, shrub and herb cover, leaf litter cover and crust type. In addition the depth to the top of the laterite was noted in 34 soil pits dug along the five lines of section. The latter was done to check whether any relationship exists between the topography of the upper surface of the laterite and the various vegetation classes in the area: a greater depth to solid laterite can mean a better ability to store water for use by shrubs and herbs.

3.3. Hydrological measurements

3.3.1. Rainfall

Rainfall amount and intensity were measured using an automatic weather station, located adjacent to Line 1 at the centre of the study site (Fig. 2). The rain gauge forms part of the Vers une Estimation des Précipitations par SATellite au Sahel (EPSAT)-Niger rainfall monitoring network described in Lebel et al. (1992).

3.3.2. Measurement of surface hydraulic conductivity

Hydraulic conductivities of the soil surface in different vegetation classes were measured at selected sites along Line 1 using a tension infiltrometer based on the design of Jarvis et al. (1987). Measurements were made at two potentials, –0.5 cm and –4.0 cm, using hypodermic needles having different internal diameters. The diameter of the infiltrometer base plate was 14.7 cm. Hydraulic contact between the base plate and soil was achieved using sieved, aeolian sand (< 0.5 mm) collected locally. The sand had an air entry potential of < -40 cm water. Results have been processed in the manner proposed by Jarvis et al. (1987), where it is recommended that data be fitted to the Philip (1957) infiltration equation.

It should be noted that the Jarvis et al. (1987) procedure assumes one-dimensional flow, whereas at this site flow is three dimensional. The procedures to analyse three-dimensional flow (Ankeny et al., 1991), however, assume a uniform soil medium, a condition not met at the tiger bush site because of the presence of a surface crust. The results obtained using the Jarvis et al. procedure are thus indicative of the relative conductivities of the different surface types, rather than absolute values. Nevertheless, the values derived appear to give sensible results with respect to the times required for ponding to take place on each surface type. In separate infiltrometer tests a dye tracer (Rhodamine WT or Methylene Blue) was added to the water to check for preferential flow through the soil.

Particle size analysis of 12 crust samples taken along the transects was also undertaken; seven sites were located in bare ground, three under grassy open bush and two under closed bush. The results enabled estimates of surface layer matrix hydraulic conductivity to be made using the technique described by Boonstra and de Ridder (1981). The technique calculates the permeability resulting from the particle size distribution. It does not take into account the effect of soil structure and macropore flow. Though crude, the technique nevertheless offers the opportunity to evaluate relative differences between sampling points.

3.3.3. Measurement of subsurface hydraulic conductivity

Measurements of subsurface hydraulic conductivity, using a Guelph permeameter (Reynolds and Elrick, 1985), were carried out at 32 points along the lines of the topographic transects (Fig. 3). These measurements record the conductivity of the various surfaces below the surface crust.

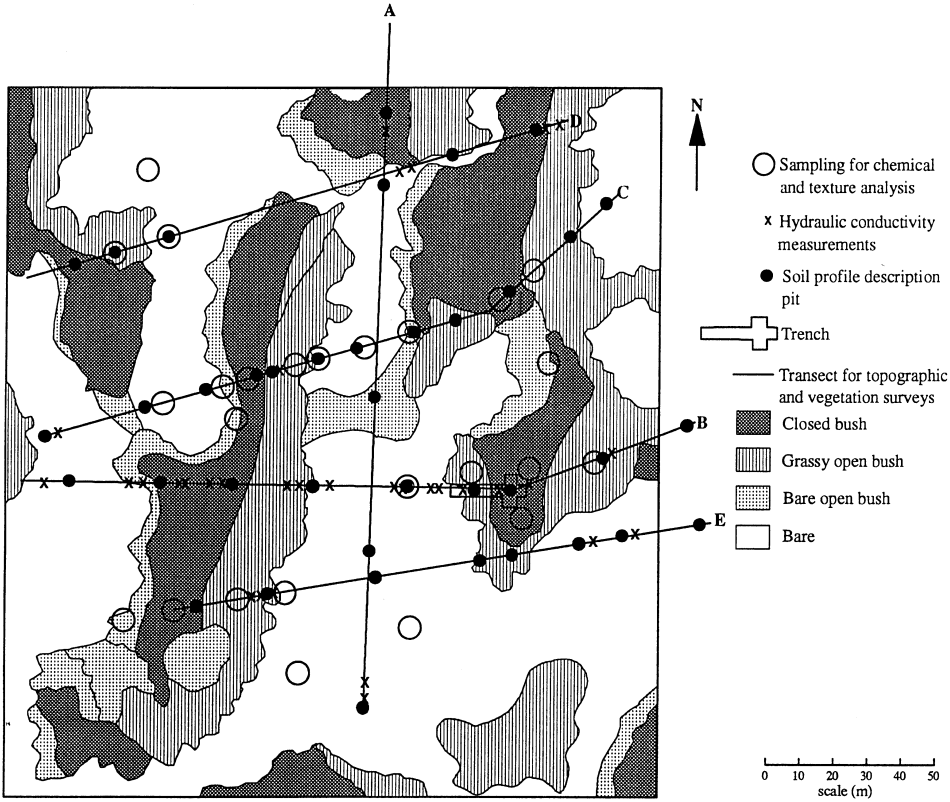

Fig. 3. Vegetation map and the location of measurements made in the survey area.

3.3.4. Soil water content measurements

Soil water content was measured in five lines of neutron probe access tubes spread over the HAPEX site, numbered 1–6 in Fig. 2 (line number 4 was abandoned). The lines, installed normal to vegetation strips, cut across all four classes of vegetated and bare areas. Each line comprised a minimum of 11 tubes, at spacings varying from 4 m to

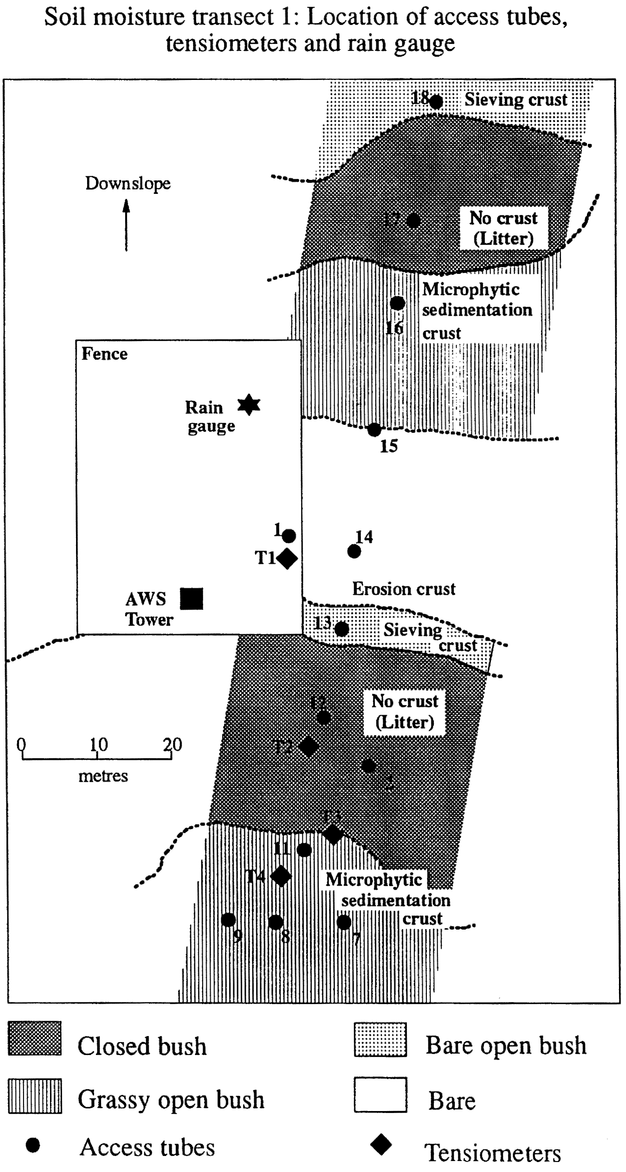

Fig. 4. Soil water Transect 1, showing location of tensiometers, access tubes, automatic weather station and vegetation classes.

30 m, according to the changes in vegetative cover (Fig. 4). The tubes were installed using an Atlas Copco ‘Cobra’ hammer drill. Close contact between tube and soil was assured by driving a steel AQ drilling rod into the hole prior to installation of the access tube in the manner described by Eeles (1969). The drill rod and access tube have the same diameter and a tight fit is ensured. After installation a narrow seal of cement was applied where the tubes entered the ground, to prevent downward leakage of rainfall and surface flow. Most tubes were placed to a depth of 1–2 m, though nine penetrated more deeply into the underling laterite to depths of up to 6 m. Soil water content measurements were made with a Didcot (Wallingford) neutron probe. The calibration equation relating water content to neutron count was determined using the neutron capture technique at the Centre Nucléaires de Cadarache, France (Couchat et al., 1975). Two soil and rock samples taken during access tube installation were used for the calibration. A correction for the top 10 cm was made following Parkes and Siam (1979).

The neutron probe was used to measure the change of water stored in the profile as soon as possible before and after rain events, so that the extent of surface redistribution of rainfall could be quantified. However, predicting rainfall in the Sahel is difficult, and in practice the time interval between the before and after rain measurements ranged from 1 to 3 days. Infiltration of water around an access tube is expressed as the ratio of ‘change in mm of water stored:mm of rainfall’ which is termed the rainfall concentration factor (RCF) (Gaze et al., 1996). Where the RCF is less than 1.0 there has been net run-off from around the access tube during the rainfall event under consideration; where the RCF is greater than 1.0, there has been net run-on. The longer the time interval between readings, the more opportunity for evaporative and drainage losses to complicate calculations. Drainage losses in particular are difficult to quantify: once the wetting front in the soil has passed the bottom of the access tube, drainage can only be calculated as a residual factor. Evaporative losses during the period of calculation can be taken into account more easily. When the soil was wet, Culf et al. (1993) measured maximum evaporation rates of 5 mm day^{-1} integrated over both bare and vegetated areas, i.e. up to 10–12 mm day^{-1} over vegetated areas. Wallace and Holwill (1996) calculated evaporation from bare areas to decrease from 4 mm day^{-1} on the day following a rainstorm to 0.5 mm day^{-1} 3 days later. These evaporation rates were used to calculate the RCF.

3.3.5. Observation of overland flow

The generation and behaviour of overland flow was observed during the course of several heavy storms in order to monitor the direction, speed and nature of the flow and to identify areas of ponding. On a number of occasions immediately following the onset of rain, a yellow dye was applied to the sheet of water on the soil surface to help identify the pattern of flow dynamics.

4. Results

4.1. Surveys

4.1.1. Vegetation survey

The vegetation survey recognised four well defined vegetation classes, which tended to occupy a consistent position with respect to each other along the regional slope. Following the maximum gradient in a downslope direction and starting in a bare area, the following sequence is usually encountered (Fig. 3):

1. Bare ground.
2. Grassy open bush (*Guiera senegalensis* and *Combretum micranthum* dominant).
3. Closed bush (*Combretum nigricans*, *Acacia ataxacantha* and *A. macrostachya* dominant).
4. Bare open bush (*Combretum micranthum* in poor condition dominant).
5. Bare ground, etc.

4.1.2. Surface features survey

Using the classification of surface types established by Valentin (1985; 1986) and Casenave and Valentin (1992), the following classes were identified within the survey area (Fig. 5):

1. Structural (or sieving) crusts (estimated 5% of the mapped area), are usually found in bare open areas, downslope from regions of closed bush (Figs 3, and 5). They form in situ by a sieving process which leads to a characteristic downward fining sequence (Chen et al., 1980; Valentin and Bresson, 1992). Due to the fine textured layer developed at its base, this type of crust has a low infiltration capacity.
2. Erosion crusts (35%), are widespread and commonly found on the upslope parts of bare areas, and frequently exhibit a dark patina, caused by the presence of algae. They form a single, hard layer of fine particles giving rise to a smooth but often uneven surface, with porosity restricted to a few cracks and vesicles. Infiltration is severely inhibited, promoting extreme run-off.
3. Microsteps are abrupt small changes of slope caused by sheet erosion. They are particularly common in areas of erosion crusts (Fig. 5).
4. Gravel crusts (7%), are restricted to bare areas and consist of irregular, haphazardly distributed patches of coarse gravel embedded in a type of sieving crust, which because of the armouring effect of the gravel, protrudes above the surrounding level. Infiltration is again severely inhibited by the fine grained lower layer of the embedding sieving crust.
5. Sedimentation or still-depositional crusts (11%), are generally best developed in lower lying locations, just upslope from grassy open bush areas. This variety of crust results from deposition in standing water and characteristically exhibit a fining upward sequence with the larger heavier particles being deposited first. When dry, these crusts crack and break into curled-up plates. Infiltration capacity is somewhat higher than for the preceding crusts.
6. Microphytic sedimentation crusts (20%), are similar to still-depositional crusts but more platy in structure, do not curl up, are often colonised by algae, and exhibit a high porosity generated by numerous small (1–2-mm) cracks and termite activity. Termite activity also tends to increase the infiltration capacity.
7. Litter (22%) represents partly decomposed plant material providing protection to the soil surface and inhibiting the formation of surface crusts. A few isolated remnants of

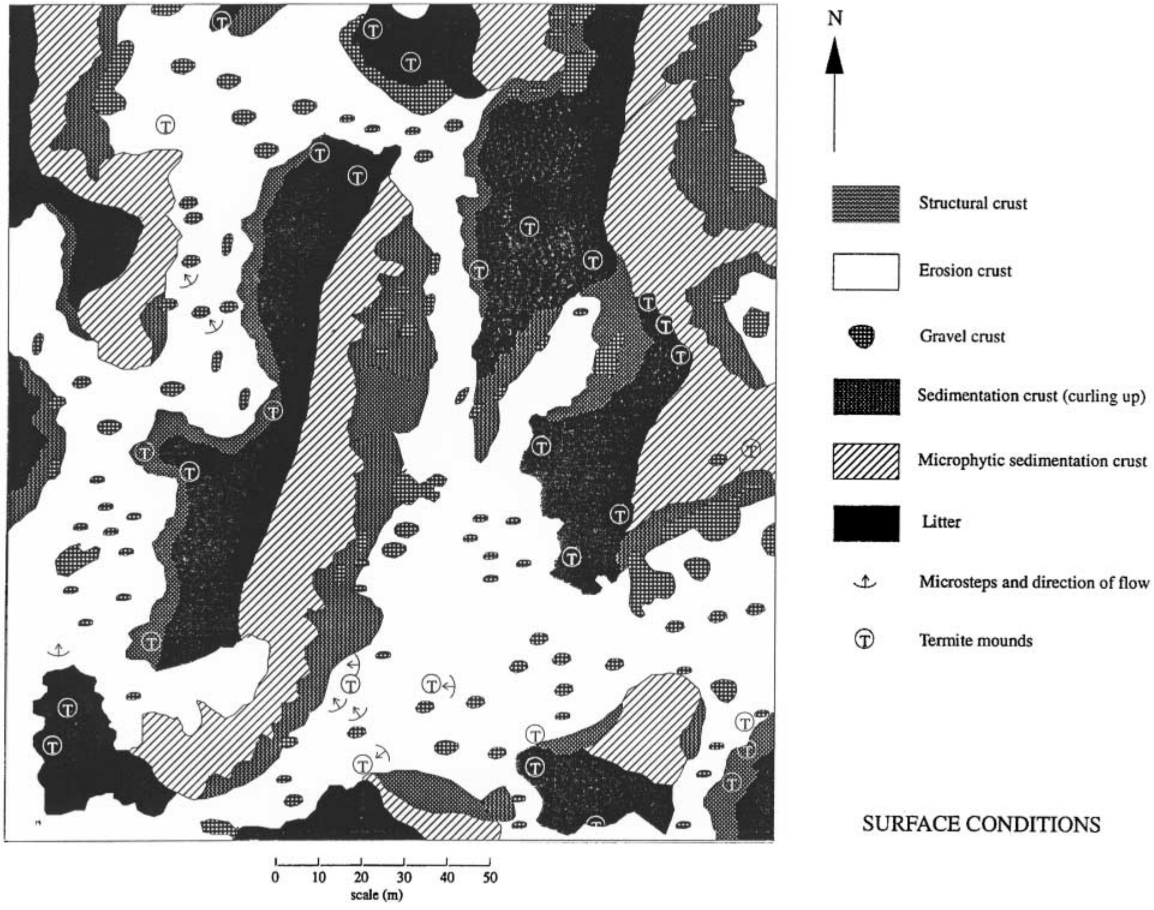

Fig. 5. Surface features map of survey area.

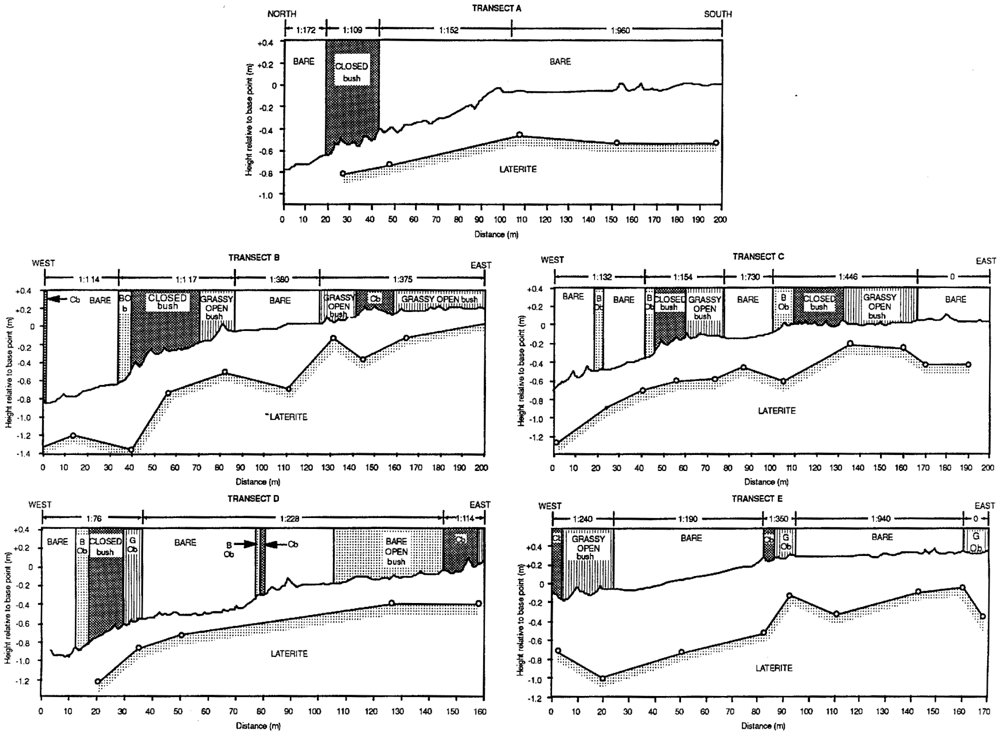

Fig. 6. Surface topography and depth to solid laterite along five topographic transects showing local gradients (e.g. 1:730). Vegetation symbols are the same as those used in Fig. 3.

pre-existing crust occasionally survive, but most crusts have been broken up by intense termite activity. The infiltration capacity in these areas is very high.

8. Termite mounds are prominent throughout the area. A total of 31 large *Macrotermes* termite mounds were found in the 4 ha mapped, or almost 8 ha^{-1}. The mounds varied from 1.5 m high to barely recognisable, slightly raised, smooth mounds several metres across.

4.1.3. Topographic survey and depth to bedrock

Along all transects the soil surface slopes downwards in a northerly or a westerly direction, indicative of an overall north westerly gradient. The gradient progressively steepens from close to zero in the south east to an overall slope of approximately 1:100 in the north west, though short sections are steeper (Fig. 6). The flat lying ground in the south east of the study area probably represents the summit level of the slightly domed plateau.

The slope of the soil surface does not show any correlation with the vegetation class. What does emerge from Fig. 6 is that there is a gradual build-up of soil material under the grassy open bush and particularly the closed bush, followed by a small but clear drop-off where the closed bush at its downslope edge borders on bare open bush.

The general slope of the soil surface follows that of the underlying solid laterite. Although the top of the solid laterite shows an irregular topography, these irregularities cannot be related to vegetation classes. Table 2 shows the mean depth to solid laterite for the four vegetation classes, and the standard deviations. The probability of a vegetation class effect on depth to solid laterite is only 67%. When the depth to laterite under the closed bush is corrected for the build-up of soil material (reduction of measured soil depth by 0.10 m), the probability of a vegetation class effect drops to 17%.

4.2. Hydrological measurements

4.2.1. Rainfall

Total rainfall during 1992 was 544 mm, with 63% falling during July and August. Maximum recorded intensity over 5 min was 113 mm h^{-1}.

4.2.2. Measurement of surface hydraulic conductivity

The mean results of the infiltrometer tests are given in Table 3. On bare ground, all types of crust have very similar hydraulic conductivities when measured at a matric potential of –4.0 cm. At this potential, flow would mostly be through the soil matrix. At the same potential, the results for the sedimentation crust under grassy open bush, and the non-crusted surface of the closed bush are slightly lower. The lower values probably reflect the presence of clay and silt particles deposited on and washed into these surfaces during rainstorms.

Under a matric potential of –0.5 cm, which is nearer saturation, hydraulic conductivities for bare ground and grassy open bush are again similar, both to each other and to those values obtained at –4.0 cm potential. In contrast, results for non-crusted soil under closed vegetation are an order of magnitude higher. The reason for the higher conductivities

Table 2
Depth (mm) to solid laterite under the different vegetation classes

Vegetation class	Mean	s.d.	min.	max.	*n*
Bare	46	16.3	22	80	16
Grassy open bush	39	20.9	20	90	10
Closed bush	55	16.3	34	90	10
Bare open bush	43	26.1	20	80	4

below closed bush can be explained by the presence of large diameter pores (macropores) in the surface of this cover type. Flow through these larger pores, however, is only generated under near-saturated conditions, which is why the higher conductivities are detected only when low suctions (i.e. –0.5 cm) are used. Under drier conditions (i.e. –4.0 cm) flow is restricted to the smaller pores of the matrix and the measured conductivity is thus lower. The lower conductivities measured at low suction (–0.5 cm) under the bare ground and grassy open imply an absence or at least a reduced occurrence of macro-pores under these surface types.

The conductivity measurements are supported by the results of dye trace experiments which showed classic bulb-shaped wetting patterns under bare areas, indicating matrix, rather than macropore dominated flow. However, under the densely vegetated areas the dye revealed the presence of preferential flow along active and inactive root channels and termite tunnels, in addition to matrix flow. Furthermore, visual observation revealed considerable ant and termite activity at the surface under closed bush, some activity in open bush and little to no activity in bare areas.

Confirmation that the matrix surface conductivity (i.e. not including macropores) for each class are similar, is obtained from particle size analysis of crust samples using the technique described in Boonstra and de Ridder (1981). The results for the three types of crust sampled are also summarised in Table 3. Average closed bush and bare ground values are 7.2×10^{-6} and 5.9×10^{-6} m s^{-1}, respectively. The slightly higher value of 1.1×10^{-5} m s^{-1} for the open grassy bush is influenced by one extreme sample having a

Table 3
Measured surface saturated hydraulic conductivity K ($\times 10^{-6}$ m s^{-1}) of different surface types compared with values obtained from grain size analysis and with published data from Casenave and Valentin (1992) for similar surface types elsewhere in the Sahel

Vegetation class (Casenave and Valentin surface type)	Matric potential (cm)		Casenave and Valentin average *K* value for surface type	*K* value obtained from grain size analysis
	– 4.0 cm	– 0.5 cm		
Bare open bush (structural crust—ST3)	3.4	2.6	0.6	–
Bare areas (gravel crust—G)	4.2	3.9	0.3	–
Bare areas (erosion crust—ERO)	3.6	–	0.3	5.9
Grassy open bush (microphytic crust—SED1)	2.2	1.9	1.5	1.1
Closed bush (no crust—TW)	1.7	10.4	9.0	7.2

Surface types (ST3, G, ERO, TW and SED1) are defined in Table 2 and Fig. 2 in Casenave and Valentin (1992).

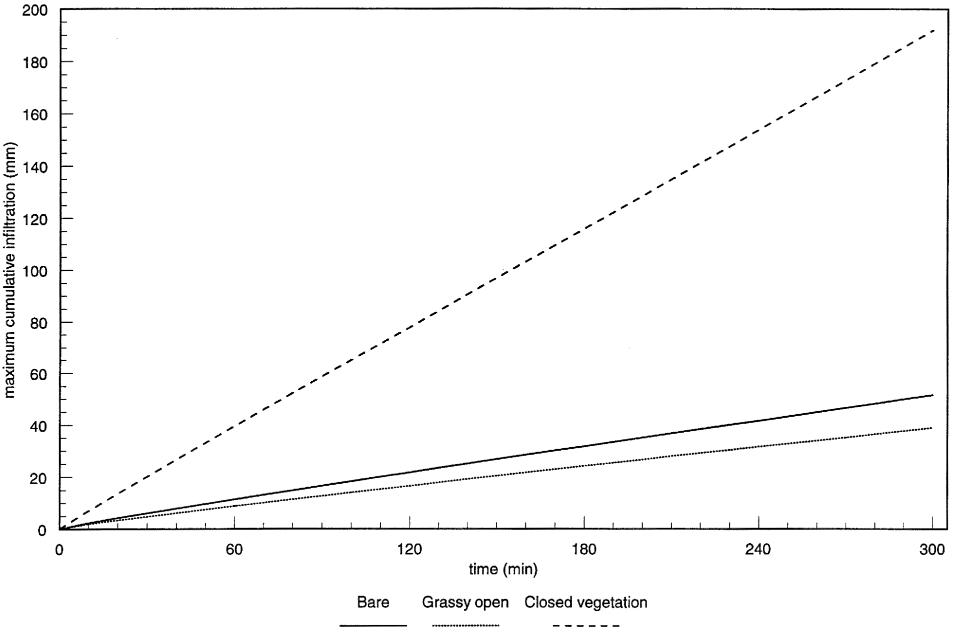

Fig. 7. Cumulative infiltration over time for different soil surface types using *K* values obtained at –0.5 cm suction.

high coarse sand and gravel content. Without this sample the *K* value is reduced to 4.6×10^{-6} m s^{-1}, bringing it closer to the other two groups. Hydraulic conductivity obtained using this technique represents only the matrix permeability and does not take into account the effect of macropores, which are an inherent property of the soil structure. They are thus more comparable to the tension infiltrometer results taken at tensions of –4.0 cm which measure the conductivity of the smaller pores, less than 0.75 mm in diameter. Although hydraulic conductivities derived from grain size data are slightly higher, the results obtained from both techniques are much the same and confirm the uniform nature of matrix conductivity of surface layers between all classes.

Measured surface hydraulic conductivity values at a matric potential of –0.5 cm have been used to calculate maximum cumulative infiltration over time for various soil surface types. Results are given in Fig. 7. On bare ground and grassy open bush, surface ponding will occur within a few minutes at a rainfall intensity of 20 mm h^{-1} or above. In contrast, under closed bush, the soil surface can cope with infiltration rates exceeding 40 mm h^{-1}.

4.2.3. Measurement of subsurface hydraulic conductivity

Of 32 subsurface hydraulic conductivity tests, 13 were unsuccessful due to the presence in the subsoil of macropores (mostly root holes and termite tunnels). Of the unsuccessful sites four were located in closed bush, three in bare open bush and six on bare ground. The results of the 19 successful tests are summarised in Table 4. They show that saturated hydraulic conductivity is quite variable below all the surface types. Unexpectedly, however, the highest average values, 20×10^{-6} m s^{-1}, were recorded below bare ground

Table 4
Subsurface saturated hydraulic conductivity K ($\times 10^{-6}$ m s^{-1}) under different vegetation classes

Vegetation class	Average subsurface K (m s^{-1})	Range of K values (m s^{-1})	n
Bare	20	3.7–72	9
Grassy open bush	13	2.9–25	4
Decaying open bush	9.5	9.5	1
Closed bush	4.7	2.1–8.9	3

and the lowest, 4.7×10^{-6} m s^{-1}, below closed vegetation. Both upslope and downslope open bush areas have intermediate values. The high values recorded for bare regions may reflect the presence of old root holes and now abandoned termite tunnels formed at an earlier time and which now lie sealed below a surface crust. In closed bush areas the lower permeabilities are likely to be related to the high percentage of fine particles washed into the area from bare regions upslope, and the fact that where root holes are present they are more likely to be occupied and at least partly blocked by living roots.

4.2.4. Soil water contents and rainfall concentration factors

The variation in rainfall concentration factors (RCF) along access tube Line 1 (Fig. 4) in 1992 is shown in Fig. 8 for four rainfall events greater than 10 mm. The changes can only be considered approximate because precise calibration of neutron probes for laterite soils is virtually impossible: the soils are very rocky and variable and accurate representative samples, of known volume and convenient size, cannot be taken. There is also a relatively small uncertainty in the amounts of evaporation and drainage from around the tubes between measurements, particularly from vegetated areas.

For any given tube the magnitude of the RCF varies between rainfall events. This can be explained in part by the variability of intensity between rainfall events. The generally low RCFs calculated for 30 August for tubes that normally have a high RCF (Tubes 11, 15 and 16) can be explained by rapid drainage below the bottom of the neutron probe access tubes in areas where soils are at or near field capacity. The tubes immediately downslope of 11 and 16 (Tubes 02 and 17) are indeed much less affected. During the relatively small event of 29th August, run off probably did not reach Tube 12, which was also well shielded from direct rainfall by the leaf canopy.

Fig. 8 confirms that on bare areas there is, almost invariably, net run-off and reduced infiltration. In contrast areas of grassy open and closed bush generally experience net run-on. There is no obvious difference between grassy open and closed bush in terms of net infiltration, despite differences in surface conductivity. The highest RCF value is recorded where there is a microphytic sedimentation crust in an area of grassy open bush (Tube 11); the lowest RCF is for the erosion crust furthest downslope (Tube 01). Although the highest RCF at this site has been recorded in a grassy open area, it is known that at other tiger bush sites the highest values are found below closed bush (S. Galle, personal communication, 1996). However, such differences are inevitable when dealing with site specific studies in regions that are complex and heterogeneous. Nevertheless, the main conclusion remains unaltered; there is evidence for considerable concentration of run on in the main vegetated areas (grassy open and closed bush) and for net run off over bare ground.

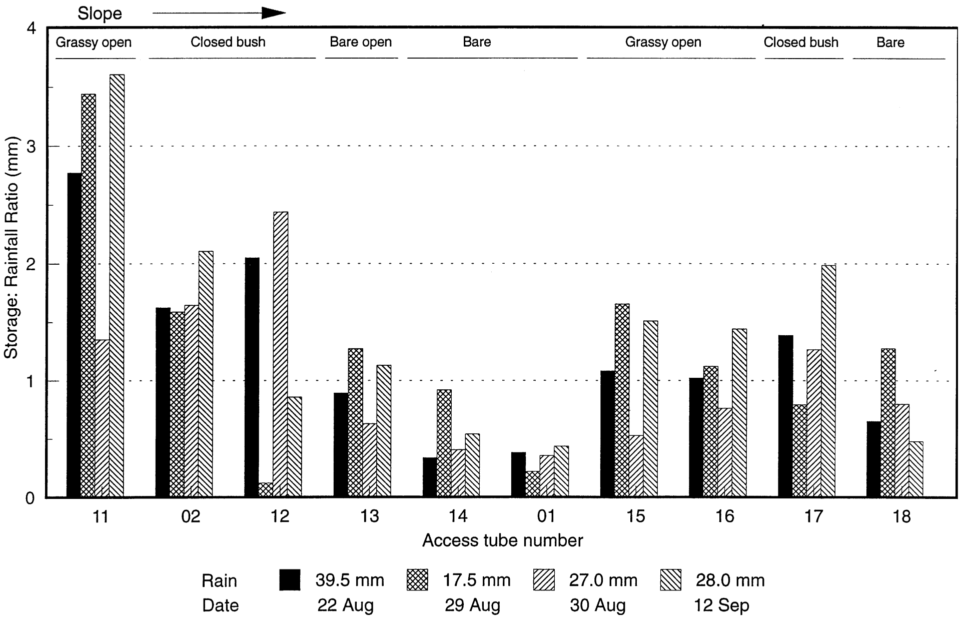

Fig. 8. The ratio of change in mm water stored in the profile:rainfall for each of the access tubes in Transect 1. Ratios are given for four storms over 10 mm during August–September 1992. For example on the 22nd August the amount of storage change at Tube 11 was equivalent to 2.75 times the rainfall on that day.

4.2.5. Overland flow

Observations revealed that run-off from bare areas begins within minutes of the start of rainfall. In bare ground the soil only wets to a depth of about 5 mm before ponding commences, and to less than 10 mm before run-off is generated. In full spate, flow depths averaged 10 mm, with a velocity of about 0.5 m s^{-1}. Gravel cobbles up to 80 g in weight were seen to be moved over the soil surface by the combined action of wind and water.

Once generated, overland flow is irregular, being influenced by the micro-topography and by strong gusts of wind. However, despite local irregularities, the general direction of flow is down the regional gradient toward the upslope side of the next band of vegetation where the water tended to pond in slight depressions. The overflow from these depressions disappeared into the litter cover near and under the closed bush.

In places, run-off became channelled through gaps in the vegetation. Here concentrated flow reached velocities of up to 1–2 m s^{-1} with depths of up to 50 mm. Considerable erosive power was thus generated, causing the transport of a substantial sediment load.

5. Discussion

5.1. Run-off observations

The results allow a detailed response to the questions posed earlier. Firstly ‘‘does run-off from bare areas contribute to, and thus help sustain the vegetated areas?''. A combination of the topographic and observational data clearly shows that run-off from bare areas by and large follows the regional slope of the soil surface, and concentrates below vegetated areas. Such concentration means that the effective rainfall below vegetation is higher than actual rainfall, a feature which inevitably enhances the ability of the vegetation to survive in an environment where water availability is notoriously erratic from one year to the next. At the same time there is no evidence that the location of vegetated bands is governed by soil depth or by the surface topography of the underlying laterite. This is in contrast to cases recorded in Australia (Mabbut and Fanning, 1987) and the Sudan (Wickens and Collier, 1971) where a relationship between increased soil depth and vegetation is established. Ambouta (1984), working with much longer profiles in an area of tiger bush 50 km to the north east of Niamey, found that slopes across wooded areas tend to be less steep than bare regions. The same overall relationship does not exist at the current site although the slopes under grassy open and closed bush areas have been substantially modified by the build-up of soil material. This is caused by wind and water borne sediment being trapped by vegetation, by a build-up of leaf litter, and by the activity of termites and other soil fauna. Where these processes do not take place for lack of vegetation or unfavourable micro-topography, the more active and fertile topsoil is quickly stripped away by run-off, exposing the setting subsoil, which hardens and becomes impermeable.

5.2. Run-off generation

The second question was ''…how is run-off generated?''. It has been shown that run-off generation is intimately linked to the distribution and type of soil surface crusting, a feature emphasised by the close similarity between the soil surface type map (Fig. 5) and the vegetation class map (Fig. 3). By and large, bare areas commonly possess erosion, gravel, or curling sedimentation crusts; grassy open bush areas are mostly covered by microphytic sedimentation crusts; closed bush is covered with leaf litter and characteristically has no or very little crust, while in bare open bush areas structural sieving crusts dominate.

It is important to realise that crusts are not simply unchanging features, but that they are dynamic and evolve one from the other in response to changing hydrological conditions. A typical cycle of crust development is: structural (sieving) crust → erosion crust → (gravel crust) → sedimentation crust → microphytic sedimentation crust → no crust → sieving crust, etc. (Bresson and Valentin, 1990; 1992). In tiger bush, this sequence is repeated in a downslope direction as successive bands of bare ground and vegetation are encountered, and it is this cycle that controls the surface re-distribution of water.

The process of water re-distribution is illustrated diagrammatically in Fig. 9. Discussion best begins in the bare open bush areas, where structural crusts dominate, and which lie immediately downslope from closed bush. In bare open bush the soil is less protected than it is under closed bush. As a result rain washes litter from the soil, which is subsequently compacted by the impact of rain drops, to form a structural sieving crust having a permeability of the order of 10^{-6} m s^{-1} (Casenave and Valentin, 1989; Valentin and Bresson, 1992).

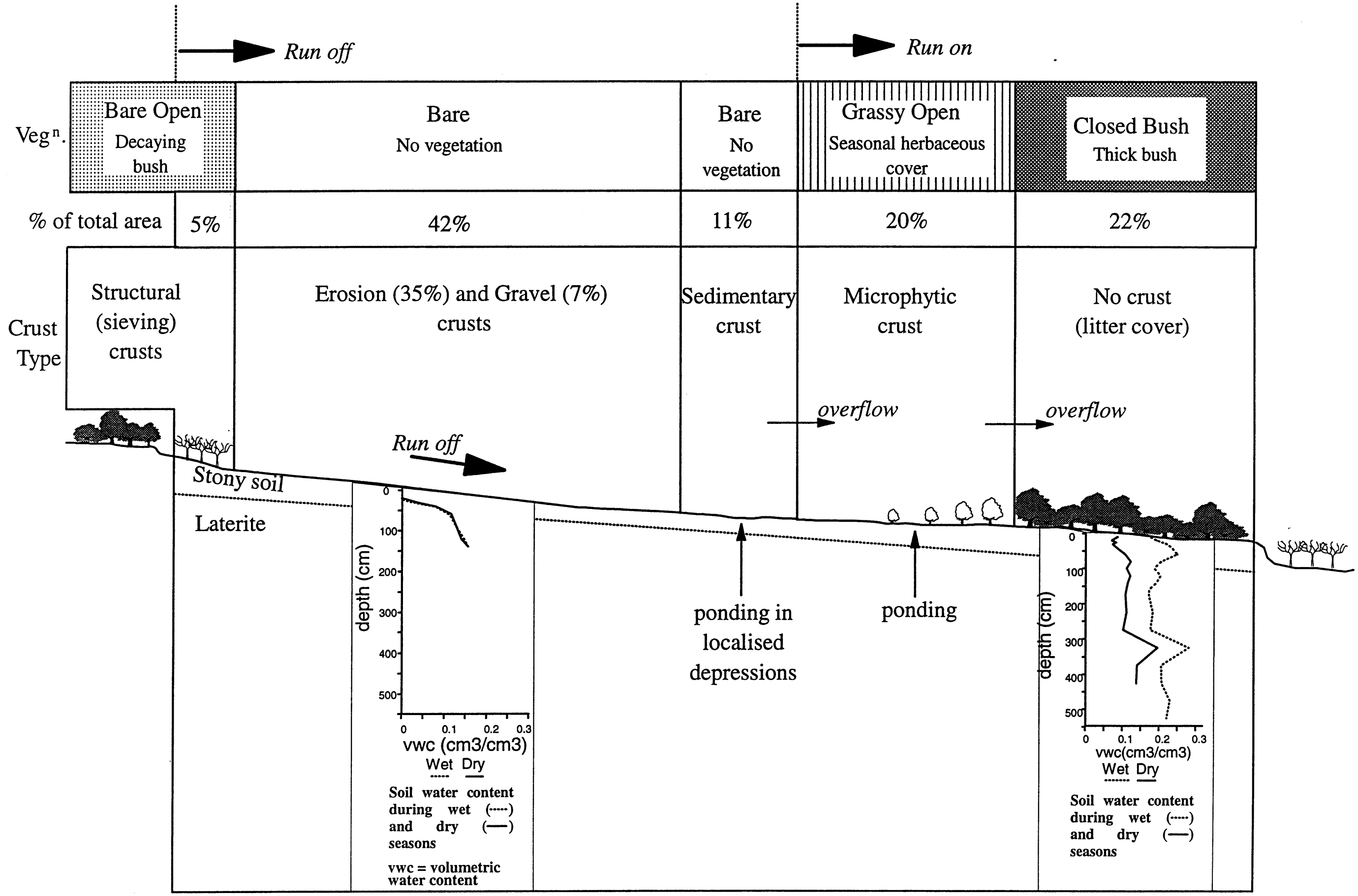

Fig. 9. Diagram to show the distribution of vegetation and surface types, surface flows and infiltration characteristics.

Further downslope, the vegetation becomes more sparse, and increased rainfall impact and run-off leads to the development of erosion crusts particularly on the upslope side of bare ground. Erosion crusts evolve from sieving crusts by the removal of the upper layers through wind and water action leaving a single fine grained layer having low permeability (10^{-7} m s^{-1}). In places, severe water erosion has removed even more material to expose a layer of gravel beneath and form gravel crusts. Embedded in fine grained material the gravel armours the surface, which tends to protrude above the surrounding level. Gravel crusts are thought to develop where laterite has weathered less deeply, e.g. over high parts of the original laterite surface or where the laterite is harder through more iron having being during formation of laterite. This would explain their seemingly haphazard distribution (Fig. 5).

The presence of erosion crusts in bare regions ensures that high intensity rainfall has little chance to infiltrate before run-off is generated and moves down the regional gradient toward the upslope side of the next vegetation band. In places, local meso-topography can cause a diversion or even a local reversal of flow, but the overall movement is governed by the regional gradient. Because of the gentle nature of the regional slope (less than 1:100) water moves as sheet wash rather than forming channels. Where flow is confined by the micro- or meso-topography, or through gaps in the vegetation, it becomes more erosive and may form microsteps or even rills. Run-off also rapidly degrades any termite mounds in bare areas.

Small irregularities in the surface of bare areas give rise to small depressions, where sedimentation crusts are formed by material scoured from structural and erosive crusts. Due to barriers formed in the grassy open bush areas, these depressions are particularly prevalent on the lower parts of bare areas, and in grassy open bush (Fig. 6). The sedimentary crusts typically crack and curl when dry. Continued deposition eventually silts up depressions, at which point further flooding causes encroachment upslope onto neighbouring erosion and sieving crusts.

Run-off not intercepted in the lower lying parts of bare areas, or which is intercepted but overflows from shallow depressions, continues downslope to pond in areas of grassy open bush. Here further deposition of sediment from suspension, and colonisation by algae, causes the formation of microphytic sedimentation crusts and allows the establishment of a seasonal herbaceous cover. Ponding takes place as water is backed up against the thicker vegetation and slightly raised soil surface of closed bush areas downslope (Figs 6, and 9). Following heavy rainstorms water is ponded for periods of several hours allowing time for the entire soil depth down to the underlying laterite to be wetted up. Because of this, and of increased termite activity it is in grassy open bush areas that some of the highest cumulative infiltration was recorded (Tube 11, Fig. 4), despite the permeability of microphytic crusts being only slightly higher than erosive types found on bare ground (Table 3).

When sufficient run-off is generated there is a spill over from grassy open areas onto adjacent closed bush. However, because of its position further down the supply line, the closed bush is likely to receive less run-on than grassy open areas, particularly during light rains. Reduced run-on, however, is offset by increased surface hydraulic conductivity, which in closed bush is typically an order of magnitude higher than elsewhere. The reasons for increased hydraulic conductivity are as follows: firstly, termite and root activity combined with the protection offered by litter cover mean that crusts are not able to form or are quickly fragmented; secondly, the presence of termite tunnels and root channels offer rapid by-pass routes under saturated conditions. As discussed matrix hydraulic conductivity of the surface mineral soil under the closed bush is similar to that of sedimentation and erosion crusts (10^{-6} m s^{-1}). However, the presence of macro-pores such as root channels and termite mounds increase values by an order of magnitude to 10^{-5} m s^{-1} (Table 3). These higher overall infiltration rates are similar to subsurface hydraulic conductivity values for closed bush, which also take into account macropore flow (Table 4). The resulting high infiltration rates under the closed bush are reflected in Fig. 8.

Exceptionally, during severe rainstorms, the surface storage capacity of the closed bush may be exceeded, in which case there is overflow into bare open bush areas further downslope (Tube 13, Fig. 8). Such overflow, however, does not take place frequently and the opportunity for infiltration is limited. As a result it becomes difficult to sustain a complete vegetation cover. Subsequent bare soil gaps at the downslope side of the closed bush become exposed to the beating action of raindrops to form sieving (downward fining) crusts, which are typical of this zone. In the event of dry conditions persisting for extended periods the vegetation here eventually dies back to the point where sheet flow can be initiated over the ever widening bare patches of ground. If continued, this process then leads to the formation of erosion crusts typical of the adjacent bare region downslope, and the cycle of crust types and surface cover classes begins again.

5.3. Run-off implications for water balance

Finally ‘‘what implications does the run-off pattern described above have for the water balance of both the bare and vegetated areas?’’ Observations during rainstorms and neutron probe data (Fig. 9) have confirmed that infiltration into areas covered with an erosion or gravel (or structural) crust is minimal but that below areas with a vegetation cover it is significant. But what percentage of rainfall actually runs off from the bare areas, and how are the various elements of the water balance, particularly deep infiltration affected?

Overall, approximately 58% of the soil surface in the study area is covered by run-off generating non-vegetated crusts: structural (5%), erosion (35%), gravel (7%) and sedimentary (11%). The remaining 42% (microphytic 20% and litter 22%) are in areas with some to very heavy vegetation cover and considerable surface storage capacity. This is shown diagrammatically in Fig. 9.

Run-off totals from bare areas can be calculated by using the rainfall simulator generated run-off coefficients given in Casenave and Valentin (1992) for each of the bare surface crust types. These coefficients are 80% for structural crusts, 85% for erosion crusts, 90% for gravel crusts and 72.5% for sedimentary crusts. The weighted overall run-off coefficient (Kr) for the bare region is given by:

$$\mathrm{Kr}=[(5\times 80)+(35\times 85)+(7\times 90)+(11\times 72.5)]/58=83\%$$

Using this figure it is possible to calculate the amount of run-on to the two types of vegetated area, the grassy open bush (microphytic crust) and the closed bush (no crust). Thus for the grassy open bush areas the average rainfall concentration factor (RCF) for a given rainfall (R) is:

$$\mathrm{RCF} = R + [(58/22) \times 0.83 \times R)]/R$$

The concentration factor in this case is 3.2. In other words the amount of water received by grassy open areas is 3.2 times the actual rainfall. However, it should be noted that this calculation does not take into account water stored within small depressions in the bare region, which does not contribute to run off. This means that the concentration factor obtained should be regarded as a maximum value. Nevertheless, the result agrees very well with the concentration factors for the same surface type calculated using the change in soil moisture storage given in Fig. 8 (Tube 11). The results perhaps suggests that in the down slope part of the bare areas, where sedimentary crusts occur, surface storage is not a major factor affecting run off.

To calculate the concentration factor for the closed bush (litter) area is more complex. The problem is that surface water received from the grassy open area immediately upslope will have two components: firstly, surface flow generated within the grassy open area itself, and secondly water that has run-on from the bare ground further upslope and which is being passed on. Since there is no way to separate these two components the RCF for litter can only be calculated as a maximum and minimum value.

First of all consider the situation where the only run-on received by the closed bush is that generated within the grassy open area itself, in other words where there is no transfer of run-off from the bare ground further upslope. In this case it is necessary to use a run-off coefficient appropriate to microphytic crust, since this is the surface type characteristic of grassy open areas. Casenave and Valentin (1992) give a coefficient of 50% for this type of surface. The minimum average RCF for closed bush then becomes:

$$\mathrm{RCF} = R + [(22/20) \times 0.5 \times R]/R = 1.6$$

This gives a concentration factor of 1.6. To calculate a maximum value, the total run-off component from the bare ground needs to be added. Thus:

$$\mathrm{RCF} = R + [(22/20) \times 0.5 \times R]/R + [(58/20) \times 0.83 \times R]/R = 3.9$$

This gives a maximum concentration factor of 3.9. It thus appears that the RCF of closed bush lies somewhere between 1.6 and 3.9, the precise value being determined by prevailing conditions such as rainfall intensity and duration, antecedent soil moisture conditions and local topography.

The above results are also consistent with the work of Wallace and Holwill (1996). Using evaporation and rainfall measurements taken over a bare area situated about 100 m to the east of Transect 1 (Fig. 4), they developed a model to predict evaporation and run-off from bare areas. In the model it was implicitly assumed that since there is no uptake of water by plants from bare areas, nor any deep infiltration, all rainfall not evaporated must run off. Results implied that when annual rainfall is about 450 mm the vegetation receives a total water input equivalent to twice the rainfall (990 mm), but that this concentration factor tends to increase with increasing rainfall. Thus with a rainfall of 750 mm the factor rises to 2.5 (1875 mm), a figure though which still falls comfortably within the range obtained by the current study.

Using soil moisture change data, run-off coefficients and evaporation modelling it has thus been shown that vegetated areas receive up to a three and a half fold concentration of rainfall during rainfall events. Such concentration of water ensures the survival of vegetation throughout the long dry season and it has been observed that following good rains the bushes stay green longer into the dry season. In addition to providing extra water to sustain vegetation the concentration of water also influences the process of groundwater recharge in patterned vegetation areas.

Culf et al. (1993), using a Hydra eddy correlation system (Shuttleworth et al., 1988) to measure average evapotranspiration integrated over a large area of tiger bush at the same site, calculated that during a year of relatively low rainfall (1990, 450 mm) there would very little recharge: all water not evaporated directly from the soil would be transpired by the vegetation. Only a small part of the run-off generated near the edge of the tiger bush area would be likely to flow off into adjacent fields and gullies. Similar results were obtained by Bromley et al. (1996) who used a solute profile technique to obtain a historical record of recharge going back 800 years in a tiger bush area 20 km to the north-west of the HAPEX-Sahel site. They found that recharge varied between 9–24 mm year^{-1} with a long term average of 13 mm year^{-1}. This result is supported by groundwater modelling of the southern HAPEX area carried out by Moriarty (1995). The implication from these results is that groundwater recharge is limited and only takes place periodically following periods of exceptionally high rainfall. Infiltration below vegetated areas has been shown to take place to depths of at least 5 m (Fig. 9), but it appears that despite such deep infiltration transpiration removes this moisture in all but the most exceptional seasons.

6. Concluding remarks

Field work carried out at a patterned vegetation site in south-west Niger has demonstrated that run-off from bare surfaces moves down the regional slope to be intercepted and to pond over vegetated areas. Run-off is generated by the presence of a succession of surface crusts in the bare areas. The various types of crust tend to occupy the same position with respect to the vegetation bands and to each other along the regional slope. Under closed vegetation rapid infiltration takes place due to a combination of concentration of run-off from bare areas, the absence of a surface crust and the presence of macropore flow. In grassy open areas increased infiltration results mainly from concentration and ponding of run on. It has been shown that run off can concentrate rainfall by up to a factor of 3.7 below vegetated areas. Finally despite increased infiltration below areas of vegetation it seems that most of this water is used by the plants throughout the dry season, so that deep drainage is only likely to provide potential recharge to the groundwater table during exceptional rainfall events.

Acknowledgements

Financial assistance was received from the European Union (funding of HAPEX-Sahel under contracts EPOC-C90-0024-C and EV5V-CT91-0033), the Natural Environment Research Council, UK, (NERC) and the Dutch Ministry of Foreign Affairs. We would also like to acknowledge ICRISAT (Niger) for providing logistical assistance, Alfari and Jake Sudlow for carrying out fieldwork, ORSTOM (Niger) for the rainfall data and finally Karen Sage for the preparation of diagrams.

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