4. Runoff and Erosion Processes

Richard S.B. Greene, Christian Valentin, and Michel Esteves

Introduction

Banded vegetation patterning consisting of densely vegetated bands alternating regularly with relatively bare areas of soil is common in many semiarid and arid regions of the world. These areas occur as either woodlands or shrublands in the continents of Australia, Africa, Europe, and North America (chapter 2, this volume). These two-phase mosaics form some of the most important grazing lands in the world. The bands are important areas for primary production, especially on the upward slope from the band. The trees or shrubs in the bands are also important for fuel, as well as providing fodder during droughts.

However, due to a range of factors such as climate change, new and competing land use, and changing social needs, these banded landscapes are coming under increasing pressure (chapter 11, this volume). Even though their existence and some of their characteristics have been well documented over the past 40 years, knowledge about the hydrological functioning of these areas is only now emerging. As a result, they are gradually being degraded. The need to implement this new information is urgent, so that the impact of management does not impinge their long-term viability. Runoff and erosion processes are two of the most important processes determining the long-term stability of these lands because it is likely that sustainable functioning is a delicate balance between appropriate and excessive rates.

The infiltration of rainfall and redistribution of runoff are critical processes in determining the long-term stability of rangelands in arid and semiarid environments. These hydrological processes affect the subsequent spatial variation in available soil water in the landscape and hence have significant effects on diversity and production (Noy-Meir 1973). However, the partitioning of rainfall between infiltration and runoff is difficult to predict with precision. It is mainly controlled by soil surface conditions, especially the nature of the surface crust (Valentin and Bresson 1992) and the amount and type of vegetative cover (Mauchamp and Janeau 1993; Greene, Kinnell, and Wood 1994). Both these types of condition are difficult to quantify, due to significant spatial and temporal variability.

Runoff is also important in rangelands because of its effects on a range of other soil processes. Excessive runoff on sloping land can accelerate soil erosion, as well as enhance processes of nutrient and seed transport from sources to sinks. These processes can have beneficial as well as detrimental impacts on the landscape (Römkens, Prasad, and Whisle 1990). Erosion processes by wind are also important, largely because of their impact on organic matter, seed, and nutrient redistribution in the landscape (Greene et al. 1998).

The aims of this chapter are to

1. outline the occurrence and describe the characteristics of runoff and erosion processes in landscapes with banded vegetation patterns
2. evaluate the role of surface soil characteristics, especially crusting and plant cover, on runoff generation and water harvesting processes
3. draw conclusions about the effects and role of management regulating runoff and erosion processes and hence on the longevity of banded vegetation patterning

Occurrence and Characteristics of Banded Vegetation Patterning

Two-phase mosaics, or banded vegetation patterning (consisting of relatively bare areas alternating with densely vegetated bands), are excellent examples of where the nature of the surface hydrology is directly related to a particular distribution of vegetation. The occurrence of banded vegetation patterning was first recorded in British Somaliland (MacFayden 1950). Since then, these banded patterns of vegetation in woodlands and shrublands have been recorded in several continents, especially in Australia, Africa, Europe, and North America.

Despite regional differences in patterning, they all occur where there is a combination of low total rainfall and sheet flooding processes on medium-textured soils of low permeability (chapter 2, this volume). Sheet-flow mainly originates on bare areas, with excess runoff being shed into downslope bands of dense vegetation, where it is substantially all infiltrated. Laminar runoff is thought to be one key factor involved in the development of banded vegetation (Thiéry, d'Herbés, and Valentin 1995). Changes in surface runoff patterns, and in particular the occurrence of linear flow when rainfall exceeds a certain threshold (685 mm in Niger according to Valentin and d'Herbés 1999), tends to limit the development of long banded patterns (parallel to the contours) and favors the formation of dotted bush (Leprun 1999; Valentin and d'Herbès 1999). However, less than 200 mm rainfall is insufficient for the processes to occur in Mali (Leprun 1999). An optimum rainfall for banded pattern occurrence can be thus defined: nearly 400 mm under Mediterranean semiarid conditions (Spain: Bergkamp, Cerdà, and Imeson 1999), 550 mm under tropical semiarid conditions (Niger: Valentin and d'Herbès 1999), and approximately 300 mm or less in dry semiarid and arid areas of Australia (Tongway and Ludwig 1990; Dunkerley and Brown 1995). These thresholds and optima depend not only on climatic conditions but also on surface soil conditions including surface crusting, degree of roughness, and the amount and type of vegetative cover. The following is an account of the characteristics of banded vegetation patterning in different continents. The effects of surface soil conditions including surface crusting, roughness, and vegetative cover on runoff are discussed later.

Occurrence of Banded Vegetation Patterning in Australia

Banded vegetation patterning occurs in many parts of Australia, mainly in the arid and semiarid zones. Examples are the chenopod (*Atriplex vesicaria*) shrublands in

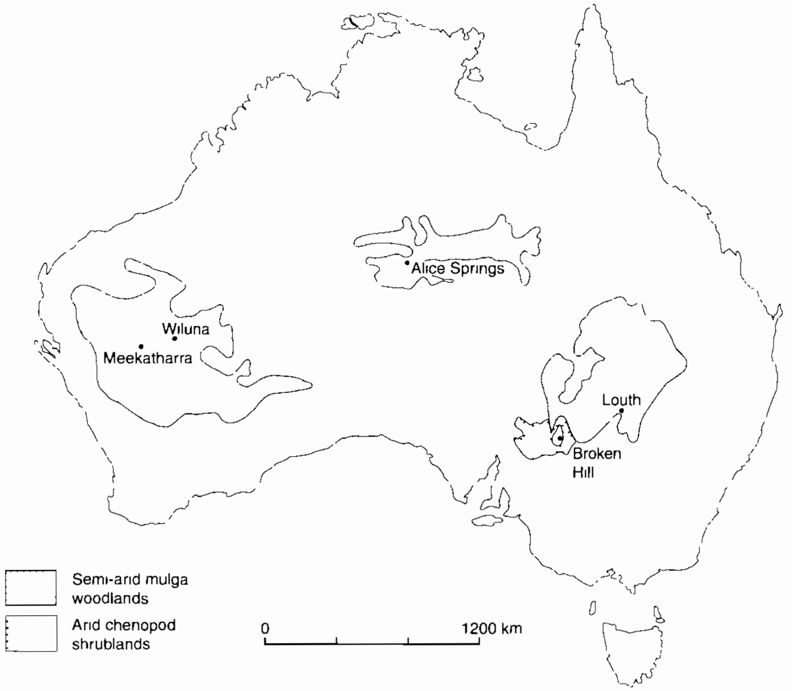

Figure 4.1. Distribution of banded vegetation patterning in chenopod shrublands and mulga woodlands in Australia

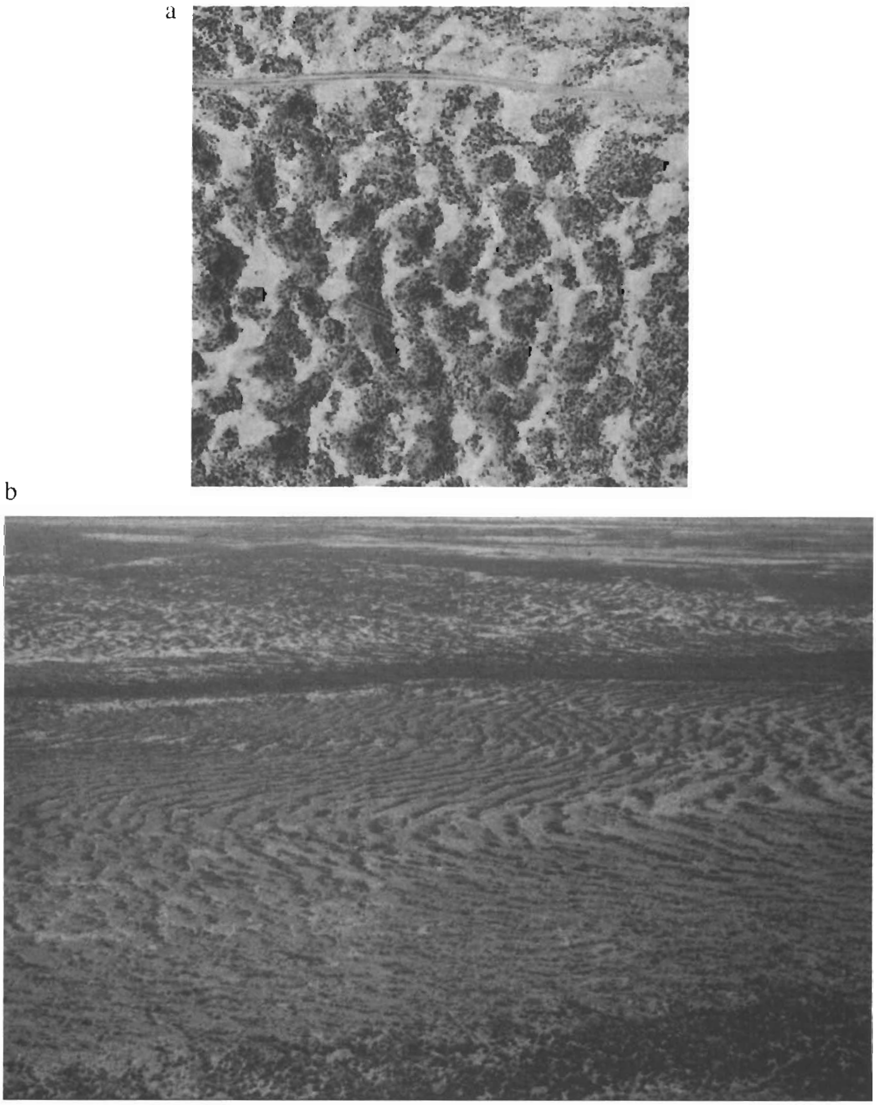

Figure 4.2. Aerial view of banded vegetation patterning. (a) Chenopod shrublands (Broken Hill, New South Wales). (Photograph courtesy of Professor J.A. Mabbutt.) (b) Mulga woodlands (Alice Springs, Northern Territory). (Photograph courtesy of Mr. W. van Aken.)

arid areas of western New South Wales (around Broken Hill) and the northeast of South Australia and the mulga (*Acacia aneura*) woodlands of semiarid areas of eastern Australia (around Louth) and arid areas of Western Australia (Wiluna-Meekatharra) and central Australia (near Alice Springs) (Figure 4.1). Aerial photos depict typical areas of chenopod shrubland (Figure 4.2a) and mulga woodland

(Figure 4.2b), respectively. In Australia, most of the descriptions of banded vegetation patterning have concentrated on mulga woodlands. Banded vegetation patterning in chenopod shrublands has previously been only briefly described by Mabbutt (1972) and Burrell (1974).

Dunkerley and Brown (1995) described in detail the banded chenopod shrublands near Fowlers Gap, New South Wales. The chenopod shrubs are in vegetation bands with intervening bare bands almost completely devoid of vascular plants. However, the soil surface in the bare bands is crusted and veneered with stones. Few surface stones are in the vegetated areas. The main type of patterning is one in which the vegetated areas take the form of isolated patches completely encircled by a bare, gibber-strewn surface. Gibbers are pebbles or boulders (Goudie 1990). These patches are oriented parallel to the contour and are broader in the cross-slope direction than in the downslope direction. Particularly well-developed band patterns that are laterally persistent over hundreds of meters are less common. From aerial photos, it appears that on gentle slopes well-developed banded patterns occur, whereas on steeper gradients, the elongated patch form is dominant.

The first account of banded mulga vegetation in Australia was by Slatyer (1961), who described an extensive area of desert woodland community dominated by mulga (*Acacia aneura*), north of Alice Springs in the Northern Territory (see Figure 4.1). The gradients were less than 0.5% over tens of kilometers, and the mulga was arranged in bands at right angles to the slope. The bands are a kilometer or more in length but only tens of meters wide and are separated by lightly timbered interbands of similar dimensions. The area has an average annual rainfall of approximately 250 mm, with a strong summer maximum. The mulga communities occur on moderately deep, red-earth soils (Stace et al. 1968), which increase in texture from coarse-medium at the surface to medium-fine at about 60 cm.

Another early account of banded vegetation patterning in Australia was given by Litchfield and Mabbutt (1962), who described alluvial wash plains with mulga bands on an interior plateau of Western Australia. The bands were only a few meters across and were sharply demarcated; interbands were several times larger and almost bare. The climate in the region was arid, with a variable rainfall averaging between 200 and 250 mm. The soils were red-earths underlain at shallow-to-moderate depths by an almost ubiquitous siliceous hardpan. The soil depth appears to be greater under the vegetation bands than the bare areas (Figure 4.3).

Mabbutt and Fanning (1987) further described banded vegetation patterning in Western Australia in the Wiluna-Meekatharra area (see Figure 4.1). In this area, there were extensive gentle slopes with gradients between 0.2 and 2%, across which the surface runoff occurs as dispersed sheet-flow or was more concentrated in unchanneled shallow linear depressions or in water lanes. Two main types of vegetation could be recognized in the Wiluna-Meekatharra area. The first type consisted of narrow bands, generally between 10 and 20 m broad and with a band ratio of less than 30%. The second type consisted of broad bands, commonly more than 20 m in breadth and with a band ratio of 30% and greater. The vegetation pattern appeared to be controlled by the depth to hardpan, namely, a greater depth overall in the broad pattern and a marked contrast in depth between band and

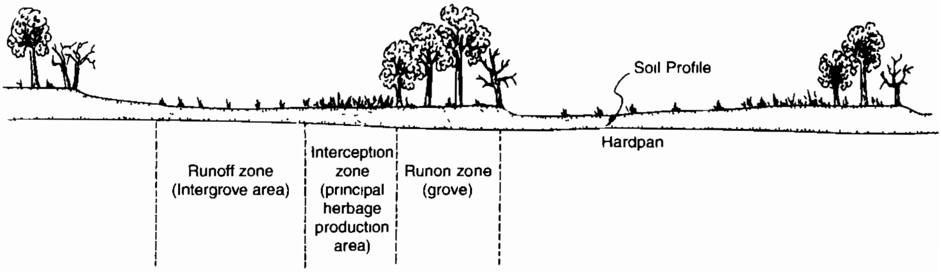

Figure 4.3. Diagrammatic representation of geomorphic sequence in a semiarid mulga woodland.

interband in the narrow pattern (Figure 4.3). The main soils associated with the vegetation banding were red-earths, with a textural range from clayey-sands to sandy-clays.

Banded vegetation patterning in eastern Australia was described in detail by Tongway and Ludwig (1990), who identified and described a patterned sequence of alternating bands and interbands in the semiarid mulga woodlands near Louth, New South Wales (see Figure 4.1). The patterned sequence had three geomorphic zones, each with its distinct vegetation type (Figure 4.3). The zones were as follows: (1) a runoff slope of sparse *Eragrostis eriopoda* savanna (runoff zone), (2) a runon zone of *Monachather paradoxa* grassland at the toe of the runoff slope (interception zone), and (3) a runon zone of *Acacia aneura* woodland (mulga band). The vegetation band–interband patterning in eastern Australia is similar to but differs in detail from such patterns reported for arid and semiarid western and central Australia. The bands in western and central Australia tend to occur on the downslope side of "risers" or on "convex slope-breaks," whereas in eastern Australia such bands occur in distinct "steps" or "flats" in the landscape (Tongway and Ludwig 1990).

Occurrence of Banded Vegetation Patterning in Other Continents

Africa

Vegetation arcs or bands alternating with bare areas are common in arid and semiarid regions of Africa. Clos-Arceduc (1956) first described the so-called *brousse tigrée* (tiger bush) patterned vegetation in Niger. The tiger bush pattern occurs only on the laterite-capped plateaus composed of "Continental Terminal" sandstone with gentle slope (0.2%). The shallow soil is 10 to 100 cm thick over a laterite material and has a sandy clay-loam texture in the upper 60 cm (Seghieri et al. 1997). The woody population is mainly composed of *Combretium micranthum* and *Guiera senegalensis.* The mean annual rainfall of 560 mm of this area and other areas of tiger bush in West Africa is higher than that for other areas of banded vegetation. For example, the mean annual rainfall of areas of vegetation bands in the northern region of Somaliland ranges from 150 to 250 mm, and in southeastern Mauritania, it occurs in a 250-mm rainfall zone (Audry and Rossetti 1962). Worrall (1959) also described grass bands in the Sudan where the annual rainfall ranges from 100 mm in the north to 400 mm in the south.

North and South America

Two-phase mosaics consisting of dense vegetation bands (with the main axis parallel to contour lines) alternating with relatively bare spaces have also been reported in the Chihuahuan Desert in Mexico (Cornet, Delhoume, and Montaña 1988; Montaña 1992). The bare areas consist of an open scrub community with vegetation cover generally less than 5%, whereas the vegetation bands are dense, mixed herb-scrub communities with a cover of approximately 100% (Montaña, López-Portillo, and Mauchamp 1990). The main herbaceous perennial is *Hilaria mutica,* and the two most common woody species are *Prosopis glandulosa* and *Flourensia cernua.* The annual rainfall is 264 mm, 71% of which comes in summer showers of high intensity (López-Portillo, Montaña, and Ezcurra 1996).

Similarly, banded patterns have been investigated in a *Nothofagus betuloides* primeval forest from Bahía del Buen Suceso, on the eastern edge of Tierra del Fuego Island (Argentina). The mean annual rainfall is 600 mm, and the bands are orientated perpendicular to the prevailing wind direction, with older and dying trees in the windward edge and a seedling regrowth in the lee side of each band (Puigdefábregas et al. 1999).

Europe

The only published studies on banded vegetation patterning in Europe appear to have been carried out in Spain, where banded patterns in soils and vegetation form part of important discontinuities on semiarid slopes. Banding of the vegetation occurs at a scale of meters and is present in a scattered way along the contour lines. It consists of small discontinuous bands of vegetation located at the outer rims of small stony terracettes, behind which mostly bare and often crusted surfaces are found (Bergkamp, Cerdà, and Imeson 1999). In this environment, there is movement of surface water and nutrients from the less well-vegetated bands into the vegetation bands. Cammeraat and Imeson (1999) presented examples from two locations in southeastern and northeastern Spain where patterned or banded vegetation are found on seminatural and abandoned land or where vegetation is recovering from wildfire.

Runoff and Erosion Processes

Most studies have been concerned with runoff processes as such, with very few including erosion. The studies of runoff processes in different continents are first outlined, followed by erosion studies.

Australian Studies of Runoff

In Australia, the hydrological functioning of banded vegetation patterning has only been investigated at a few specific sites (Winkworth 1970). Earlier studies all concentrated on mulga woodlands. For example, Slatyer (1961) measured infiltration rates in the bands and interbands at Alice Springs by using 300-mm-diameter infiltration rings. The banding mainly consisted of the broad band pattern described by Mabbutt and Fanning (1987). The rates varied from 25 mm h^{-1} near the base of mulga trees to 10 mm h^{-1} in the interband areas. The work near Alice Springs also established that runoff occurred with rainfall events in excess of 10 to 15 mm and that it varied between 15% and 50% of rainfall depending on the intensity and duration of the event. It is probable that in the majority of rainfall events, the interband and the band constitute a closed system, with no net runoff through the tier. Perry (1970), working in the mulga woodlands near Alice Springs, concluded that for rainfall events up to 25-mm runoff was contained in the interband–band system. Mabbut and Fanning (1987) also carried out infiltration measurements in the Wiluna-Meekatharra study site at one narrow banding and one broad banding site. These results also showed that generally there were higher infiltration rates in the bands than in the interbands.

Recently, there have been several studies in semiarid and arid areas of Australia of the hydrological functioning of banded vegetation patterning with special emphasis on the soil surface conditions and plant properties that are responsible for both runoff generation and water harvesting processes (Greene, Kinnell, and Wood 1994; Dunkerley and Brown 1995; Dunkerley and Brown 1999). These studies have taken place in the semiarid mulga woodlands of eastern Australia, near Louth, New South Wales, and the arid chenopod shrublands in western New South Wales, near Broken Hill (see Figure 4.1). Each of these studies is now discussed in detail.

Louth (Lake Mere) Site, New South Wales (Mulga Woodlands)

The aim of the studies near Louth was to investigate the processes of infiltration and runoff in banded vegetation patterning and the effect of soil surface conditions on those processes. The Louth site was on Lake Mere station, 35 km north of Louth, New South Wales (see Figure 4.1), and consisted of an area of semiarid mulga woodlands having a banded vegetation pattern in near-pristine condition. The area has been extensively surveyed (Tongway and Ludwig 1990; Ludwig and Tongway 1995), the mulga banding at the site and the occurrence of three distinct geomorphic zones (Figure 4.3) were described. A range of techniques that measured soil hydraulic properties at different scales was then used in each of these three geomorphic zones (Greene 1992, 1993; Greene and Sawtell 1992; Greene, Kinnell, and Wood 1994).

The disc permeameter (Perroux and White 1988) was used to measure soil hydraulic properties at a potential of +10 mm (ponded) and −40 mm (nonponded). In the runoff and interception zones, the measurements were carried out on bare undisturbed surfaces away from the base of tussocks, and in the mulga bands, the A_0 layer of litter (mainly leaves from *Acacia aneura*) was carefully removed be-

Table 4.1. Disc Permeameter Measurements at Supply Potentials of +10 and −40 mm on Three Geomorphic Zones[a]

Final infiltration rates (mm h^{-1}) (supply potentials)[b]	Geomorphic zone			
	Runoff zone	Interception zone	Mulga band	Significance[c]
$\psi = +10$ mm	25.0	47.0	263.6	*
$\psi = -40$ mm	12.8	14.7	13.3	ns

[a] From Greene (1992).
[b] Quasi-steady-state outflow rate from the disc permeameter.
[c] * $p < 0.05$; ns, not significant.

fore carrying out the measurements. Under ponded infiltration (+10 mm), there were significant differences in the hydraulic properties between the three zones, as seen, for example, in the infiltration rates (Table 4.1). The mulga band zone has a significantly higher infiltration rate than the runoff and interception zones. However, at −40-mm supply potential, there were no significant differences in the infiltration rates between the three zones. These results can be largely explained by the presence of macropores in the mulga bands, as discussed later.

The difference in soil hydraulic properties between the three zones was further investigated by using a rotating disc rainfall simulator that applied a uniform rainfall intensity of 30 mm h^{-1}. Runoff was collected in a 1-m^2 steel quadrat carefully located in the ground directly under the nozzle (Greene and Sawtell 1992). The simulator was used in each of the three zones over areas of ground that were largely devoid of vegetative cover. The results obtained were similar to those obtained by Tongway and Ludwig (1990) (i.e., the runoff zone had the greatest runoff rate [~27 mm h^{-1}; Figure 4.4], the interception zone had the next highest [~10 mm h^{-1}], and the bands virtually had no runoff [0 mm h^{-1}]). There was no evidence of runoff from the mulga band, even after 40 minutes, indicating that the infiltration rate was maintained at greater than 30 mm h^{-1}. The two sets of infiltration data obtained by using the disc permeameter and the rainfall simulator both demonstrated the lower infiltration capacity of the soils of the runoff zone compared with soils of the interception zone and mulga band (i.e., runoff zone < interception zone << mulga zone).

Even though the rainfall simulator can be used to study the effects of surface crusting processes and vegetative cover on runoff generation, it is desirable to be able to relate these findings to what occurs during an actual rainfall event. Greene (1993) used large, completely bounded, runoff plots to measure the hydraulic properties of various units at Lake Mere. The plots, 5 m wide and 17 m long, were installed at right angles to the contours. At the bottom of the plot, overland runoff water was collected in a trough and led into a calibrated tipping bucket (Williams and Bonell 1988). Events were monitored by a Compulog data logger via a magnet attached to the bucket and a mercoid switch secured to the tipping frame. A tipping bucket rain gauge adjacent to the plots was also logged to provide rainfall data over time.

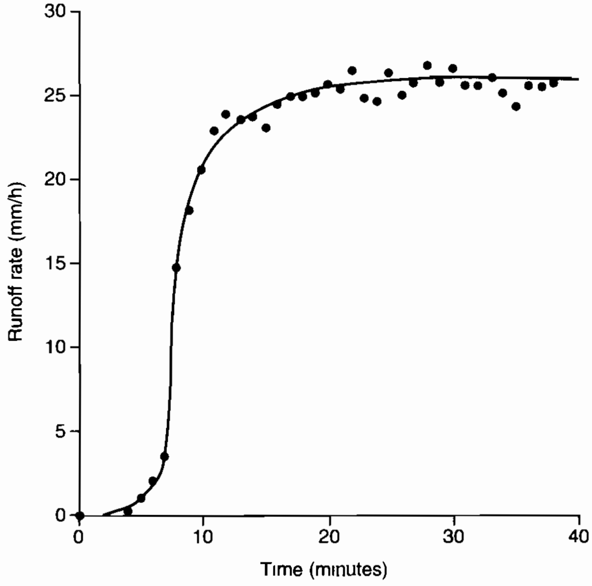

Figure 4.4. Infiltration behavior on a runoff slope.

Data from a typical rainstorm occurring on May 20, 1991, shows cumulative rainfall and cumulative runoff as a function of time (Figure 4.5), and assuming steady-state conditions exist, the difference between the two gives cumulative infiltration. During the first 18 minutes of this rainfall event, the averaged measured intensity of 22 mm h^{-1} was similar to that used in the rainfall simulator/cover experiments (i.e., 30 mm h^{-1}). It is interesting to note that the infiltration rates measured by using both methods were similar (i.e., 7.3 mm h^{-1} for the runoff plots compared with 11.2 mm h^{-1} for the rainfall simulator). Greene (1993) concluded that in some cases the simulator could be used to approximate very closely the infiltration and runoff conditions that occur during natural rainstorms. It is also interesting to note that during this event of 11.6 mm, the runoff coefficient Cr (volume of total runoff/volume of total rainfall) was 0.55, indicating that more than half the rainfall was lost as runoff. This is in agreement with the work of Slatyer (1961) and others (e.g., Winkworth 1970), who concluded that runoff from the interbands occurs with rainfalls in excess of 10 to 15 mm.

Runoff is shed to the bands downslope, where microrelief, vegetation, soil fabric, and surface litter cause the runoff to infiltrate. The redistribution of rainfall as runoff results in the interception zone and band receiving a larger proportion of the rainfall. Measurement of soil water contents after an event of 37.5 mm in March 1 to 2, 1987 indicated that the runoff zone, interception zone, and mulga band received 15.7, 33.7, and 51.6 mm of water, respectively (Greene 1992). The implications for herbage production as a consequence of the enhanced water status of

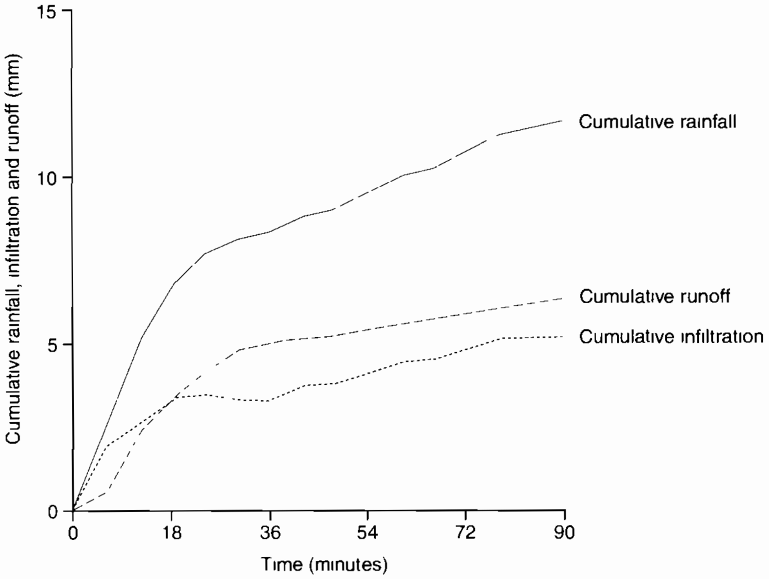

Figure 4.5. Cumulative rainfall, cumulative runoff, and cumulative infiltration on the runoff zone expressed as a function of time for a typical winter rainfall rainstorm.

the runon areas are discussed by Noble, Greene, and Müller (1998) and in chapter 11 of this volume.

Broken Hill Site, New South Wales (Chenopod Shrublands)

Dunkerley and Brown (1995) studied runoff and runon processes in patterned chenopod shrubland at a site near Fowlers Gap, 115 km north of Broken Hill (see Figure 4.1). The vegetation occurs on hillslopes having gradients of as little as 1% and displays a stepped microrelief of about 10 cm. Dunkerley and Brown (1995) observed that the bare surfaces shed surface runoff from rainstorms of as little as 4 to 5 mm and are thus a efficient source of runoff. Water accumulated on the lower margins of the bare zones where the gradient is lowest and then trickled into the vegetated areas, where it drained down abundant gilgai depressions (collapse features caused by a marked swell/shrink soil characteristic on wetting and drying).

Dunkerley and Brown (1999) further studied the effects of surface soil properties on hydrological behavior at another site approximately 40 km southeast of Broken Hill in a mixed chenopod shrubland-grassland community. They observed that surface roughness increases downslope through the interband and the zone of forbs at the upslope margin of a vegetated band, reaching its maximum within the vegetated band. Surface runoff is increasingly hindered during flow from the interband into the band by surface roughness. At the same time, soil resistance to entrainment increases in opposition to the shear forces generated by the runoff. In concert, these tendencies imply that little sediment transport is possible across the mosaic (Dunkerley and Brown 1999).

Macdonald, Melville, and White (1999) also described the interrelationships between soil cations, soil properties, and plant spatial variation in patterned ground at the Fowlers Gap site. The disc permeameter (Perroux and White 1988) was used in the patterned ground gilgai complex to detect differences in behavior between the bare areas and the vegetation bands. The microtopography of the patterned ground is generated by the gilgais (Mabbutt 1973). Macdonald, Melville, and White (1999) showed that the distribution of cations was not even. The cations, of which sodium is dominant, are concentrated within the bare areas. The sodium concentration decreases toward the center of the vegetation bands. The pattern of salt distribution was caused by the interaction of the preferential infiltration of water into the vegetation bands, the gilgai complex, and the vegetation-induced salt turnover. These factors cause the lateral movement of salts out of the vegetation bands into the bare ground.

Studies of Runoff in Other Continents

Africa

Banizoumbou Site, Niger (Tiger Bush). Several studies of the processes of runoff and erosion in banded vegetation patterning in Africa have been carried out. A major study of runoff production in a tiger bush catchment was carried out by ORSTOM (Peugeot et al. 1997) at a site located about 70 km east from Niamey in the west of Niger (Figure 4.6). The landscape is composed of dissected laterite-capped plateaus, with steep edge slopes that dominate wide topographic depressions located about 30 m below. The experimental site was located on a catena containing three main geomorphological units: (1) the plateau with loamy-clayey soils (30% clay) and low slope (0 to 0.5%), (2) the breakaway at the edge of the plateau (slopes: 4 to 8%), and (3) a dendritic drainage line at the break of slope. The plateau exhibits an alternating pattern of bare surface areas and vegetation bands roughly running along the contour lines (Ambouta 1984; Thiéry, d'Herbès, and Valentin 1995).

Precipitation exhibits an irregular distribution, but large storms occur from early May to late September, providing 95% of the annual rainfall, while the seven other months are dry. The mean annual rainfall for that region is 560 mm, calculated from 1905 to 1989. The storms are mostly convective. In this region, the median rainfall intensity is 35 mm h^{-1}, and 35% of the rain falls with an intensity greater than 50 mm h^{-1} (Lebel et al. 1992). Discharges from the catchment were measured from a gauging station located in the dendritic drainage line (Figure 4.6) and compared with that of a runoff plot located on the plateau bare soil surface (Table 4.2).

The results indicated that the runoff response to rainfall is quick, and there is no base flow. Base flow may occur in some drainage basins as a background flow component (Goudie 1990). Hortonian overland flow is the main process of runoff

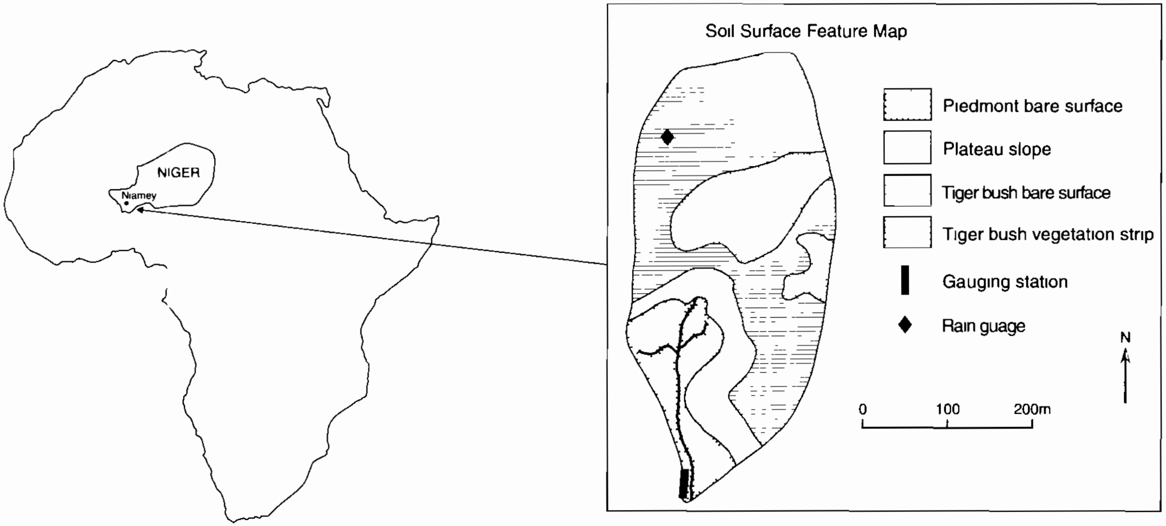

Figure 4.6. Location map of study site in Niger and soil surface feature map in catchment.

production in this region. Hortonian overland flow occurs during rainstorms after the soil's infiltration rate falls below that of the intensity of the rainfall. For the catchment, the mean seasonal values of the runoff coefficient Cr (volume of total runoff/volume of total rainfall over a season) observed during the two rainy seasons 1993 and 1994 ranged from 30 to 44% (Table 4.2), characterizing a catchment with high runoff production capability. At the runnoff plot scale, the values are slightly higher, ranging from 45 to 47%. Even though the number of floods is rather similar for the two observed years, the efficiency of the catchment was greatly increased in 1994. This difference between the 2 years does not appear at the runoff plot scale. The maximum Cr values were recorded for the storm on the July 21, 1994, which occurred under wet soil conditions. This storm produced similar values for the plot and the catchment.

The values of the runoff coefficient observed during the two rainy seasons allows the runoff capability of the catchment to be compared with that of a runoff plot located on the plateau bare soil surface (Table 4.2). The data collected in 1993 revealed that there are significant losses as the runoff moves from the zone of production to the catchment outlet. Both intermediate absorption and channel seepage on the plateau slope contribute to the decrease in flow. The overland flow produced on the bare surfaces runs into and is slowed down by the vegetation bands located perpendicular to the slope, and a significant part of the water infiltrates when crossing the vegetation bands. This explains the lower number of floods observed at catchment outlet, as the small storms do not produce enough runoff to reach the gauging station.

The difference in the mean runoff coefficient observed at the catchment scale between 1993 and 1994 is not observed at the runoff plot scale. The values of the runoff coefficient mean and maximum are very close at both scales in 1994. This was not the case in 1993. These differences can be explained by the greater amount of rainfall in 1994 (671 mm) compared with 1993 (484 mm) and its regular distribution during the second half of the rainy season that decreased the intermediate losses. The greater amount of runoff observed in 1994 was not the consequence of an increase in the runoff efficiency of the catchment but was due to lower surface water transfer losses. The soil moisture investigations made during the experiment are presented by Galle, Ehrmann, and Peugeot (1999) and chapter 5 of this volume.

Table 4.2. Runoff Coefficient Observed on the Catchment and on the Runoff Plot Situated on the Bare Zone of the Plateau

	Catchment 1993	Catchment 1994	Runoff plot 1993	Runoff plot 1994
Date	07/30 08/13	07/21	07/29	07/21
Number of floods	21	25	27	29
Runoff coefficient mean	30.3	44.1	45	47
Runoff coefficient max	44.7	68.7	71	69

Europe

A rainfall simulator was used in banded formations in three areas of Spain to quantify the surface water redistribution at fine spatial scales (Bergkamp, Cerdà, and Imeson 1999). These results were combined with an analysis of the rainfall magnitude-frequency characteristics of the three areas. There was a high variability in surface water redistribution, with most of the surface water originating from short storms of 10 minutes, duration.

North America

Cornet, Delhoume, and Montaña (1988) estimated that due to rainfall redistribution the vegetation bands in the Chihuahuan Desert in Mexico receive 1.5 to 2.5 times the rainfall at the site. Delhoume (1996) also describes that at his experimental site there are two scales at which water harvesting can occur. Although the vegetation bands of tiger bush function as previously explained, with runoff from the interbands into the runon zones, the overall tiger bush landscape is located in a runon zone at the foot of a long and crusted hillslope (Delhoume 1996). This type of two scale functioning has been also observed in areas of banded vegetation in Australia (J. Mabbutt, pers. comm.).

Studies of Water and Wind Erosion

As the artificial radionuclide cesium 137 (^{137}Cs) is an artefact of atmospheric nuclear weapons testing in the 1950s and 1960s, it can be used to measure erosion or deposition since then. Chappell and associates (1999) used this technique to measure erosion and deposition processes in Nigerien tiger bush. A 70-m transect encompassing two vegetation bands and the intervening bare band was studied. Using this technique, they showed that the net soil flux did not exceed the average annual dust accumulation rate (4 t ha^{-1} yr^{-1}) (Chappell 1995), although it did exceed the monitored 8-year dust deposition rate (2 t ha^{-1} yr^{-1}) for the region (Drees, Manu, and Wilding 1993). The discrepancy between these rates could be attributed to the imprecision of short-term monitoring and also to the difference in the efficiency of natural (vegetation) and artificial dust traps. These results suggest that the net soil gain at the depositional site was probably not only due to the accumulation of dust but also to some accumulation of material redistributed by surface wash. Single ^{137}Cs measurements from other vegetated bands and interbands in the region (Chappell 1995) have resulted in a net soil gain of 4 t ha^{-1} yr^{-1} and net soil loss of -3 t ha^{-1} yr^{-1}, respectively. These patterns correspond with the location of the erosion and sedimentation crusts identified by using a standardized classification (Valentin and Bresson 1992). Miles (1993) also used the radioactive isotope ^{137}Cs to measure soil erosion in the semiarid mulga woodlands on southwestern Queensland. Based on the ^{137}Cs profiles, the mulga lands of southwestern Queensland have lost approximately 30 mm of soil on average in the past 35 years. Besides water erosion, two types of semiarid, wind-induced vegetation patterning have been cited in the literature. One is related to former and leveled dunes, as described for northern Nigeria (Zonneveld 1999). Clayton (1966, 1969) referred to the same Sangwina sands. The orientation of the bands (about NNW to SSE) is perpendicular to the prevailing wind direction (ENE to WSW) during the period of formation of the former dunes. The other corresponds to present processes. In Mali, Leprun (1999) mentioned that on the bare crusted band, the eroded and sorted soil particles experience two different processes. The finer clay and loam fractions are removed downslope by the overland flow and accumulate in the depressions to form the wooded band where vegetation and fauna subsequently concentrate. The sandy particles are shifted by aeolian deflation and are deposited upslope, forming a microdune. In particular, the stratification, with a monoclinal lithology oriented NE to SW, namely, perpendicularly to the dominant wind direction and its slope facing the wind, controls the process and the direction of the band migration. Not being necessary to the formation of the contracted bush, the action of the wind would favor relatively rapid migration of the vegetation (up to 0.7 m yr^{-1}).

Effect of Soil Surface Conditions on Runoff

The runoff and erosion properties of banded vegetation are largely controlled by the nature of the soil surface conditions in the band and in the bare interband areas. Several factors influencing surface soil conditions in these two areas are discussed.

Macropores Resulting from Activities of Soil Biota

The results from the disc permeameter studies (Greene 1992) show the importance of pores greater than 0.75-mm diameter in conducting water into the soil. At a supply potential of –40 mm, when pores greater than 0.75-mm diameter are not contributing to water flow, the soils in each zone have similar infiltration rates (Table 4.1). However, the greatly enhanced infiltration rates (under ponded conditions) in the mulga band soils indicate that this sized pore must be prominent in these soils. These stable macropores of greater than 0.75-mm diameter, however, are largely absent from the upslope runoff areas. The absence of these pores in the runoff zones has been correlated with termite populations, which are lower in the interband areas compared with bands (Whitford, Ludwig, and Noble 1992). The differences can also be related to surface crusting (Greene 1992).

Surface Crusting

Surface crusting has been identified by many authors as the major factor of runoff production in the bare interbands. Difference in surface hydrology between the bare and the vegetated bands can be caused by variation in soil sealing due to a small difference in silt content between the two zones. Such differences have been ascribed to former early Holocene to late Pleistocene dunes leveled by sheet erosion (pediplanation) separated by filled-in valleys in northern Nigeria (Zonneveld

1999). Most often, the interband is subdividable in several parts characterized by surface conditions. Dunkerley and Brown (1999) noticed in Australia that the upslope part is relatively stone-free compared with the lower part. Thiéry, d'Herbés, and Valentin (1995) described the most common succession of surface crust along a transect across the bare interband. From a water-flow point of view, it is significant to consider the successive steps of the crusting process from the low fringe of the vegetated band to the destruction of the crusts within the core of the vegetated band.

In the downslope edge of the vegetated band, vegetation declines because of a chronically insufficient water supply. Owing also to the reduced litter cover and soil-faunal activity, structural crusts tend to develop. They consist of three well-sorted layers. The uppermost layer is composed of loose coarse sand; the middle one consists of fine, densely packed grains with vesicular pores; and the lower layer shows a higher content of fine particles with considerably reduced porosity. Frequently, the upper layer contains very fine gravel and very coarse sand. The well-defined textural differentiation results from a process resembling the particle size discrimination obtained from a nest of sieves, hence the term *sieving crust* is given to this type (Valentin and Bresson 1992). Raindrop impact forms micro-craters, the walls of which present a clear vertical sorting of particles. Wind and runoff can readily remove loose particles in the sandy microlayers of the sieving structural crusts. The lower fine-textured layer is responsible for the low infiltration rates of such crusts (Casenave and Valentin 1992).

In the bare areas, three major types of crust occur in a more-or-less clear succession: erosion, pavement, and sedimentation crusts. Erosion crusts are built up with a single smooth hard layer made of fine particles. Porosity is restricted to a few cracks and vesicles, so that the infiltration rate is low. Erosion crusts are formed of sieving crusts from which the loose sandy layers have been removed by overland flow and wind. They mainly occur in the upslope part of the bare areas and develop a dark patina, most likely due to colonization by cyanobacteria (Malam Issa et al. 1999). Once formed, these crusts promote runoff and are usually not observed to be colonized by vegetation because of the impedance they provide to seedling emergence and the dry pedoclimate they produce. Wind and overland flow invariably remove seeds that may be deposited on the soil surface.

Pavement crusts contain coarse fragments embedded in a crust the microstructure of which is similar to the sieving crust described above. Vesicular porosity is much more pronounced, especially below the coarse fragments. The distribution of patches with pavement crust is rather indiscriminate due to the irregularity of the depth of the gravel layers. Because these pavement crusts tend to armor the soil underneath, they tend to protrude slightly from the adjoining erosion crusts. Such pavement crusts are also common in the bare interband of banding patterns in Australia (Dunkerley and Brown 1999; Macdonald, Melville, and White 1999).

Sedimentation crusts or "still depositional crusts" (Valentin and Bresson 1992) consist of densely packed and well-sorted particles, the size of which progressively increases with depth. The vertical particle-size distribution, with coarser particles at the bottom and finer particles at the top, is the reverse of that observed in the sieving crusts. When dry, these crusts often break up into curled-up plates. "Still-depositional" crusts form in standing water and develop where surface flow is hindered. In puddles, the larger particles sink rapidly and form the bottom layer, whereas the finer particles deposit at the top. During drying, cracks and curled plates can develop owing to the difference in shrinkage forces among the microlayers. These crusts develop in the lowest patches of the bare areas, directly adjoining the grassy depositional open bush areas.

The general distribution of the three major types of crust can be modified due to local topographic accidents, but it is common in many bare interbands of banding patterns, for example, in northern Mexico (Janeau, Mauchamp, and Tarin 1999). In the grassy areas that correspond to the upper zones of the vegetated bands, the crusts are depositional but differ slightly from those previously described. They are often more platey in structure, do not curl up, and are often colonized by algae ("microphytic sedimentation crusts" or "microbiotic crusts") (Eldridge and Greene 1994). Their pronounced porosity consists of numerous broad cracks (1 to 2 mm) and abundant holes perforated by termites. In the core of the vegetated bands, the thick litter provides an efficient protection to soil surfaces, but intense termite activity tends to destroy the crust (Ouédraogo 1997). However, this litter and the faunal activity are not uniform, so that in some patches the previous crust can be locally maintained.

Comparison of the infiltration rates of the crusts in the interband area demonstrated that the final infiltration rates measured with the rainfall simulator were lower than those measured with the disc permeameter. Therefore, the additional effects of raindrop impact and surface flow obtained with a rainfall simulator cause the soil to have a lower permeability. Greene and Ringrose-Voase (1994) further investigated the hydrological properties of surface crusts occurring on the runoff zone. The crusts examined were of two types: those that had been present for sometime, and those that were recently generated by using the mobile rainfall simulator. Micromorphological examination of the surface crusts distinguished four main categories of surfaces that were always present in a crust (i.e., a matric crust, skelic crust, porphyric crust, and disturbed crust). These categories were described according to Brewer and Sleeman (1988). The matric crusts have a concentration of clay at their surface as a thin crust of clay microaggregates approximately 50 µm thick, whereas the skelic crusts are 500–800 µm thick and consist of a concentration of sand-sized quartz grains at the surface. Porphyric crusts have no fraction concentrated at their surface, and a disturbed crust is broken up. Because the categories are based only on the immediate surface layer alone, it is not always possible to relate them to crust categories used by other workers. Nevertheless, the matric crust and skelic crust relate, respectively, to the erosion and sieved structural crusts described by Valentin and Bresson (1992).

Examination of the crusts showed that the proportions in the various categories change as the soil is subjected to different treatments. Therefore, it is probable that in the soil from the runoff zone, the crust morphology observed after a single significant rainfall event gradually reverts during a dry period to a condition similar to that found before the event. Greene and Ringrose-Voase (1994) proposed that the micromorphological properties of surface crusts are cyclic over time. Because the microstructure of surface crusts has a large effect on soil hydraulic properties, it is probable that the infiltration rate would also be cyclic over time, decreasing during rain and increasing progressively again after dry periods. This was shown by some additional infiltration measurements carried out with a disc permeameter on the runoff slopes. Greene and Ringrose-Voase (1994) showed that after a series of high-intensity rainfall events in 1988, the soil infiltration rate dropped from 24.0 to 5.1 mm h^{-1}. However, during the subsequent dry period the rate returned a similar value (23.0 mm h^{-1}) to the prerainfall event. Others researchers have also observed similar seasonally cyclic patterns in soil properties, for example, in grazed pastures in West Africa (Casenave and Valentin 1989) and in Texas in the United States (Thurow, Blackburn, and Taylor 1988).

Vegetative Cover

Besides surface crusting, the other major surface property affecting infiltration and redistribution of water on the runoff zones will be surface vegetative cover, particularly that of perennial grasses. Even though the vegetative cover in the runoff zone at Lake Mere is relatively low (i.e., 7% grass cover) compared with that in the interception zone and mulga band (Tongway and Ludwig 1990), the role of vegetative cover in this zone is still important. There are two main reasons for this: (1) the vegetative cover protects the soil surface from raindrop splash and surface sealing effects, and (2) there is a positive feedback from the vegetative growth into the soil in the form of maintenance of nutrients, especially organic carbon, which improve soil stability (Tongway and Ludwig 1994). Both of these effects would be expected to improve infiltration and water-holding capacity.

Rainfall simulations using a uniform intensity of rainfall (30 mm h^{-1}) were carried out on cover levels ranging from bare ground to approximately 80% total projected cover of perennial grasses (Greene, Kinnell, and Wood 1994). The cover levels were recorded by taking a photograph of the 1-m^2 quadrat by using a camera mounted 1.5 m directly above the plot. Cover included both dead and alive perennial grasses, as well as litter. The runoff measurements were carried out at a constant low stocking rate (0.2 sheep ha^{-1}) to avoid problems with possible direct effects of stock grazing on the soil surface and hence on hydrological properties. There was a highly significant negative relationship between the final runoff rate (y) and the amount of plant cover (x) (Figure 4.7):

$$y = 22.3 - 0.15\,x;\ (r^2 = 0.58;\ n = 15,\ p < .01)$$

The final runoff rates for a high stocking rate paddock (0.53 sheep ha^{-1}) are also shown in Figure 4.7. The average of these, 23.4 mm h^{-1}, is not significantly different from the average final runoff rate (22.3 mm h^{-1}) at 0% cover for the low stocking rate, indicating that in this experiment the two stocking regimes had not influenced runoff other than through their effect on cover.

Several other workers have already demonstrated in rangelands that vegetative cover leads to lower runoff and higher infiltration rates. For example, Scholte

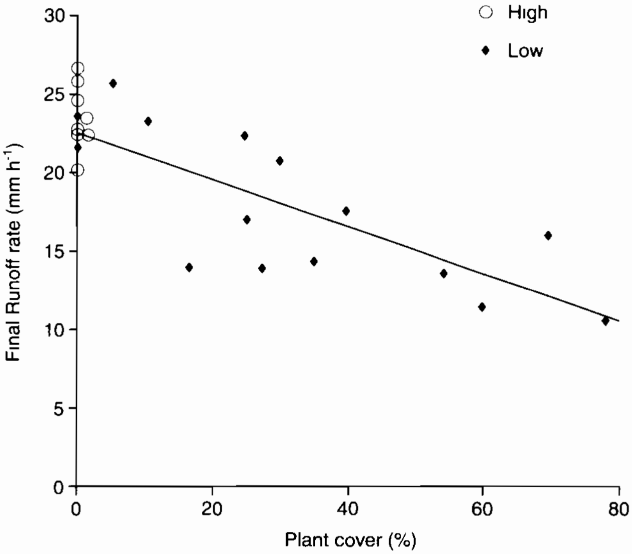

Figure 4.7. Effect of plant cover on final runoff rate.

(1989) showed that there was a greater infiltration rate under shrubs than on the sealed surface soil. Lyford and Qashu (1969) and Blackburn (1975) showed that the infiltration measured near the stems of plants was higher than the area between plants.

Compressive Stress and Bulk Density

Soil susceptibility to water erosion is usually related to compressive stress and bulk density. These characteristics have been assessed along two banded vegetation transects in Australia by Dunkerley and Brown (1999). Unconfined compressive strength (UCS) of the uppermost 1 to 3 cm of regolith was measured at 1-m intervals along the transects with a hand-operated penetrometer equipped with interchangeable domed tips. The patterns of UCS were not entirely regular. However, profiles at both sites display values that generally remain less than 500 kPa. The prominent peaks (2,000 to 3,000 kPa) are associated with zones of forbs (defined as herbaceous nongrass species occurring in savanna grasslands) (Goudie 1990). These zones may coincide with greater amounts of cementing agents such as carbonates or clays delivered from upslope. The trends support the notion that increasing deposition of binding agents of some kind within lower microtopographic elements has occurred. Prominent peak of bulk density (1.48 g cc^{-1}) was recorded at or near the zone of forbs. Within the bands, bulk density fluctuates irregularly (1.33 to 1.41 g cc^{-1}) and tends to be lower than in interbands (1.37 to 1.39 g cc^{-1}). The data are consistent with more frequent dilations of soils within the bands and with their more abundant organic matter, and hence with a more porous, open, and friable soil structure.

Management of Runoff and Erosion in Banded Vegetation

From the previous sections, it can be seen that banded vegetation systems are self-generating and provide a natural water harvesting situation. Valentin and d'Herbès (1999) developed a simple model of rainwater redistribution based on a crust typology relating surface characteristics to hydrological properties (Casenave and Valentin 1992). They found that the ratio between the watershedding zone (which includes the lower decaying part of the vegetated band) and the infiltration zone (restricted to the core of the vegetated band), based on field crust survey, was a better predictor for the water harvesting efficiency of the system than was the interband–band ratio. This water harvesting model could be used as a satisfactory predictor for woody biomass. These authors showed that the water harvesting and concentration process enables wood production equaling that of the forest in much more humid southern zones. The woody biomass of unpatterned vegetation remains approximately half of that of the tiger bush.

Erosion processes can also assist in maintaining the structure of banded vegetation. The erosion processes operating in the banded vegetation act to establish and maintain a series of erosion cell mosaics. Taken together, the topographic sequence of bare interbands and vegetated bands (or in the case of mulga woodlands, three zones: runoff zone, interception zone, and mulga band) make up a single unit referred to as an erosion cell (Pickup 1985). During high-intensity rainfall events, the interband (or runoff zone) sheds water, sediment, and nutrients to the vegetation band (or interception zone and the mulga band). Under a stable system, the losses from the runoff zone (production zone) are balanced by the gains in the mulga band (deposition zone).

The key management question is how do we manage this banded vegetation patterning to ensure the maintenance of the processes of water redistribution and that water is not lost out of the system? This is discussed in detail in chapter 11 of this volume. There are many recorded instances in which poor management has been attributed with effects detrimental to this aim. For example, Mabbutt and Fanning (1987) discussed how degradation of banded vegetation patterning in the Wiluna-Meekatharra area of Western Australia occurred as a result of overgrazing. They reported that moderately degraded mulga woodlands in the Wiluna-Meekatharra area of Western Australia were characterized by bare sheet-eroded interbands and gullying to hardpan on the lower margins of the bands. Greene, Kinnell, and Wood (1994) also discussed the implications of overgrazing on the functioning of the mulga band in the semiarid rangelands of eastern Australia. Overgrazing not only increased the amount of runoff into the bands, but their high infiltration rates were also lowered. Under heavy rainfall events, excess runoff would bypass the bands and be lost out of the land system. The end result is the breakdown of the banded vegetation patterning. Dunkerley and Brown (1995) also showed that similar degradation can occur in arid chenopod shrublands. Tongway and Ludwig (1997) described such landscapes as dysfunctional. Valentin, d'Herbès, and Poesen (1999) further discussed the role of both human disturbance and climate change in altering banded landscapes.

The key tactical approach is to set management-induced impacts to maintain current infiltration rates in the interbands (thereby not greatly increasing the current amount of runoff) and to maintain the infiltration capacity of the bands such that the system behaves as a closed tier (Greene, Kinnell, and Wood 1994). In addition to grazing, road construction, drainage works, and pasture improvement, all need to be managed to maintain the hydrology of the patterned surfaces. The processes of runoff and redistribution are thus critical for maintaining a highly efficient system of water harvesting and primary production in systems of banded vegetation patterning in both arid and semiarid environments.

Summary

We have outlined the results of various soil runoff and erosion studies in a range of continents. They have all demonstrated the role of rainfall infiltration and redistribution as essential characteristics for the maintenance of banded vegetation patterning. The marked differences in soil hydraulic properties between the two mosaic phases (i.e., higher infiltration rates in the bands compared with the interband areas) largely account for the redistribution of water that occurs during rainstorms. The differences are largely controlled by the surface soil conditions of the respective zones, particularly the high crusting tendency of the interband surface, coupled with the high amounts of perennial grass and shrub cover in the vegetative band. The redistribution of water and its concentration in the runon areas further enhances the levels of cover in the vegetation bands, which, in turn, enhances soil physical properties, especially infiltration rates.

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