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VEGETATION INFLUENCES ON WATER YIELDS FROM GRASSLAND AND SHRUBLAND ECOSYSTEMS IN THE CHIHUAHUAN DESERT

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ABSTRACT

This study examines runoff generated under simulated rainfall on Summerford bajada in the Jornada Basin, New Mexico, USA. Forty-five simulation experiments were conducted on 1 m^2 and 2 m^2 runoff plots on grassland, degraded grassland, shrub and intershrub environments located in grassland and shrubland communities. Average hydrographs generated for each environment show that runoff originates earlier on the vegetated plots than on the unvegetated plots. This early generation of runoff is attributed to soil infiltration rates being overwhelmed by the rapid concentration of water at the base of plants by stemflow. Hydrographs from the degraded grassland and intershrub plots rise continuously throughout the 30 min simulation events indicating that these plots do not achieve equilibrium runoff. This continuously rising form is attributed to the progressive development of raindrop-induced surface seals. Most grassland and shrub plots level out after the initial early rise indicating equilibrium runoff is achieved. Some shrub plots, however, display a decline in discharge after the early rise. The delayed infiltration of water into macropores beneath shrubs with vegetation in their understories is proposed to explain this declining form. Water yields predicted at the community level indicate that the shrubland sheds 150 per cent more water for a given storm event than the grassland.

KEY WORDS: water yield; semiarid runoff; simulated rainfall

INTRODUCTION

Surveys undertaken in the Jornada del Muerto Basin in southern New Mexico, USA, indicate that in 1858 the region was extensively covered by semiarid grasses (Buffington and Herbel, 1965). Today, however, a variety of shrub species, such as creosotebush (*Larrea tridentata*), mesquite (*Prosopis glandulosa*), and tarbush (*Flourensia cernua*), dominate the basin flora (ARS, 1994). The causes of this change in vegetation are complex and intricate; some that have been proposed include climatic change, fire suppression, increasing atmospheric CO_2, and overgrazing (Neilson, 1986; Grover and Musick, 1990; Milchunas and Laurenroth, 1993; W. H. Schlesinger, unpublished work). Whatever the factors responsible for the initial disruption of the grasslands, the consequence has been the growth of apparently self-perpetuating shrubland ecosystems which appear to be very resilient to environmental disruption or change and therefore extremely persistent.

One important aspect of the invasion of shrubs in the Jornada Basin has been a redistribution of resources. Semiarid grasslands afford soils a relatively complete and homogeneous cover. Semiarid shrubland communities, however, typically display a heterogeneous distribution of vegetation. The shrubs become focal points, or 'islands of fertility', beneath which soil infiltration rates are relatively high and nutrients accumulate and are cycled. At the same time, adjacent intershrub areas become hostile zones of exposed soils and low nutrient availability (W. H. Schlesinger, unpublished work).

The focus of the Jornada Long-Term Ecological Research (LTER) programme is on the processes that have led to the desertification of the northern Chihuahuan Desert ecosystems in the Jornada Basin and on the concomitant changes in ecosystem structure (Whitford, 1993; W. H. Schlesinger, unpublished work). This

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study aims to contribute to this large body of work through an examination and characterization of water movement under simulated rainfall on a grassland and shrubland community in the Jornada del Muerto Basin.

In arid and semiarid environments, runoff production reflects a complex combination of hydrologic, lithologic, and rainfall factors (Scoging, 1989). Infiltration, interception, and surface ponding all show considerable variation across hillslopes (Luk, 1982). These variations result from the natural heterogeneity of factors such as vegetation density and form, and soil moisture, texture and stone content (Hills and Reynolds, 1969). The purpose of this investigation is to examine and quantify the role that changing vegetation has played in altering the hydrologic response of a semiarid hillslope. Thus, the findings of this study will be of relevance beyond its immediate application to the Jornada LTER project.

STUDY SITE

The Jornada del Muerto Basin is located in southern New Mexico, USA. The basin formed over the past 26 million years by down-faulting and warping relative to the adjacent San Andreas, Dona Ana, and Caballo mountains (Gile *et al.*, 1981; Peterson, 1981; Wondzell *et al.*, 1987). Today, coalescing alluvial fans (bajadas) extend from these mountain ranges down to the essentially level basin floor. These bajadas are crossed by sand-bedded arroyos, between which the surfaces are drained by overland flow that collects in networks of small channels. These small channels are especially well developed in the shrubland and evidence from aerial photographs suggests that they have increased in density in association with the transformation of grassland to shrubland.

The climate of the basin is warm and semiarid with an average annual temperature of 15·6 °C (Gile *et al.*, 1981; Schlesinger *et al.*, 1990) and an average annual precipitation of approximately 230 mm (Gibbens and Beck, 1988). The majority of this precipitation (64 per cent) is received in the summer months of July to October and comes in the form of intense, short-duration convective storms that produce significant volumes of surface runoff. The winter and spring rains (November to June) are generated by broad frontal storms that originate over the Pacific Ocean (Gibbens and Beck, 1988). Most of the moisture from these low-intensity storms infiltrates into the soil limiting the generation of overland flow.

The present study was performed on a bajada surface extending from the foot of Summerford Mountain on the western edge of the Jornada Basin (Figure 1). The vegetation on this bajada, hereafter named Summerford bajada, is dominated by two different communities. A grassland community, consisting of black grama (*Bouteloua eripoda*) grasses interspersed with occasional mesquite (*Prosopis juliflora*) and mormon tea (*Ephedra trifurca*) bushes, is located at the base of Summerford Mountain. Downslope of the grassland, the bajada surface supports a shrubland community dominated by creosotebush (*Larrea tridentata*).

The purpose of this study is to characterize the movement of water within these two communities. Accordingly, three field sites were selected to represent the vegetation on Summerford bajada. The first two sites are positioned within the established grassland and shrubland communities. The third site, hereafter named the degraded grassland site, was located at the periphery of a shrubland and was chosen to represent the temporal transition between a grassland and a shrubland. The degraded grassland contained a sparse covering of black grama grasses and shrubs that are younger than those seen in the fully developed shrubland.

MATERIALS AND METHODS

Runoff plots

This study examines the movement of water under simulated rainfall within the grassland, degraded grassland, and shrubland communities. Eight rainfall simulation experiments were performed on the grassland and ten on the degraded grassland.

Within the shrubland community, however, the distribution of vegetation gives rise to a binary system of nutrient-rich shrub and relatively infertile intershrub surfaces. Soils beneath shrub canopies are protected from raindrop impact and have relatively high infiltrabilities. In contrast, soils in the intershrub areas are devoid of vegetation, have sealed surfaces, and relatively low infiltrabilities (W. H. Schlesinger, unpublished work). It was expected that these two soils would exhibit different runoff characteristics, and the runoff plots were

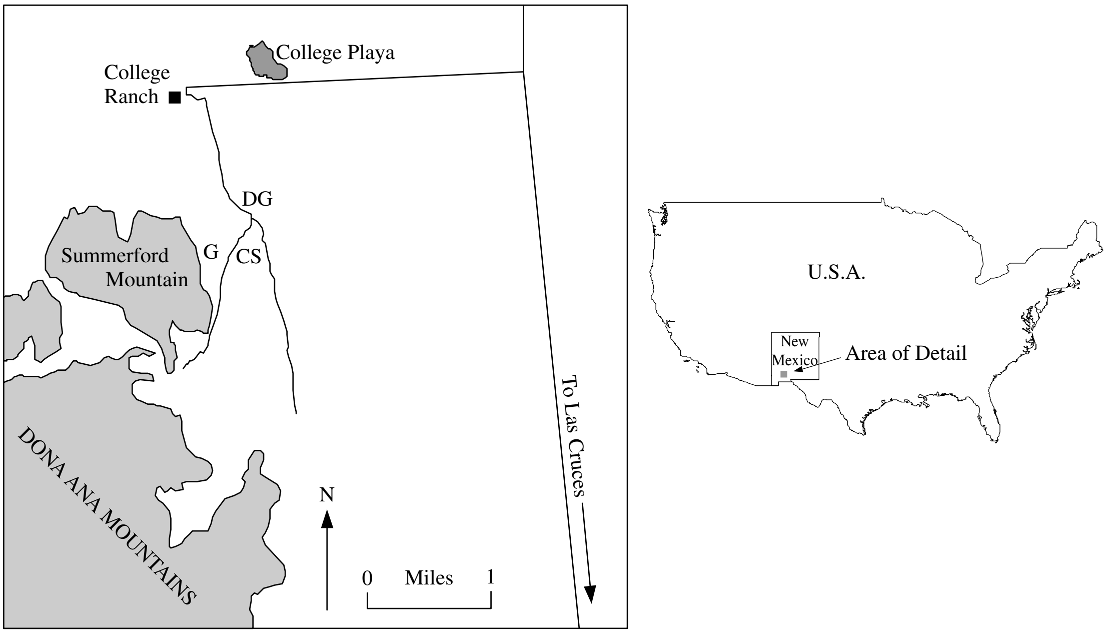

Figure 1. Approximate location of study sites on Summerford bajada. G, black grama grassland; DG, degraded grassland; CS, creosotebush shrubland

positioned to reflect this. Within the shrubland community, therefore, 14 runoff plots were located beneath shrub canopies and 13 were positioned in the bare intershrub areas.

For the remainder of this paper the terms 'ecosystem' and 'community' are used interchangeably to refer to the grassland, degraded grassland, and shrubland. The term 'environment', however, is reserved for the four surface types on which the rainfall simulations were performed, namely grassland, degraded grassland, shrub and intershrub.

Surface properties

The runoff plots were 1 m wide and 2 m long, except for those beneath shrub canopies which were 1 m wide and 1 m long to ensure the entire plot lay beneath the canopy.

Prior to the simulation experiments, the surface characteristics of the runoff plots were assessed using a 10 cm grid. The grid was placed over each plot and the nature of the ground surface was assessed beneath the intersection points of the grid. For each plot the percentage vegetation cover ($\%V$), litter cover ($\%L$), gravel (particle diameter >2 mm; $\%G$) and fines (particle diameter ≤ 2 mm; $\%F$) on the surface were determined. Shrub plots also had the percentage canopy ($\%C$) recorded. The average surface properties for each environment are listed in Table I.

Surface property data were also collected for each community using 10 m transects. These data were necessary to determine the proportion of surface properties within each ecosystem. This could not be determined from the runoff plots which were sited to sample specific cover types. The average surface properties for each community are also listed in Table I.

Rainfall simulation

The rainfall simulator was based upon the design of Luk *et al.* (1986) and had a fall height a 4·57 m. Luk *et al.* (1986) report drop size distributions for this simulator of 0·35 to 6·36 mm with a median of 2·40 mm. Simulated rainfall was delivered to each plot at an average intensity of 133 mm h^{-1} for 30 min. The rainfall was measured using rain gauges distributed around the edges of the plots. These gauges provided a rainfall total for each event which was then divided by duration to get average intensity.

Table I. Average surface property data for the environments and communities on Summerford bajada

	Fines (%)	Gravel (%)	Vegetation (%)	Litter (%)	Canopy (%)
Environment					
Grassland	16	29	34	21	
Degraded grassland	39	29	18	14	
Shrub	22	13	35	30	66
Intershrub	44	35	12	9	
Community					
Grassland	17	30	40	13	1
Degraded grassland	33	33	14	20	5
Shrubland	28	30	34	8	27

Rainfall intensities in excess of 100 mm h^{-1} are not uncommon in the Jornada Basin. For example, tipping bucket rain gauges established for less than a three year period on Summerford bajada recorded several events where intensities exceeded 100 mm h^{-1} (Wainwright, in press). However, only an extreme precipitation event would maintain an intensity of 133 mm h^{-1} for a duration of 30 min. Indeed, the regionally averaged NOAA precipitation atlas for New Mexico indicates that the average 2 year, 30 min rainfall intensity in the vicinity of the Jornada Basin is approximately 30 mm h^{-1} (Miller *et al*., 1973). None-the-less, a rainfall intensity of 133 mm h^{-1} for a 30 min duration was employed in this study for two reasons: firstly, it was required to promote runoff from the small plots with high vegetation covers (both grass and shrub); and, secondly, it was required to ensure that equilibrium runoff conditions would be achieved.

Timed runoff samples were collected throughout each simulation event. These samples were analysed gravimetrically to determine discharge (Q) and water yield (W_Y).

The general character of the hydrologic responses of the four environments to simulated rainfall is assessed using a *composite* hydrograph. This hydrograph was derived in the following way. For each rainfall simulation event discharge was estimated at 2·5 min intervals. These discharges were then averaged to produce a single hydrograph for each environment. The resulting hydrographs represent the typical response of each environment to a simulated rainstorm with an average intensity of 133 mm h^{-1} for 30 min (Figure 2).

RESULTS

Composite hydrographs

The composite hydrographs for the grassland and shrub environments exhibit an early and sharp rise in discharge. The average times to runoff for these two environments are 2·31 and 2·28 min, respectively. The average times to runoff for the degraded grassland and intershrub environments are 3·03 and 4·11 min, respectively. These data indicate that, on average, the denser the vegetation cover, the earlier runoff begins. Indeed the longest time to runoff recorded for an individual plot was 10·27 min for an intershrub plot that had no vegetation at all.

The short time to runoff and rapid rise in the composite shrub hydrograph is probably a consequence of the concentration of water at the base of the shrubs by stemflow. Water in stemflow may accumulate so rapidly that local soil infiltration rates are overwhelmed. This causes overland flow to occur beneath a shrub before it occurs in adjacent intershrub areas, even though infiltration rates beneath shrubs are higher (Martinez-Meza and Whitford, 1996; Whitford *et al*., 1997; Abrahams *et al*., in press). It is speculated that a similar process operates on tuft grasses, although it has not been observed. This would also explain the early generation of runoff on the grassland.

Once runoff begins, discharges on the grassland and shrub environments rise rapidly and then level off. The tendency for discharge to level off suggests that equilibrium runoff is achieved. For the grassland environment,

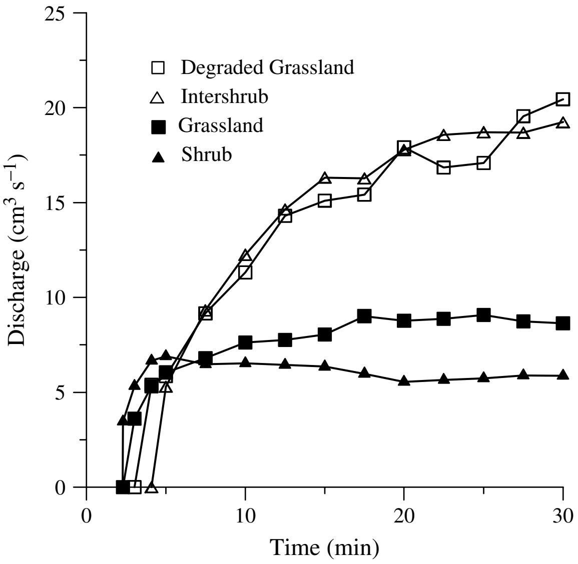

Figure 2. Composite hydrographs calculated from the runoff plot data

hydrographs for the individual plots are similar in form to the composite hydrograph. In contrast, the composite hydrograph for the shrub plots is an average of two groups of individual hydrographs with different basic forms. All the shrub hydrographs are characterized by an initial rapid rise. Thereafter, discharge in some plots remains relatively constant (Figure 3a), indicating that they are at or close to equilibrium, whereas on other plots discharge reaches an early peak and then declines (Figure 3b). These two hydrograph forms appear to be related to the composition of the shrub understorey. Plots with sparse litter and ground vegetation (grass) covers tend to have hydrographs resembling that in Figure 3a, whereas those with relatively dense litter and subcanopy vegetation (grass) covers have hydrographs like that in Figure 3b.

The decline in runoff volumes might be explained in terms of the condition of the ground surface beneath shrub canopies. One possible explanation is that litter increases surface ponding by damming overland flow. Litter dams were commonly observed to increase in volume throughout runoff events. These increases resulted

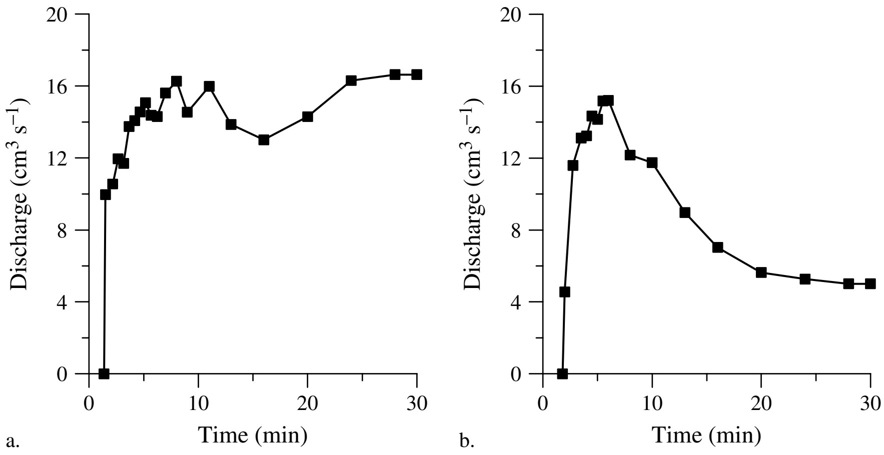

Figure 3. Hydrographs for two shrub plots showing that discharge sometimes plateaus (a) and sometimes declines (b) after the initial rise

from loose litter being trapped by obstacles in the overland flow path and causing obstructions to the flow. While this process certainly occurs, it is doubtful whether the volume of water that can be dammed by litter is sufficient to account for the observed decline in discharge following the hydrograph peak.

Another plausible explanation for discharge declining 5 to 10 min after the onset of rain is that following an initial decline, infiltration rates begin to increase. Commonly, the shrub plots with declining hydrographs have litter or grass in their understoreys. This organic material may be promoting greater macropore development within the soil beneath the shrubs. Where macropores are present infiltrating water may be selectively entering and filling the smaller soil pores prior to the macropores (Jury *et al.*, 1991). This means that infiltration rates will be initially low, and declining. Once the smaller pore spaces have all filled, water will begin to enter the macropores and infiltration rates will increase. A hydrograph generated under such conditions will display a period of falling discharge in response to this increase in infiltration.

The composite hydrographs for the degraded grassland and intershrub environments are remarkably similar (Figure 2). In essence, these hydrographs both show an initial period of rapid rise followed by a period in which discharge continues to rise but at a less rapid rate.

The tendency for discharge to increase throughout a 30 min experiment on the sparsely vegetated plots might be explained in terms of the progressive development of surface seals. Field observations in intershrub areas reveal that these soils often have a thin surface layer, 3 to 6 mm thick, that is denser than the material immediately below it. Penetrometer readings in the intershrub environment confirm that soil resistance varies considerably depending upon the presence or absence of a sealed surface layer. Two sets of 48 penetrometer readings each were taken in undisturbed and disturbed intershrub environments. The undisturbed soils had an average penetration resistance of $0{\cdot}182 \pm 0{\cdot}047$ kg cm^{-2} whereas the disturbed soils had an average resistance of $0{\cdot}087 \pm 0{\cdot}023$ kg cm^{-2}.

Field observations indicate that these seals develop during rainfall events. Intershrub sites that have their soil surfaces disturbed prior to the onset of rain display newly formed seals after the rain ceases. This observation suggests that the seals are formed either by compaction of the ground surface by raindrop impact, by the deposition of fine particles in the soil pore spaces, or by some combination of these two processes (Romkens *et al.*, 1990).

Because seals are commonly caused by raindrop impact, surfaces without a protective cover of litter and/or vegetation are particularly susceptible to their development. As seals form, they reduce soil permeability, thereby increasing overland flow discharge (Mauchamp and Janeau, 1993). If this development progresses throughout a rainfall event, discharge might be expected to increase steadily. This would explain the tendency for discharge to continually rise throughout the 30 min simulated rainfall events on the unvegetated plots. Hydrographs for individual degraded grassland and intershrub plots are similar in form to the composite hydrographs for these environments.

Runoff coefficients

Thus far, comments on differences in runoff between environments have been based upon hydrograph shape and height. A difficulty with comparing hydrographs is that, where rainfall has not been applied to each plot at exactly the same rate, variations in hydrograph shape or height may simply reflect variations in rainfall rate. Although the goal was to apply rainfall to the small plots at an average intensity of 133 mm h^{-1} for 30 min, there was some variation in intensity between plots. A runoff variable that is less sensitive to rainfall rate than are hydrograph shape and height is the runoff coefficient. The runoff coefficient is the ratio of the volume of water leaving the plot as runoff to the volume of water arriving on the plot as rainfall. Average runoff coefficients were calculated for each environment at 2·5 min intervals throughout the simulated rainfall events (Figure 4).

The intershrub and degraded grassland plots show a continual increase in runoff coefficient over the 30 min rainfall period. This supports the hypothesis that seal development on these exposed plots is progressive throughout rainfall events. Sealing causes a more rapid decline in infiltrability than would otherwise occur. By contrast, the average runoff coefficient for the shrub plots shows an initial early and rapid rise. Indeed, these plots have the highest average runoff coefficient until the 12·5 min mark of the rainfall event, after which they level out to approximately 0·18. This reflects the influence of stemflow runoff in this environment.

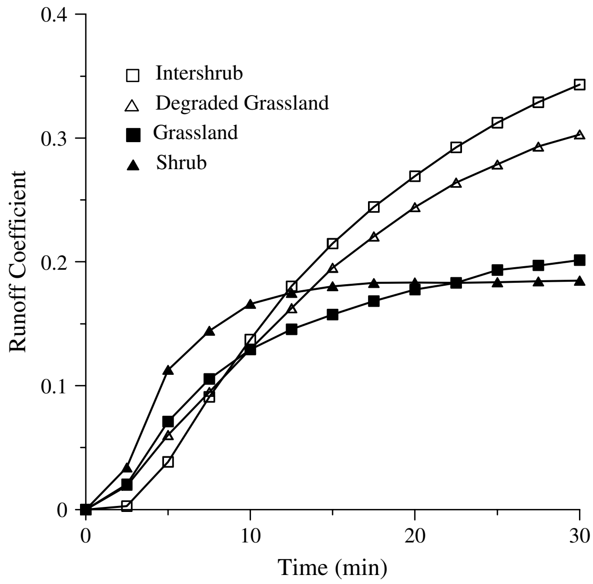

Figure 4. Average runoff coefficients for the four plot environments

Stemflow concentrates water at the base of the shrubs early in a rainfall event, giving rise to higher runoff coefficients than expected given the infiltrability of the soil. As the rainfall event proceeds, infiltration rates under shrubs do not decline at the same rate as those in the degraded grassland and intershrub environments because the shrubs protect the soils and impede the formation of surface seals.

The average runoff coefficients for the degraded grassland and intershrub plots at the end of the 30 min rainfall event are 0·30 and 0·34, respectively, indicating that approximately 30 per cent of the rainfall on these plots runs off as overland flow. In contrast, the average coefficients for the grassland and shrub plots are 0·20 and 0·18, respectively, signifying that almost 20 per cent of the rainfall on these plots runs off as overland flow. Thus, the environments with the denser vegetation covers retain approximately 10 per cent more of the total rainfall than those with the sparser covers.

Water yields

Water yields and peak discharges from the unvegetated plots are typically much greater than those from the vegetated plots. On average, the degraded grassland and intershrub plots generate 2·34 and 2·37 $\mathrm{cm}^3\ \mathrm{s}^{-1}\ \mathrm{cm}^{-2}$ of runoff per storm and have peak discharges of 43·34 and 41·44 $\mathrm{cm}^3\ \mathrm{s}^{-1}$, respectively. This compares to the grassland and shrub plots that generate 1·32 and 1·02 $\mathrm{cm}^3\ \mathrm{s}^{-1}\ \mathrm{cm}^{-2}$ of runoff per storm and have peak discharges of 18·18 and 13·48 $\mathrm{cm}^3\ \mathrm{s}^{-1}$, respectively.

Neave and Abrahams (2001) reported that W_Y in the grassland environment is inversely controlled by $\%V$ ($r^2 = 0{\cdot}56$) and in the shrub environment is positively correlated with $\%F$ ($r^2 = 0{\cdot}615$) (Table II). These relations indicate the importance of vegetation as a control on soil infiltrabilities. As vegetation cover increases, root macropore development and soil organic content also increase while surface sealing decreases. These factors combine to increase infiltration which leads to a corresponding reduction in water yield.

In the degraded grassland and intershrub environments W_Y shows a negative relation with $\%L$ ($r^2 = 0{\cdot}53$ and 0·23, respectively) (Table II). The control of litter cover on runoff is explained by the formation of litter dams that increase surface ponding and promote infiltration, and by the role of litter in reducing surface seal development (Neave and Abrahams, 2001). Soils covered by litter are protected from the direct impact of raindrops and therefore are likely to exhibit less surface sealing and have correspondingly higher infiltrabilities than exposed soils.

Table II. Regression equations between water yield and surface properties for the small plot experiments (Neave and Abrahams, 2001; reproduced by permission of Elsevier Science)

Environment	Regression equation	r^2	Sig*	n	Standard error
Grassland	$\log W_Y = 0{\cdot}542 - 1{\cdot}830 \times 10^{-2}\%V$	0·563	0·032	8	16·08
Degraded	$\log W_Y = 0{\cdot}863 - 4{\cdot}620 \times 10^{-2}\%L$	0·534	0·016	10	5·36
Shrub	$\log W_Y = -0{\cdot}874 + 2{\cdot}623 \times 10^{-2}\%F$	0·615	0·001	14	12·71
Intershrub	$\log W_Y = 0{\cdot}457 - 1{\cdot}278 \times 10^{-2}\%L$	0·230	0·097	13	5·65

*Sig, significance of equation.

Comparison of water yields across communities

Water yields from the different communities on Summerford bajada were compared for the 30 min simulated rainfall event. The procedure involved calculating water yields using the community surface property information obtained from the transects (Table I) and the regression equations in Table II. For the grassland and degraded grassland communities, water yields are controlled by the surface property variables of $\%V$ and $\%L$, respectively. The transect data indicate that for the grassland community $\%V = 40$. This value is then entered into the regression equation for the grassland (Table II) to obtain an estimated water yield of 0·65 $\text{cm}^3\ \text{s}^{-1}\ \text{cm}^{-2}$. The degraded grassland community has an average litter cover of 20 per cent. Substituting this value into the appropriate regression equation gives a predicted water yield of 0·87 $\text{cm}^3\ \text{s}^{-1}\ \text{cm}^{-2}$. For the shrubland community both the shrub and intershrub environments must be considered. The transect data indicate that approximately 27 per cent of the ground surface in the shrubland community is covered with shrubs, with the remaining 73 per cent of the community being intershrub. Water yields from the shrub and intershrub environments are controlled by $\%F$ and $\%L$, respectively. For the shrub surfaces $\%F = 27$, which gives a water yield of 0·68 cm. For the intershrub surfaces $\%L = 12$ which gives a water yield of 2·01 $\text{cm}^3\ \text{s}^{-1}\ \text{cm}^{-2}$. Multiplying these water yields by the proportions of the community that are shrub and intershrub produces an overall water yield of 1·65 $\text{cm}^3\ \text{s}^{-1}\ \text{cm}^{-2}$ for the shrubland community.

These results illustrate the hydrologic impact of the change in vegetation on Summerford bajada. For a given rainfall, the transformation of grassland to degraded grassland to shrubland results in progressively higher quantities of runoff. For prolonged, high-intensity simulated rainfall events, the water yield increased by 150 per cent. Although this increase is likely to be less for shorter, low-intensity events and factors such as runon infiltration in the shrubland are ignored, it is still apparent that the replacement of grassland by shrubland on Summerford bajada has resulted in a substantial increase in surface runoff.

CONCLUSIONS

The principal controls of hydrograph form on Summerford bajada are litter and vegetation cover. The grassland and shrub environments, which have relatively high litter and/or ground vegetation covers, generate hydrographs that exhibit an early rapid rise. This early rise is attributed to the concentration of water at the base of plants by stemflow. Following the rise, most grassland and shrub hydrographs level out at a relatively low equilibrium discharge. However, on some shrub plots discharge declines following the early rise. It is hypothesized that water percolating into macropores after infiltration has proceeded for several minutes causes infiltration rates to rise. In response, runoff volumes decline.

The degraded grassland and intershrub environments, which have low litter and ground vegetation covers, have hydrographs that rise steadily for as long as rainfall continues. This hydrograph form is attributed to the progressive development of a sealed soil layer during the rainfall event. The development of a sealed surface results in a decline in soil infiltration rates and a subsequent increase in overland flow discharge.

Regression analyses performed between water yield and surface property variables support the theory that litter and vegetation covers control runoff on Summerford bajada (Neave and Abrahams, 2001). Water yield is negatively related to %V on the grassland environment ($r^2 = 0{\cdot}563$), positively related to %F on the shrub environment ($r^2 = 0{\cdot}615$), and negatively related to %L on the degraded grassland and intershrub environments ($r^2 = 0{\cdot}543$ and $r^2 = 0{\cdot}230$, respectively). As a consequence, higher peak discharges and water yields are observed in the degraded grassland and intershrub environments, which have low organic covers, than on the grassland and shrub environments with high organic covers.

A comparison of water yields predicted across the vegetation communities on Summerford bajada indicates that the shrubland community is more efficient in shedding water as surface runoff. For a design storm of 133 mm h^{-1} for 30 min the shrubland generated an estimated water yield of 1·65 $cm^3\ s^{-1}\ cm^{-2}$. This compares to an estimated water yield of 0·87 $cm^3\ s^{-1}\ cm^{-2}$ for the degraded grassland and 0·65 $cm^3\ s^{-1}\ cm^{-2}$ for the grassland. Thus, the shrubland yields 150 per cent more water as runoff than the grassland. This finding indicates the importance of the changing vegetation on the hydrology of Summerford bajada. As the grasslands have been transformed into communities dominated by shrub species, the patchy distribution of vegetation has resulted in higher runoff coefficients and water yields for a given rainfall event.

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