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Systematic variation of soil infiltration rates within and between the components of the vegetation mosaic in an Australian desert landscape

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Abstract:

Vegetation mosaics have commonly been thought to include two principal zones with distinctly different hydrology: relatively bare and impermeable runoff source zones (*intergroves*) and more strongly absorbing vegetated runon zones (*groves*). However, the data required to verify the internal uniformity of hydrologic response within these components of mosaic landscapes have been lacking, as have data on the nature (abrupt or gradational) of the boundaries between them. This study examines the degree of internal uniformity of key soil properties in the intergroves and groves of an Australian vegetation mosaic.

Infiltration rates, soil water content, shear strength, bulk density and texture were determined at intervals of 1·5–2·5 m across several grove–intergrove cycles of an Australian banded shrubland. Results demonstrate that order-of-magnitude variability in soil infiltration rates can occur across intergroves, with lesser variation in groves. Patterns of infiltration are systematically related to slope position. Rates are relatively high in the uppermost parts of the intergrove, and fall to low values only in the lowermost intergrove where soils are mechanically strong. Infiltration rates increase rapidly from the lowermost intergrove to reach maxima within the upper to middle grove, from where rates once again decline toward the next intergrove. However, there is only a gradational change in infiltration rates across the pioneer zone–grove boundary, which is the sharpest of the mosaic boundaries when identified using plant cover data.

Hydrologic models built on the presumption that mapped plant cover units are equally distinct hydrologically may need to be refined to incorporate the presence of systematic internal variability of infiltration rates and gradational change in soil hydraulic properties. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS infiltration rate; mosaic vegetation; soil moisture; grove; intergrove; Menindee Australia

INTRODUCTION

Mosaic plant communities are widely known from semi-arid landscapes in many parts of the world (Tongway and Ludwig, 1990; Montaña, 1992; Culf *et al.*, 1993; Dunkerley and Brown, 1995). Research has documented aspects of the vegetation, soils, hydrology and impacts of human land-use on these landscapes (Anderson and Hodgkinson, 1997; Valentin *et al.*, 1999). Certain properties of mosaic plant communities are striking, including the multi-component spatial structure of the vegetation, which may include parts of the landscape that are almost devoid of vascular plants, 'pioneer' zones on the upslope edge of more densely vegetated groves or thickets and 'senescent' zones on their downslope margin (e.g. Thiéry *et al.*, 1995; Bromley *et al.*, 1997). For example, Tongway and Ludwig (1990) used cluster analysis of field plant cover data to identify three components within a groved mulga (*Acacia aneura*) landscape in a semi-arid part of New South Wales (NSW), Australia. These were *Eragrostis eriopoda* savanna, *Monachather paradoxa* savanna and *Acacia aneura* woodland, occurring in a regular and repeating contour-aligned pattern associated with a gently

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stepped microtopography. Field interpretation and modelling have both suggested that vegetation mosaics such as this reflect the operation of runoff–runon systems in which bare or less vegetated areas such as the *E. eriopoda* savanna are runoff sources and more heavily vegetated areas such as mulga groves are strongly-absorbing runon sinks (Thiéry *et al.*, 1995; Dunkerley, 1997). Nutrients, seeds and other materials are also involved critically in the fluxes between the various landscape components (Ludwig and Marsden, 1995). Other properties of mosaic landscapes have been explored less than the plant community structure. Perhaps surprisingly, one of these is the variation in soil water uptake rates (infiltration rates) within and between the components of the mosaic. Prior investigations of the hydrologic behaviour of banded landscapes (reviewed next), together with modelling studies such as those cited above, have largely proceeded on the basis that each of the clearly distinct vegetation zones corresponds to an identifiable class of hydrologic response (for example, unvegetated areas are relatively impermeable runoff sources while vegetated areas are much more permeable runon sinks). The success of models formulated on this basis can be taken as providing some support for the correspondence of hydrologic units and plant cover zones. However, it is also possible that significant, and perhaps systematic, internal variability in soil hydraulic properties exists within plant cover units such as the less-vegetated runoff sources. If this is so, then it is very relevant to the refinement of hydrologic and developmental models of mosaic plant communities, since it would have implications for the infiltration and runoff volumes arising in the different parts of the landscape.

The primary objective of the work reported here was to investigate the nature and extent of any variability in infiltration rates within the different mosaic components of a landscape in the Australian drylands. In particular, it was hypothesized that intergroves might exhibit internal gradational change in infiltration rates, rather than rates uniformly and distinctively lower than those found in grove, pioneer zone or other soils of the mosaic. This hypothesis was adopted in view of the probability that upper intergroves receive little or no runon water (and hence few or no eroded materials delivered from upslope), but lose materials to the lower parts of intergroves where water is known to pond against plants and litter prior to passing into the grove. The hypothesized outcome was gradual differentiation soil properties, with gradational change across the intergrove. Likewise, it was anticipated that soils of the uppermost grove, that receive some runon water from the intergrove, might also be differentiated from soils further within the grove that would receive less runoff from upslope. At the same time, grove soils were hypothesized to exhibit less systematic variation in infiltration rates related to slope position than intergrove soils, owing to the prevalence within groves of soil shrink–swell and related phenomena such as collapse piping, that are widely reported and which would tend to promote soil mixing and so more homogeneous soil properties. However, the direct and indirect effects of plants (such as the addition of organic matter and the creation of root spaces) are also known to lead to local differentiation of soils and so to non-uniform infiltration behaviour (see below), so that grove soils should exhibit spatially varied water uptake rates for reasons unrelated to the path and volume of runoff. These hypotheses were tested by making infiltration rate, soil moisture and other determinations at multiple sites along several upslope–downslope transects spanning adjoining intergrove and grove locations.

A brief review of prior work on infiltration rates in mosaic landscapes is provided in the following section, to highlight the perceived gaps that are addressed subsequently.

Infiltration and soil water abundance in mosaic plant communities

In pioneering work in contour-aligned mulga grove landscapes in central Australia, Slatyer (1961, 1965) showed that infiltration rates for grove soils all exceeded 18 mm h^{-1} and reached 150 mm h^{-1} close to the stems of the trees, whilst rates were only about 10 mm h^{-1} in intergroves. This pioneering work demonstrated that in fact infiltration rates in plant groves are spatially variable, because of factors like the radiating roots systems, that can extend up to 13 m from the trunk of these 3–5 m tall trees (Anderson and Hodgkinson, 1997). This was confirmed in a different vegetation type by Dunkerley (2000), who showed that in a mosaic chenopod shrubland near Broken Hill in arid western NSW, Australia, soil infiltration rates within groves reached maxima close to the stems of shrubs, declining outward toward open shrub interspace rates that were only recorded well beyond the canopy margin. These radial patterns probably exist within the vegetation groves of many mosaic landscapes in addition to the Australian mulga and chenopod communities. To date, no systematic studies have investigated whether there are additional systematic changes in infiltration rates across vegetation groves related to position in the runon path (i.e. distance below the intergrove). In view of the complex patterns of radial variability around plants of uneven spacing (where the zone affected by two or more neighbouring plants might overlap), the infiltration rates of grove soils seem almost certain to exhibit quite complex patterns of spatial variability. It is clear, however, that where radial trends in infiltration rate of the kind reported by Slatyer (1961, 1965) and Dunkerley (2000) occur, reliance on a single representative test measurement of the infiltration rate for the grove component of a vegetation mosaic provides an incomplete picture of the relevant soil hydraulic properties. Rather, such vegetation groves are themselves composed of an internal mosaic of different soil infiltration rates.

Tongway and Ludwig (1990), however, reported soil infiltration rates for a NSW mulga grove site on the basis of stratified sampling whose categories were based on plant cover units. They noted (Tongway and Ludwig, 1990, Figure 5) infiltration rates in mulga groves to be about 28 mm h^{-1}, *E. eriopoda* savanna of about 12 mm h^{-1} and the intervening *M. paradoxa* savanna about 18 mm h^{-1}. Using simulated rain at 29 mm h^{-1}, they observed runoff from the *E. eriopoda* after only 7 min, but none from mulga grove soils, which absorbed all applied water. Similar sampling, with a single site in each vegetation component, was adopted by Cornet *et al.* (1988) when monitoring soil moisture in a striped plant community of the Chihuahuan Desert.

More recently, much detailed information on infiltration, soil water recharge and seasonal variability in soil water was developed from the major HAPEX-Sahel studies conducted primarily in Niger (Cuenca *et al.*, 1997). There, Bromley *et al.* (1997) recognized four distinct vegetation classes (bare ground, grassy open bush, closed bush and bare open bush), and suggested that these exhibited distinct behaviour in terms of soil water uptake. They reported infiltration rates at −0·5 cm water tension (close to saturation) of about 37 mm h^{-1} in closed bush, 6·8 mm h^{-1} in grassy open bush, 9·4 mm h^{-1} in bare open bush and 14 mm h^{-1} on bare soil carrying a gravel crust. Bromley *et al.* (1997) did not address radial variation of soil properties in groves, but highlighted the importance of the areal variation in soil surface crusts, such as erosion, sieving and sedimentation crusts (Casenave and Valentin, 1992) in determining surface conductivities, noting that erosion crusts commonly covered the upslope parts of bare areas, whilst sedimentation crusts were associated with areas just upslope of grassy open bush areas (and followed downslope by the closed bush). Thus, Bromley *et al.* (1997) did recognize the existence of variability in infiltration rates in runoff source areas as a result of the presence of different kinds of soil surface crust; they also estimated a weighted runoff coefficient for such areas based upon the fraction of the surface area covered by each kind of crust together with an infiltration rate taken to apply to all areas carrying the same crust type. Bromley *et al.* (1997) furthermore reported subsoil hydraulic conductivities, found using a Guelph permeameter, in four categories corresponding to the four vegetation cover classes, which were once again viewed as hydrologic entities as well as units based on measures of plant cover.

Janeau *et al.* (1999) also adopted the stratification of hydrologic investigation on the basis of plant cover types in a study made in the Mapimi Biosphere Reserve in the Chihuahuan Desert of Mexico. Four plots were exposed to simulated rain, corresponding to the four landscape components recognized (in downslope progression, these were a bare runoff zone, pioneer zone, central vegetation zone and senescence zone). For each plot, five different rain intensities were used. In general, the results showed lowest infiltration rates in the bare soils, rising through the pioneer zone to a maximum in the central zone, declining once more in the senescence zone. Rates reached 30–40 mm h^{-1} in the central zone, but were nearer 3–7 mm h^{-1} on the bare soils. Additional results of this kind were reported by Galle *et al.* (1999) from bounded runoff plots in Niger, but in a study where natural rain and runoff were observed over a period of 4 years. The plots were again located so as to represent whole components of the mosaic landscape.

Thus, stratified sampling based on a presumed correspondence of plant cover zones and soil hydraulic response zones appears to have been widely used in investigations of hydrologic behaviour in mosaic landscapes. No systematic studies of infiltration rates appear to have addressed the internal variability within components of the mosaic. The reporting of soil infiltration rates (or subsoil hydraulic conductivities), soil moisture data and temporal trends in soil water use and recharge only as mean values stratified according to vegetation cover class means that internal variability within the different components cannot be assessed. Consequently, the reality of the inferred hydrologic response units is not really resolved in such studies. Attention is now paid to this issue using new field data. Most attention is paid to the relatively bare runoff sources, since the task of analyzing the spatial distribution of infiltration rates in groves is complicated by the need to first resolve the radial component referred to earlier. Nevertheless, some preliminary transect-based data from grove sites are also reported below, in order to provide an indication of the variation of infiltration rates with distance from the intergrove.

FIELD AREA AND RESEARCH METHODS

The field area examined is located about 40 km south-east of Broken Hill in arid western NSW, Australia. This area, together with much of inland Australia, received record or near-record monthly rainfalls in February and April 2000, and had previously received high monthly totals in the last months of 1999. In February 2000, Broken Hill received about half its median annual rainfall. Major flooding of ephemeral river systems resulted, and the elevated levels of soil water resulted in extensive growth of annual and ephemeral plants.

The field area contains a striking mosaic vegetation community dominated by Mitchell grass (*Astrebla pectinata*), together with chenopod shrubs and various ephemerals (described below). The vegetation mosaic extends over large areas of a gently-sloping landscape and takes the form of contour-parallel bands of vegetation separated by intergroves that are quite bare in years of near-normal rainfall. This area was studied by Dunkerley and Brown (1999) who established permanent transects across multiple cycles of the vegetation banding, and who described more fully the surface features and microtopography of the area. Briefly, gradients are generally less than 1 and surface soils are of spatially uniform loam and sandy loam texture, reflecting the dominance of aeolian deposition. The wind-blown materials are presumed to have been derived from desert environments to the west, during late glacial times of drier palaeoclimate (Greene *et al*., 2001).

Field observations of soil moisture, plant cover and other variables were made in June 2000 on a benchmarked transect of 250 m that had been established in 1995, spanning a tiered sequence of seven groves and intergroves. In order to refine these observations, three detailed subtransects of about 30 m were set out, each extending across one intergrove, and into the adjacent grove. On these smaller transects, infiltration rate was determined every 2·5 m and soil shear strength every 1 m. Similar subtransects at adjacent locations were used to collect bulk density and plant and stone cover data at 2 m intervals.

Soil moisture was assessed at 1-m intervals along the primary 250-m transect using a commercial dielectric-constant probe (Delta-T Devices, 1997) whose electrodes extended to a depth of 6 cm below the soil surface. The relationship between the recorded data and gravimetric water content was calibrated using 100 cm^3 soil samples from the same location, removed with a steel core cutter and dried at 105 C for 24 h. Using the same steel cutter, bulk density was assessed after oven drying according to the method of Blake and Hartge (1986). Soil pH and electrical conductivity were assessed electrometrically using 1 : 5 soil:water suspensions following the procedure of Rhoades (1982). Soil particle size distributions were determined by wet sieving to separate the gravel and sand fractions, followed by pipette analysis for the silt and clay fractions according to the methods of Gee and Bauder (1986). In order to record relevant surface features, plant and stone cover were assessed from photographs taken vertically above the surface at 2 m intervals along the transect, with a 0·25 m^2 quadrat frame resting on the surface to ensure that identical areas were measured in each photograph. Plants present in the various landscape components were identified from published guides including Cunningham *et al.* (1981). The unconfined compressive strength (ucs) of the soils was assessed using a Proctor penetrometer, with observations collected at 1-m intervals on the 250-m transect.

Infiltration rates were measured using miniature single-ring infiltrometers (94 mm inside diameter) embedded 5–10 mm into the soil. At most test sites, the soil was sufficiently soft that the sharp-edged infiltrometer ring could be embedded in the soil using only hand pressure, but where soils were too hard, the cylinder was inserted with careful hammer blows onto a wooden block resting across the infiltration cylinder to ensure even and progressive embedment. An electronic point gauge as used by Dunkerley (2000) was used as an aid to the maintenance of constant water level in the infiltrometer pond, which was topped up at 30-s intervals from a wash-bottle that was repeatedly weighed on a portable digital balance. The electronic point gauge enabled the pond depth to be kept constant within 1 mm. Infiltration tests were generally run for 15 min, but up to 30 min in some cases, and infiltration rates were generally constant for most of this time. Rates were assessed from the last 10 min of data only, using least-squares linear regression of cumulative infiltrated water volume against elapsed time.

The procedure of Dunkerley (2000) was applied to correct for lateral seepage. This is based on a geometrical approximation of the volume of water that is carried outward beyond the inner wall of the infiltrometer. The volume of water lost into this annular zone is subtracted from the total infiltrated depth, and this reduces uncorrected infiltration rates by approximately 75%. The calculated rates are very similar to those derived from the independent seepage-correction procedure of Reynolds (1993). There is some uncertainty attached to the correction of any infiltration data, especially at sites where it is possible that some macropore flow (as well as matrix flow) was involved in conducting the water through the soil. Differing proportions of matrix and macropore flow would alter the correction required for lateral seepage. After each measurement, the test site was excavated and the pattern (depth, lateral spread) of the wetting front was recorded. These suggested that in most cases the correction referred to above was appropriate, since a symmetrical bulb of wetted soil indicated quite uniform water movement through the soil matrix. Nevertheless, a tendency was noted for the dimensions of the wetted bulb to differ between bare sites and those close to grass tussocks, with possibly less lateral seepage in grove soils. However, since the primary interest of the present study is the variability of infiltration rates, rather than their absolute magnitude (which would in any case vary through time with antecedent soil wetness, the seasonal growth of plants and the associated changing activity of soil fauna), the application of a consistent measurement protocol provides a sufficient basis for comparison across the banded vegetation community. The use of rainfall simulation on larger plots would provide a more physically realistic measure of infiltration rates, but the use of large plots would prohibit the analysis of spatial variability of infiltration rates at the close spacing employed here. Additionally, there is no ready local source for the large quantities of water that would be required for rainfall simulation experiments.

RESULTS

The intergroves studied were typically 10–12 m wide and were followed downslope by groves 15–20 m wide (Table I). The analysis of the quadrat data showed that stone cover on the soil surface increases from only 1–2% near the upslope edge of an intergrove to 55–90% at the downslope edge. Most of the stones are small, <6 mm diameter, though in mid-intergrove sites pebbles of 2–3 cm diameter occur. In parallel with the downslope changes of stone cover across intergroves, the plant cover declines from 14–24% where there is a zone of forbs and ephemerals in the uppermost part of the intergrove to nil in the lowermost intergrove.

As a result of the high rainfalls in the preceding months, unusually extensive growth of ephemeral plants was noted in the study area. Marked photo stations where plant cover had been recorded in prior years confirmed this. In a few intergroves, ephemerals grew across the whole width of the normally bare soil surface, so greatly diminishing the contrast in projected foliar cover between grove and intergrove. In ordinary years, intergroves support a narrow zone of forbs only at their downslope edge where water ponds before trickling into the grove below (this is frequently referred to as the pioneer zone). During the present survey, most

Table I. Details of the intergrove and grove dimensions for transects 1–3. The column headed 'intergrove' indicates the aggregate width of this zone and is the sum of the bare and forbs subzones indicated in the three columns to the left

Transect no.	Width of vegetation zones (m)				
	Upper intergrove (forbs)	Mid-intergrove (bare)	Lower intergrove (forbs)	Intergrove	Grove
1	7·0	1·5	3·5	2·0	0·0
2	4·5	3·5	2·0	0·0	5·5
3	8·5	2·0	2·0	2·5	5·5

intergroves were not completely vegetated but instead exhibited a second zone of ephemerals on their upslope margin, adjacent to the lower boundary of the vegetation grove upslope (Figure 1). Complete coverage of the intergrove evidently resulted when these two zones approached one another and finally joined, but most intergroves retained a narrow strip of bare soil approximately along the midline, parallel to the contour.

A difference in floristic composition between the upslope and downslope zones of forbs and ephemerals was noted. The zone at the upslope margin of the intergroves, where plant cover reached 60%, was almost entirely composed of violet twinleaf (*Zygophyllum iodocarpum*). The downslope zone, in contrast, included *Z. iodocarpum* together with additional taxa such as abundant long-spined poverty bush (*Bassia longicuspis*) and other Bassia spp. together with some chenopod shrubs. Foliar cover here was lower than in the upslope zone of ephemerals, typically 20–40%. Despite the extraordinarily wet antecedent months, no signs of runoff through or from the vegetation groves was noted in the field, and no rill erosion or other surface incision was found, even on the bare parts of the intergroves. Subsoil shrink–swell and collapse had, however, been active within the grass groves, and crabhole collapse pipes were widely developed there. These provide highly efficient traps for any surface runoff that might arise within or pass onto the groves (Dunkerley and Brown, 1999). Many of the larger collapse features were ringed by concentric sets of tension cracks. No collapse features whatsoever were observed within the intergroves, nor within any of the areas covered by forbs and ephemeral plants.

Soil texture and soil moisture distribution across the groves and intergroves

Particle size analysis showed that surface soil samples were texturally either loams or sandy loams, whether from intergrove, grove or zones of ephemeral plants. However, the sand fraction tended to increase from upper to lower intergrove, whilst the clay content declined. Soil pH was alkaline, and nine test results lay in the range $7·39 < \mathrm{pH} < 7·90$. Electrical conductivity for the same nine samples lay in the range $163\ \mathrm{S\ cm^{-1}} < \mathrm{EC} < 459\ \mathrm{S\ cm^{-1}}$. The highest soil EC was at the downslope edge of a grove, whilst the lowest was only 4 m upslope, within the grove. There are thus marked changes in this property over short distances, as might be expected given the complex patterns of soil infiltration rate known from grove soils (see earlier discussion) and a fuller survey of the associated properties of grove soils is needed. Marked changes in soil bulk density were found. The highest, 1·74 g cm^{-3}, was found in the bare and hard lower intergrove, whilst the lowest (1·21 g cm^{-3}) occurred in the upslope zone of ephemeral plants (soil which in ordinary years forms part of the bare upper intergrove). Generally, the bulk density samples were stone-free, but a few samples contained small quartz pebbles.

Soil surface properties also varied with position along the transect. Upper intergrove soils, including those within the ephemeral plants, had few surface stones (<10% projected cover) but exhibited extensive brittle, cracked crusts dominated by filamentous cyanobacteria. In the downslope direction across intergroves, surface stone cover increases by 5–10% projected cover per metre, to reach 50–90% cover just above the lower zone of ephemeral plants. Toward the lower intergrove, but well above the zone of ephemerals, stone size reaches a maximum and then declines. Pebbles of 1–3 cm diameter are therefore found typically a few metres

Figure 1. View along the contour, through an intergrove in the Menindee landscape. Upslope is to the left, where a grove can be seen flanked by the upper zone of small ephemeral plants. This is followed downslope (to the right) by the bare intergrove and the lower or 'pioneer' zone of forbs, which is here narrower than the upslope zone, and finally by the next grove. Both groves are dominated by dense tussocks of Mitchell grass

upslope of the lower intergrove border, and the high stone cover at the lower margin is composed almost exclusively of granule-sized particles. On locally lower-lying parts of the surface, the granules are found in dense concentrations. It is significant for the interpretation of infiltration data offered below that the increase in stone cover across intergroves is progressive, being least upslope and greatest downslope within an intergrove.

Marked variability in gravimetric moisture levels in the surface soils was found along the intergrove–grove transect (Figure 2), the wettest areas having >17% and the driest <2% soil moisture. Trends along the transect involve very sharp jumps in water content, exceeding 2% per metre, together with more gradual declines in water content. The positions of the grove, intergrove and forb–ephemeral zone boundaries marked on Figure 2 show that these soil moisture trends are associated with the different components of the mosaic. The driest locations are the upslope edges of the zone of forbs/ephemerals just above a vegetation grove. The wettest sites lie within the groves, generally at or toward their upslope edge, downslope of which the soils dry progressively. Soil moisture declines through every intergrove and also through some groves; other groves show fluctuations but no tendency for the soil to become drier downslope. Soil moisture data provide no clear indication of any distinct boundaries within the mosaic, except for the rapid increase in wetness at the boundary separating the lowermost intergrove from the uppermost grove.

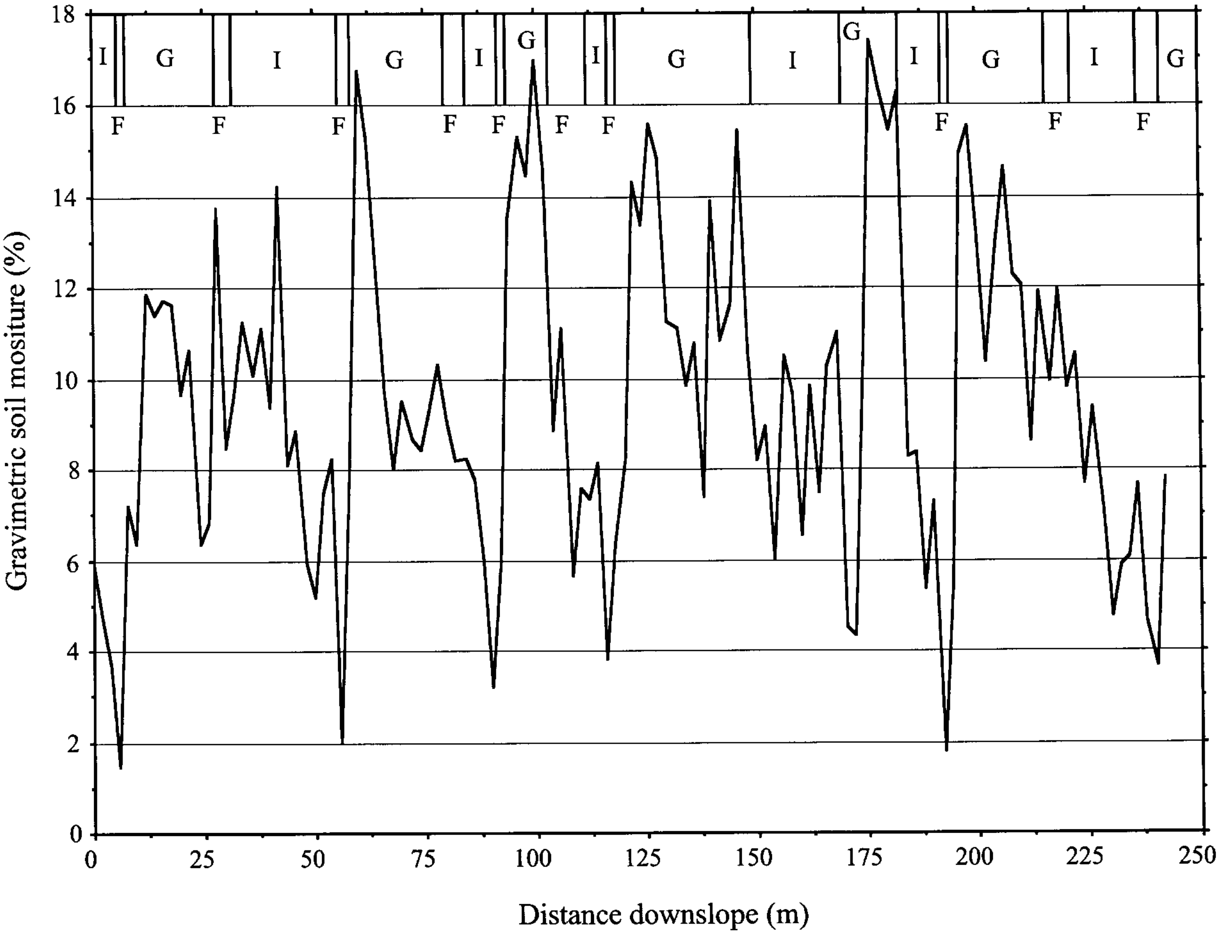

Figure 2. The pattern of soil moisture along the main 250-m transect spanning seven intergrove–grove cycles. The left-hand margin of the diagram is the upslope endpoint of the transect and the slope falls to the right. The subdivision of the landscape based upon plant cover is marked at the top of the diagram (I = bare intergrove, F = zone of forbs and ephemeral plants, G = grove)

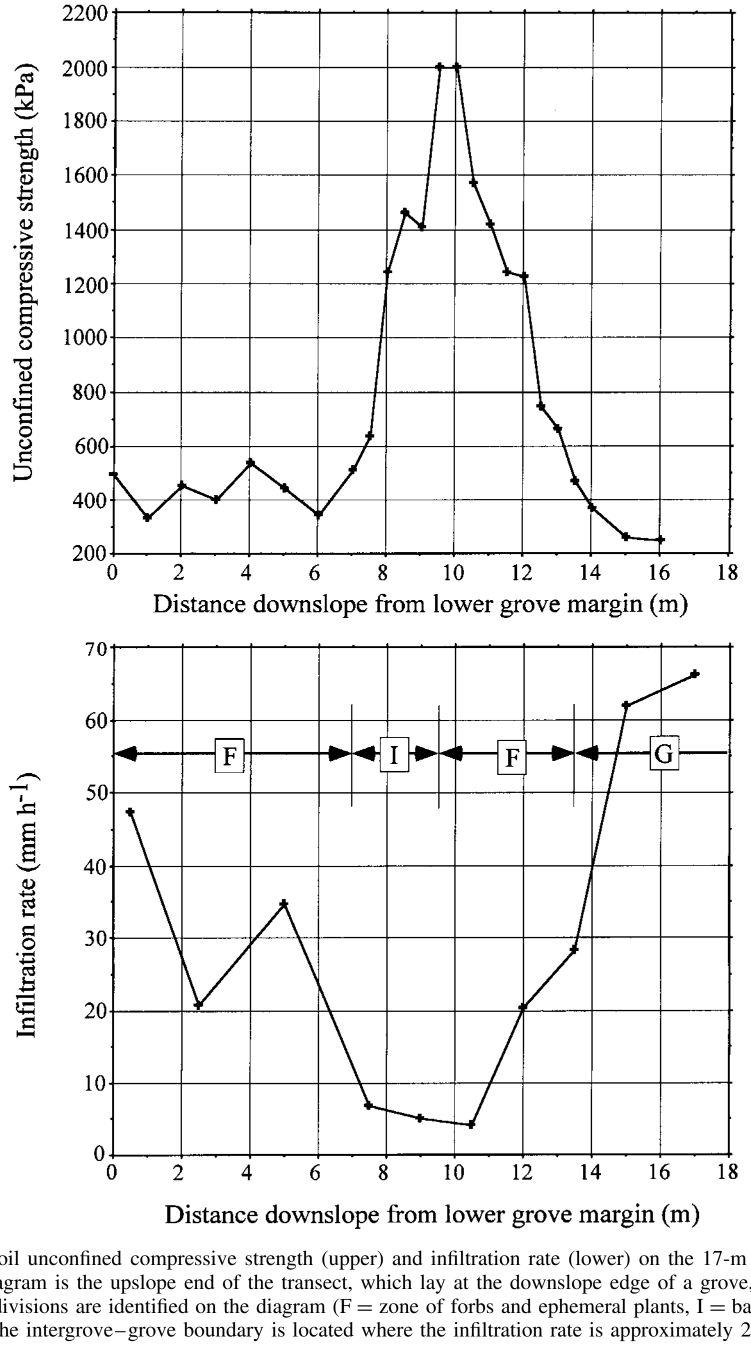

Figure 3. Distribution of soil unconfined compressive strength (upper) and infiltration rate (lower) on the 17-m intergrove transect 1. The left-hand margin of the diagram is the upslope end of the transect, which lay at the downslope edge of a grove, and the slope falls to the right. The plant cover subdivisions are identified on the diagram (F = zone of forbs and ephemeral plants, I = bare intergrove, G = grove). Note that the intergrove–grove boundary is located where the infiltration rate is approximately 28 mm h^{-1}

Infiltration rates

In the central, bare part of the intergroves, infiltration rates were low, reaching only 5–10 mm h^{-1}. Infiltration rates increased upslope through the upper zone of ephemerals, rising to 30–50 mm h^{-1} at 50 cm within 1 m of the lower edge of the grass grove (Figures 3 and 4). Likewise, infiltration rates increase downslope from the bare part of the intergrove, reaching 26–28 mm h^{-1} at the downslope edge of the zone

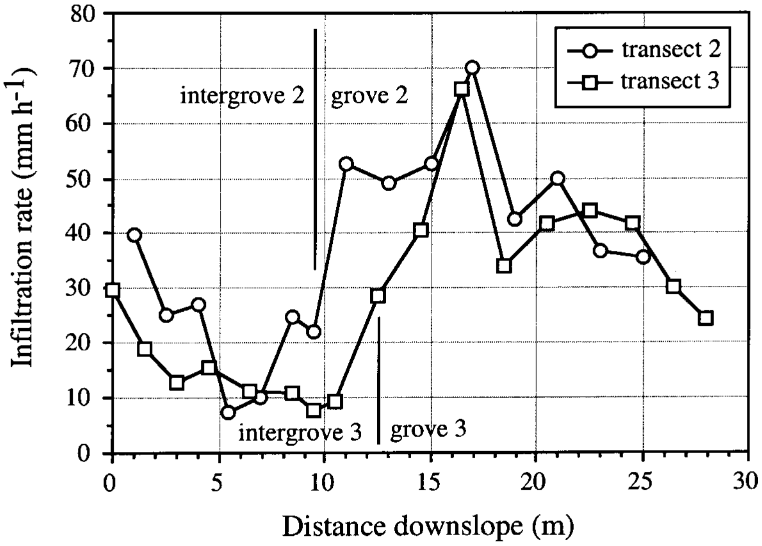

Figure 4. Infiltration data for transects 2 and 3. On each curve, the location of the intergrove–grove boundary is marked with a vertical line. Note that in each case, this boundary is located where infiltration rates are rising from minima in the intergrove toward maxima within the grove. On both transects, the intergrove–grove boundary is located where infiltration rates have risen to about 28 mm h^{-1}

of forbs/ephemerals and then rising to 65–70 mm h^{-1} inside the grove, typically reaching a maximum at a distance of 5–10 m from its upslope edge. Beyond this point in the groves, infiltration rates again fall toward the next intergrove. Thus, there is more than an order-of-magnitude of variability in the measured rates within each intergrove–grove couplet. Significantly, however, the results do not show sharp breaks where infiltration rates change at the vegetation zone boundaries; rather, the change is progressive and there is no uniformity of rates even within a single component of the landscape such as the zone of forbs and ephemerals. Significantly, across what in previous years had been regarded as relatively uniform bare intergrove, lowest infiltration rates were located in the central bare area, rising to higher values in the upslope zone of ephemerals than were found in the normally-present downslope zone of ephemerals.

Similarly, infiltration rates rise steadily from the local minimum in the bare part of each intergrove, to reach a maximum at a point well within the next grove. Therefore, the floristically sharp intergrove–grove boundary is not associated with a similarly sharp jump in infiltration rates. Instead, these rates rise monotonically across the vegetation boundary (see Figure 4).

One each of transects 1–3, small-sample *t*-tests (Freund, 1974) established that the mean intergrove infiltration rate is significantly different from the mean rate within the grove. The same tests show no significant difference among any of the three mean intergrove infiltration rates, or among the three groves. On this basis,

Table II. Results of 42 infiltration tests from transects 1–3, pooled according to location (within intergrove or grove). Infiltration rates are all expressed in mm h^{-1}

	Intergrove	Grove
Number of infiltration tests	21	21
Maximum infiltration rate	47·3	70·1
Minimum infiltration rate	4·2	2·2
Mean infiltration rate	8·5	43·7
Standard deviation	2·1	14·1

all data from each zone were pooled, to make up a larger data set (Table II). Using this, t-tests again confirm that mean grove and intergrove infiltration rates are significantly different, at $\alpha = 0{\cdot}005$. Furthermore, the minimum infiltration rate in the pooled grove data exceeds the mean infiltration rate for the pooled intergrove data (Table II).

There is an inverse relationship between shear strength and infiltration rate (Figure 3). The central, bare parts of intergroves have very strong soils, whose ucs reaches at least 2000 kPa; at this same location infiltration rates are at their lowest, reaching only 5–10 mm h^{-1}.

DISCUSSION

The finding that intergrove surface soils are wettest in the upslope part of the intergrove and drier toward the downslope part (Figure 2) suggests that intergroves do not shed rainwater uniformly as runoff. It is unlikely that the additional water present within the upslope soils, and supporting the dense cover of *Z. iodocarpum* there, is derived from surface runoff that has passed through the grove immediately above, since the soil moisture transect showed that groves tend to become drier in the downslope direction, indicating that soil moisture stores were not filled there. Furthermore, no signs of surface runoff were noted, and the very uneven surface makes the passage of any surface flow through the groves very unlikely (Dunkerley and Brown, 1999). Consequently, it seems more probable that the wetter upslope parts of intergroves have more soil moisture owing to greater direct infiltration of rainwater there. It is also possible that some seepage of water from the upslope neighbouring grove through the shallow subsoil may contribute to the water in the intergrove soils. However, the soil water data reported here are from the top 5 cm of the soil, and seem much more likely to reflect water derived from infiltration through the soil surface. If this is so, then the observed decline in soil wetness downslope through the intergroves, to reach minima of just a few percent in the lowermost intergrove, is consistent with the finding that infiltration rates are not uniform within these areas. Instead, infiltration rates are greater in the upslope part of an intergrove than downslope. The infiltration test results presented earlier (Figures 3 and 4) showed just such relatively high rates within the upslope zone of ephemeral plants, falling to a minimum in the bare area downslope, and finally rising again in the downslope zone of ephemerals, the trend continuing into the next grove. The presence of the upslope zones of forbs and ephemerals, a consequence of the exceptionally wet months preceding the fieldwork, also shows that greater soil wetness had been maintained in upper intergroves for sufficient time for germination and flowering. It is also evident that parts of the upslope zone of ephemerals close to the grove above have higher infiltration rates than the zone of forbs at the downslope side of the same intergrove. Thus, the results clearly show that infiltration rates and soil physical properties are not uniform within the Menindee intergroves.

A key finding bearing on the objectives of this work is that, on the basis of the infiltration rate data collected, it would not be possible to define a boundary separating lowermost intergrove and upper grove locations. Instead, in terms of this hydrologically critical property, one zone grades smoothly into the other (Figures 3 and 4). Interestingly, on all three transects, the intergrove–grove boundary lies where the infiltration rate is close to 28 mm h^{-1}. This rate is reached part-way along the transition from the lowest intergrove rates of 5–10 mm h^{-1} toward mid-grove maximum rates of 60–70 mm h^{-1}. This increase occurs over a distance of about 10 m. Consequently, the very distinct and rapid increase in plant cover used to define the location of the intergrove–grove boundary would appear to reflect a threshold soil water content related to the physiological requirements for plant growth, since it does not correspond with a sharp change in soil infiltration rates. Since infiltration rates change in a gradational way, then so too would soil wetness following a rain event.

Groves also exhibited internal variability in soil properties and infiltration rates. Infiltration rates reached their peak well within each grove, and then declined toward the downslope grove–intergrove boundary. Indeed, the variability of infiltration rates (as measured by the standard deviation of the pooled data) is higher in groves (14·1 mm h^{-1}) than in intergroves (12·1 mm h^{-1}) (Table II).

Therefore, the presumption reviewed earlier that a unique hydrologic response is associated with the plant cover subdivisions of mosaic landscapes is seen not to be supported by the present results. Mean infiltration rates do indeed differ statistically between the intergroves and groves (Table II), but this clearly does not establish that each is an internally uniform entity. Instead, both intergroves and groves exhibit internal variability of infiltration rates. This variability takes the form of a systematic trend in infiltration rates associated with position in the repeating intergrove–grove pattern (Figure 4).

Systematic variation of soil physical properties like shear strength, as well as infiltration rates, characterizes the intergroves in the study area. Groves also show distinctive levels of soil moisture, being wettest toward their upslope margin and increasingly dry downslope (Figure 2). The largest jumps in soil wetness occur between the lowermost intergrove and the upper grove, where increases of 15% were found over a few metres. From a maximum in the upper grove, surface soil wetness then declines through the grove by 5–10%, in an irregular and stepped progression.

CONCLUSIONS

Two key findings from the study can be highlighted.

(1) Infiltration rates are not uniform within the two main vegetation units, intergrove and grove, composing the Menindee banded landscape. Rather, intergroves show a systematic variation in infiltration rates, which reach a minimum in a bare central zone and rise both upslope and downslope into the areas occupied by ephemeral plants. Change in infiltration properties is largely gradational. Infiltration rates rise steadily from the intergrove minimum to a maximum located well inside the grove, and there is no break at the position of the intergrove–grove boundary as defined from plant cover. Models of hydrologic behaviour and mosaic development must therefore incorporate the variation documented, which suggests that upper and lower intergroves, perhaps colonized by ephemeral plants, contribute considerably less water to groves downslope than do the bare and hard central parts of the intergroves. This means that calculations of the runoff volumes that would pass downslope to support the groves would be erroneously high if the intergroves were assumed to be uniformly impermeable with infiltration rates like that of the central, bare zone.

(2) The definition of separate components of the mosaic (bare intergrove, zone of ephemeral plants, grove proper) on the basis of foliar cover and/or floristics does not demonstrate that the relevant hydraulic properties of the soils also change at these boundaries. Instead, the limits of a particular plant cover class reflect the growth requirements of the taxa involved. The properties of the associated soils, such as infiltration rate and soil wetness, may change in a gradational way. The only boundary in the Menindee landscape that is coincident when defined using plant cover or soil wetness data is that between the 'pioneer zone' and the grove. However, this same boundary vanishes, being replaced by smooth gradational change, when soil infiltration rates are used as the delimiting criterion. Thus, whilst the striking vegetation boundaries that are found in many mosaic communities have been widely taken to reflect hydrologic entities also, this need not be the case. The design of soil hydraulics studies stratified on the basis of plant cover units may lead to erroneous conclusions about the existence of hydrologically distinct soils whose properties are in fact gradational.

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