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Hydrology–vegetation interactions in areas of discontinuous flow on a semi-arid bajada, Southern New Mexico

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Flows on a bajada surface in the Chihuahuan Desert of New Mexico show a discontinuous pattern, with alternating areas of channelization and deposition. Based on their planform appearance, we have termed the depositional areas 'beads'. Instrumented catchments demonstrated that in comparison to 'normal' dendritic catchments, the beads show net infiltration in all but the largest flow events. Net accumulation of the bead surface appears to occur in years of lower than average rainfall, but the surface is dynamic and suffers net erosion in wetter years. The beads have significantly higher total vegetation covers, and contain higher proportions of grass species (*Muhlenbergia porteri*) as well as the creosotebush that characterizes the bajada surface in general. Creosotebush in the beads show consistently lower values of δ^{13}C, suggesting that they are less moisture stressed than creosotebush elsewhere on the bajada. Values of δ^{15}N are higher in the bead creosotebush, suggesting higher rates of soil–nitrogen transformations and greater loss of nitrogen to the atmosphere by denitrification. Both of these factors are again consistent with higher infiltration and thus moisture contents in the beads. In contrast, xylem-pressure potentials in creosotebush in the bead taken before the summer monsoonal season suggest that plants within the bead are more moisture stressed than those outwith the bead. Four possible explanations are offered for this apparent discrepancy: the greater cover and biomass of plants in the bead leads to higher stresses at the end of the drought period; spatial variability in soil texture means that some areas of the bead retain less moisture; more available water in the bead goes to the grass plants that concentrate their roots near the surface; and there is greater competition in the bead during times of drought stress.

Overall, these results are compatible with an 'islands of fertility' interpretation of desertification operating in the American Southwest, albeit on a larger spatial scale than usually attributed. The concentrations of nutrient, water and seed resources may mean that these sites are favourable

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for attempts to reverse the desertification process. However, they appear dynamic with a life cycle of about 30 years.

Keywords: desertification; Chihuahuan desert; creosotebush; runoff; infiltration; erosion; deposition; plant $\delta^{13}C$ and $\delta^{15}N$; xylem-pressure potential

Introduction

Over approximately the last 100 years, the American Southwest has seen significant landscape changes. A vegetation largely dominated by grasses has been replaced by one dominated by shrub species (Glendenning, 1952; Humphrey, 1958; Hastings & Turner, 1965; Cox *et al.*, 1983). At the Jornada Experimental Range in New Mexico, Buffington & Herbel (1965) detailed the extent of this process from 1858 to 1963, reflecting the change from black grama (*Bouteloua eriopoda*) grassland to mesquite (*Prosopis glandulosa*) and creosotebush (*Larrea tridentata* DC) shrubland. At the same time, significant levels of erosion have occurred, both in channels (e.g. Cooke & Reeves, 1976) and on hillslopes (e.g. Parsons *et al.*, 1996). The loss of water, sediments and nutrients by these mechanisms often accentuates the uneven distribution of resources (Abrahams *et al.*, 1995), leading to the accentuated development of 'islands of fertility' (Charley & West, 1975; Virginia & Jarrell, 1983; Schlesinger *et al.*, 1996) that reinforce the process of desertification (Schlesinger *et al.*, 1990).

One consequence of the accelerated erosion rates on hillslopes is the formation of rills (Luk *et al.*, 1993; Parsons *et al.*, 1999). These rills form as a result of concentration of overland flow in threads between shrubs (Parsons *et al.*, 1996) so that the flow exceeds the critical threshold whereby it directly entrains sediment (Parsons & Wainwright, forthcoming). On relatively steep slopes, or slopes where the contributing area is continuously increasing, these rills are generally continuous, extending to the channel or its immediate floodplain. However, discontinuous rills can occur where planform convexities cause the catchment area to decrease in proportion to the area required to maintain sediment transport, or where the local slope causes deposition. Such conditions occur on alluvial fan or bajada surfaces, which are characterized by planform convexity and profile concavity.

At the Jornada Experimental Range in New Mexico, a number of these discontinuous rills have been observed. The areas of deposition generally form splays around the channel, and the flow often continues again below the splay, leading to a repetition of this process. In planform, the sequence of discontinuous rills and splays thus appears like a necklace with a series of beads. Thus, we use the term 'beads' for the splays. There also appears a continuum between totally discontinuous bead splays, and braided channel sections. In places, this continuum may be a function of splays that have subsequently started to re-erode, probably due to headcutting where the downstream edge of the bead is oversteepened.

Bull (1997) carried out an extensive review of semi-arid discontinuous flow systems, which were first recognized in the literature by Leopold & Miller (1956). He concluded that there was a repetitive sequence of channel features, where 'streamflow passes through reaches characterized by headcuts, a single trunk channel that changes from moderately sinuous to straight, braided distributary channels, diverging sheetflow, and converging sheetflow draining to headcuts' (Bull, 1997 p. 270). It is essentially the two latter features that characterize the beads at Jornada, although sheetflow implies a sense of regularity of flow that is typically not present in these systems (e.g. Abrahams & Parsons, 1990). Bull also emphasizes slope as a critical factor for incision, but notes that a number of disturbance factors can trigger its onset. Furthermore, he states that the implication of the relationship with size of channel first suggested by Schumm & Hadley (1957) is also that larger systems will tend to be more dominated by entrenchment, earlier in the cycle.

In relation to the redistribution of resources that characterizes the land degradation in the area under study, the beads are significant because they represent localized areas of accumulation of water and sediments, and thus also nutrient resources. Thus, it might be expected that the beads have different characteristics in terms of their vegetation amount, composition and structure as these factors are controlled by local hydrology and nutrient availability. The beads should provide better growing conditions for vegetation. If the vegetation can become sufficiently established, then there should also be some form of positive feedback, whereby increased cover can provide increased stability of the bead, and perpetuate its position through time. A corollary of this suggestion, though, is provided by the literature reviewed above, in that if the vegetation should become so successful that it oversteepens the slope, then a subsequent phase of erosion can be developed. It is the aim of this paper to evaluate these hypotheses.

Field area and study methods

The study was undertaken within the Jornada Basin Long-Term Ecological Research Site (32°31′N, 106°47′W), 40 km NNE of Las Cruces, New Mexico, on the bajada surface fringing Summerford Mountain. The location experiences a semi-arid climate with a mean annual temperature of 14.7°C and a mean annual precipitation of 245 mm. The majority (69%) of this precipitation falls as intense, short-duration, convective summer storms (Wainwright, in press). The Summerford Mountain bajada is low angled, varying from about 6° just below the mountain, decreasing to essentially horizontal at a chain of small playas ~3 km distant. There is an area of remnant grassland, dominated by black grama in a small area by the mountain front, but the middle section is dominated by creosotebush, before passing downslope to playas. The soils are a grus developed from the quartz monzanite of Summerford Mountain, incorporating various quantities of igneous rocks, dependent on location. These soils are classified as Typic Haplargids and Torriorthentic Haplustolls with localized Typic Haplocalcids (Gile *et al.*, 1981; Monger, in press).

Discontinuous flows have led to the frequent development of beads on the Summerford Mountain bajada, as noted above (Fig. 1). It is possible to see a size-dependent relationship between the size of channel and types of discontinuity as suggested by Schumm & Hadley (1957), Schumm, (1973) and Bull (1997) with large, sandy washes (>2 m wide) having very infrequent braided sections, before finally splaying at the base of the bajada system, compared to the smaller rills (0·5–1 m), which may exhibit discontinuities every 100 m or so. The beads are clearly definable in the field as areas of deposition along the profile of a channel section. The boundary of the splay zone was taken to be the boundary of the bead zone, for comparison with conditions elsewhere on the bajada.

Two instrumented catchments were established on the bajada in January 1995. Each of the catchments has three supercritical flumes of the Walnut-Gulch type (Smith *et al.*, 1982). The South Watershed has a total contributing area of 1833·9 m^2, and represents a ‘normal’ dendritic network. In addition at the outlet of this catchment, the two main tributaries have flumes just before they join the main stem. These tributaries have catchment areas of 889·7 and 431·3 m^2, defined by detailed topographic survey (Fig. 2(a)). The North Watershed has a total area of 5936·1 m^2,

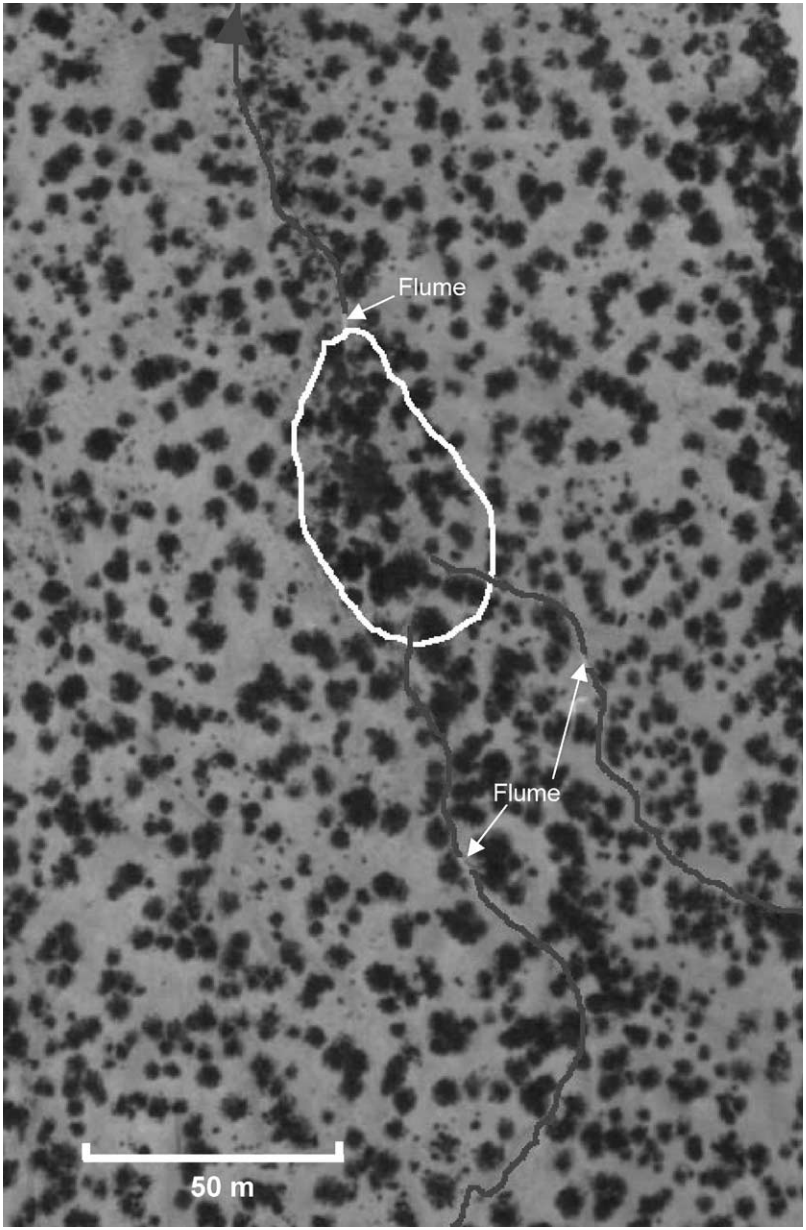
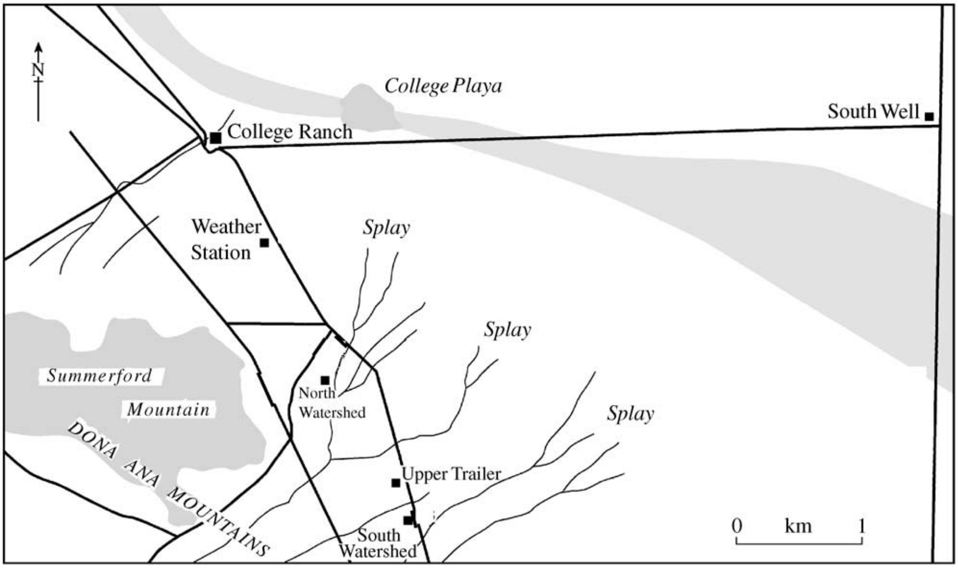


Figure 1. Aerial photograph of the North Watershed on the Summerford Mountain bajada, showing the presence of the 'bead' (outlined in white). Note the higher vegetation cover in the bead compared to surrounding areas. The main inflow and outflow rills are highlighted in blue.

with flumes again to record the tributary inflows of contributing areas of 775·2 and 3379·3 m^2. These tributaries feed into a well-developed bead (Fig. 2(b)). Serendipitously, the two catchments provide an easy comparison between the behaviour of a dendritic network and one with a bead because in both cases the upstream contributing area is approximately the same proportion of the total catchment area: 70% in the case of the North catchment and 72% in the case of the South catchment.



(a)

(b)

Figure 2. Instrumented watersheds on the Summerford Mountain bajada: (a) location; and (b) supercritical flume used to measure flow discharge and maximum stage. (▭) alluvial plain;(——),stream; (━━), road.

At each of the flumes, a stilling well was filled to the base level of the flume with water, and cork powder added (Fig. 2(b)). A rod was fixed vertically within the stilling well, so that as the water level rose during a flow event, the water would rise and the cork becomes attached progressively higher up the rod. During the falling limb of a flow event, the water level fell leaving the cork powder attached to the rod as a record of the stage. Immediately following each flow event, the maximum level of the cork powder on the rod was recorded to provide information on the maximum stage of flow during the event. The maximum stage was then converted to a peak discharge using the calibration equation given in Smith *et al.* (1982). A rainfall gauge in the centre of each of the catchments provided data on the total rain that fell during a particular event. Using these techniques, the behaviour of the dendritic catchment and the catchment with the bead was compared for the period from 26/1/95 to 20/6/99.

During this period, 22 events in the South Watershed and 20 events in the North Watershed were reliably recorded, with simultaneous information on 16 events at both locations.

Vegetation in both catchments is dominated by creosotebush. At the North Watershed, a detailed survey of the vegetation was carried out in the area of the bead. Six transects were laid out perpendicular to the long axis of the catchment, at a spacing of 10 m. The transects extended 25 m in both directions from the centre of the bead towards the catchment boundary, and included areas both within and outwith the bead. The area of the bead, defined as the area where deposition appeared to be clearly taking place, was noted so that samples could be related to the two areas. Whenever the transect intersected a plant, its species, height and the start and end points of the intersection were recorded. Where the canopies of several plants were vertically above each other, the cover of each plant was recorded. Cover estimates were calculated for the areas within and outwith the bead by dividing the total lengths between the start and end points of intersections by the relevant length of the transects.

In July 1995, a series of samples was taken from creosotebush and muhley grass (*Muhlenbergia porteri*) in the area of the bead in the North Watershed for carbon and nitrogen isotope analysis. The sampling strategy followed the transects, and provided 13 creosotebush-twig samples from the bead and 54 from the adjacent area. The twigs were selected so that they would integrate the effects of several years of recent growth. A 5-cm-long section was selected $\sim$10 cm from the end of a branch growing towards the top of the bush. In addition, seven grass samples were taken within the bead and eight outwith. To confirm these results, a second set of samples was selected in July 1999. In this case, only creosotebush twigs were selected for analysis, eight each from the bead and adjacent areas. A final set of samples was collected in July 2000 for three other beads at different locations in the bajada, in order to confirm that the pattern observed within the North Watershed had wider general validity. In all three cases, eight samples were taken in the same way as previously from each of the beads and the surrounding areas.

Isotopic analyses were carried out in order to evaluate the water-use efficiency of plants in the different areas, as well as their nutrient sources. Carbon and nitrogen percentages, $^{13}C/^{12}C$ and $^{15}N/^{14}N$ isotope ratios were measured on a SIRA Series II isotope ratio mass spectrometer (Micromass, Manchester, U.K.), operated in automatic trapping mode after Dumas combustion of samples in a C and N analyzer (NA1500 Series 1, Carlo Erba Instrumentazione, Milan Italy). The reference CO_2, calibrated against standard Pee Dee belemnite (PDB), was obtained from Oztech (Dallas, TX). For ^{13}C, data are corrected for the isotope contribution of the O_2 used in sample combustion. Isotopic data are expressed in standard delta terminology, using the PDB standard for ^{13}C and atmospheric N_2 for ^{15}N.

In addition, pre-dawn and midday xylem-pressure potentials were measured using a pressure chamber (Soil Moisture Inc. #3000 Plant Water-Status Console) in early July 1999 (Ritchie & Hinckley, 1975). Eight creosotebushes within and eight outwith the bead were tagged so that they could be compared directly at the two times. These measurements were taken in order to compare the moisture stresses experienced by plants in the two areas during the period just prior to the start of the summer monsoon rains, when the stresses should be at their highest.

Soil sampling was carried out in 1995 and 2000 in the North Watershed. The 1995 samples were taken using the same transects used for the vegetation analyses, by collecting samples at 6-m intervals. Of these, 13 samples fell within the bead and 53 outwith. These samples were analysed for carbon, nitrogen and hydrogen content using the techniques described above. The samples collected in 2000 were taken from eight randomly selected points within and eight outwith the bead. Particle-size analysis was carried out on these samples, following the removal of organic matter by hydrogen-peroxide digestion, by dry sieving to remove the fraction $7>2$ mm in diameter; wet sieving the sand fraction (2–0·0625 mm) at $1-\phi$ intervals; and using a Micromeritics Sedigraph 5100 to analyse the silt and clay fractions.

Finally, erosion-pin data were obtained for the North Watershed from a larger study to investigate patterns of erosion and deposition. Two transects of pins were installed in July 1996, one across the central part of the bead, and the other across one of the tributary rills from the interrill zones on either side. Each transect was made up of 11, 30-cm steel rods driven vertically into the ground at a distance of 1 m from each other. A record was taken of the initial depth of each rod, and repeat measurements taken in July annually (except in 1997).

Results

Hydrology

Annual rainfall measured from 1st July to 30th June (reflecting the onset of the rainy season) in the period of study was 252·8 mm in 1996–1997, 220·3 mm in 1997–1998, 259·6 in 1998–1999, and 198.9 mm in 1999–2000. Thus, the study period contains 2 years of slightly above-average rainfall, and 2 years of more marked below-average rainfall.

The flume data were used to compare the hydrological characteristics of the bead and the dendritic catchment. The minimum rainfall event that produced runoff at the catchment outlets was 5.8 mm in both cases. The maximum event in both cases was an event of 50.2 mm. In all cases, the peak discharge at each flume was calculated per unit area so that relative gains or losses of runoff through various parts of the catchment could be distinguished.

In the dendritic catchment, there are only six cases where the discharge at the outlet of the catchment is less than the inflows from the two tributaries (Fig. 3). In all six cases, the discharge per unit area is less than $1 \times 10^{-6}\,m^3\,s^{-1}\,m^{-2}$. Contrariwise, there are nine cases with equivalent discharges where the unit runoff is greater at the catchment outlet. The most extreme case has 4·29 times more unit flow at the outlet compared to the tributaries, showing that the downstream part of the catchment was contributing approximately double the runoff per unit area compared to the upstream area. Above about $5 \times 10^{-6}\,m^3\,s^{-1}\,m^{-2}$, the subcatchments tend to equilibrate, with proportional losses and gains of flow between the tributary channels and the outlet.

In contrast, the flows in the bead catchment are dominated by losses in the section of the bead. Only three cases have a peak discharge per unit area flowing through the outlet that is greater than that at the inflow to the bead. The maximum proportion of flow through the outlet compared to the inflow is 1·22 times. Above about $6 \times 10^{-6}\,m^3\,s^{-1}\,m^{-2}$, the bead catchment tends to behave in the same way as the dendritic catchment, with losses of flow generally balancing additions.

The losses of flow in the lower part of the dendritic network can be explained with reference to the transmission losses that occur through the bed of the channel. Parsons *et al.* (1999) demonstrated that in these bajada channels, transmission losses are significant, at rates of about an order of magnitude higher than infiltration losses in interrill zones. However, the results from the South Watershed catchment suggest that once a small threshold is overcome, there is sufficient flow in the system for the transmission loss to become unimportant. For the network incorporating the bead, the much greater losses cannot be explained by this mechanism, as there are no continuous channels present. As the flows reach the bead, they diffuse and encounter higher densities of vegetation (see below), so that there will be much higher rates of infiltration. Wainwright *et al.* (2000) note that interrill infiltration rates on the creosotebush areas of the bajada are 22.4% higher on vegetated sites compared to bare

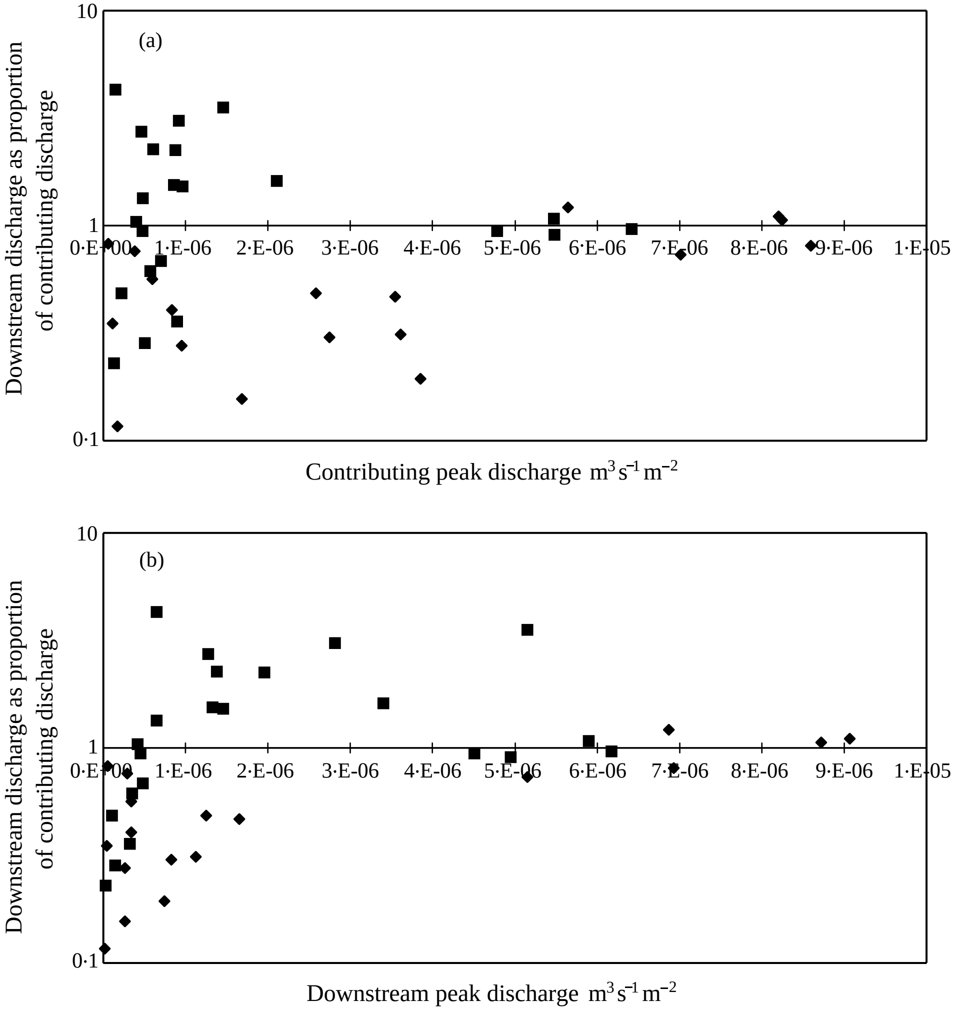


Figure 3. Proportion of discharge reaching the downstream flume in the North (bead) and South (dendritic) catchments, as a function of: (a) the contributing area peak discharge; and (b) the downstream peak discharge. (■), dendritic; (◆), bead

sites. The difference in peak discharge will also be accentuated by the increase of roughness given that the flow in the rills is hydraulically more efficient (Abrahams *et al.*, 1996; Wainwright *et al.*, 2000). Although it is also possible that spatial variability in rainfall could be an important factor in affecting the downstream change in runoff, it is not thought to be significant in this case. The difference in rainfall between the catchments was generally less than 20%, so that variability within them would be likely to be even less. In summary, the results from the flume monitoring suggest that the bead area is a zone of net infiltration in the landscape, in all but the highest flows.

Erosion

Both erosion and deposition occur intermittently on the bead and the area of the North Watershed catchment upstream of the bead on an annual basis (Table 1). The

Table 1. *Summary of erosion–pin data showing net annual erosion (negative) or deposition (positive) in mm. The 1998 data represent a 2–year period from July 1996, while the 2 other dates are measurements taken in July of the respective years*

Year	Mean	Median	S.D.	Min	Max
Bead—net erosion (−ve)/deposition (+ve) in mm					
1998	−5·8	0·5	15·0	−32·5	8·5
1999	1·8	0·0	9·2	−6·0	22·0
2000	−17·6	−11·5	24·0	−64·0	3·0
Outwith bead — net erosion (−ve)/deposition(+ve) in mm					
1998	−4·7	−2·0	7·8	−23·5	3·0
1999	−3·2	−2·0	6·6	−19·0	7·0
2000	−0·8	4·0	16·1	−43·0	14·0

mean accumulation (erosion measured as negative values) on the bead is positively related to the annual rainfall ($r = 0{\cdot}9999$; $n = -3$), whereas that outwith the bead is negatively related ($r = -0{\cdot}7132$). A similar transect across a rill in the South Watershed has a similar negative relationship ($r = -0{\cdot}8928$). Although it is impossible to generalize from such a small data set, it is possible that the difference reflects the ability of annual species on the bead to minimize erosion during average to slightly wet years, whereas in the dry years they provide insufficient cover to afford sufficient protection. The lack of vegetation in the rill transects would account for the greater erosion during wetter years, simply because of the greater flows in those years. The results also suggest that once formed, the beads remain dynamic, and can be susceptible to the critical thresholds outlined by Schumm (1973) that may be responsible for their subsequent destruction.

Vegetation

The proportion of vegetation cover within the bead was estimated as 50·0%, compared to 26·3% outwith the bead. In both cases, there is a tendency for vegetation cover to decrease in the downstream direction (Table 2). Seven different species in total were encountered: creosotebush (*Larrea tridentata*), desert holly (*Perezia nana*), muhley grass (*Muhlenbergia porteri*), prickly pear (*Opuntia violacea*), fluff grass (*Sporabolus flexuosus*), yucca (*Yucca elata*) and zinnia (*Zinnia acerosa*). Apart from fluff grass, all of these species are found in both areas, albeit in differing proportions. Within the bead, there were almost equal numbers of creosotebush and muhley grass plants. Outwith the bead, creosotebush made up half of the total plants sampled, compared to 29·1% muhley grass and 11·6% prickly pear. In terms of proportion of ground cover, the differences between creosotebush and the other species are further accentuated. Creosotebush made up 58·5% of the canopy cover within the bead and 78·3% outwith it. It should be noted that these figures relate to the areas within the outer limits of the canopy, and not the proportion of the ground surface protected by vegetation. Wainwright *et al.* (1999) found that creosotebushes on the Summerford Mountain bajada have very discontinuous canopies, with only 36·5% of the ground surface below afforded protection, on average. Using this figure and the mean canopy-cover figures, only 10·7% of the bead and 7·5% of the area outwith the bead are protected by creosotebush. Similar figures are not available for muhley grass, but it might be assumed that because of the dense, clumped nature of the species, the ground cover should be a figure similar to that of the canopy cover. If this assumption

Table 2. *Summary of vegetation results in terms of total canopy cover and percentage canopy cover per species in both the bead and non-bead areas. Species codes are as follows: (pena)* Perezia nana*, (latr)* Larrea tridentate*; (mupo)* Muhlenbergia porteri*; (opvi)* Opuntia violacea*; (spfl)* Sporabolus flexuosus*; (yuel)* Yucca elata; *and (ziac)* Zinnia *acerosa*

Canopy cover %			Percentage cover by species														
	Out with bead		Bead							Out with bead						
Transect	Bead		Pena	Latr	Mupo	Opvi	Spfl	Yuel	Ziac	Pena	Latr	Mupo	Opvi	Spfl	Yuel	Ziac
1	—	19·7	—	—	—	—	—	—	—	0·0	66·2	27·6	4·1	0·0	0·0	2·1
2	40·7	21·8	0·0	30·2	66·2	3·6	0·0	0·0	0·0	0·0	92·8	0·0	2·8	0·0	4·4	0·0
3	54·0	16·0	1·9	55·9	38·1	1·9	2·3	0·0	0·0	0·8	82·0	0·0	0·0	0·0	17·3	0·0
4	47·1	29·2	0·0	50·5	46·0	1·0	0·0	0·0	2·6	0·0	78·1	8·0	10·5	0·0	3·5	0·0
5	54·2	36·3	0·0	80·9	13·5	0·7	0·0	4·9	0·0	0·0	73·0	16·5	10·0	0·0	0·0	0·0
6	—	35·3	—	—	—	—	—	—	—	0·0	80·7	17·6	1·7	0·0	0·0	0·0
Combined data	50·0	26·3	0·5	58·5	36·8	1·4	0·6	1·4	1·0	0·1	78·3	13·8	5·1	0·0	2·4	0·3

holds, then muhley grass is actually more important than creosotebush in terms of ground cover on the bead, with a value of 18·4%, although it is much less important elsewhere, with a value of 3·6%.

Within the bead, there is a distinct spatial pattern of the species, with much higher proportions of canopy area made up of creosotebush in the upstream part, making up 80·9% of the most upstream transect. The reverse trend is seen in muhley grass, with the highest proportion (66·2%) in the furthest downstream and lowest (13·5%) in the furthest upstream transect. Creosotebush dominates the whole of the transects outwith the bead, although there is a suggestion that muhley grass occurs more dominantly away from the areas immediately fringing the bead, where it tends to be replaced by yucca.

The results of the isotopic analyses for the 1995 samples taken from creosotebush in the North Watershed show consistently lower $\delta^{13}C$ values within the bead compared to the samples taken outwith the bead ($t = 1{\cdot}91$, $p = 0{\cdot}030$; Table 3). The repeat samples taken in 1999 show a comparable difference ($t = 2{\cdot}41$, $p = 0{\cdot}015$). In all of the other three beads sampled in 2000, there were significantly lower values of $\delta^{13}C$ in the bead compared to the adjacent areas. Thus, in all five instances sampled, the creosotebush within the bead was found to have significantly lower $\delta^{13}C$ than the creosotebush outwith the bead. In contrast, the samples taken on muhley grass in 1995 showed no significant difference ($t = -1{\cdot}13$, $p = 0{\cdot}86$) between the bead samples (mean −14·92‰, standard deviation 0·33‰) and those from outwith the bead (mean − 14·76%, standard deviation 0·21‰). In both the 1995 and 1999 samples, percentage carbon content was measured, and showed no significant difference between the bead and other samples (Table 4).

The consistently higher values of $\delta^{13}C$ in the creosotebush outwith the bead suggest that these plants are significantly more water-stressed than those in the bead. This pattern is consistent with the results from the flow monitoring, which suggest that in most events the bead is an area of net accumulation of water. The lack of difference in the muhley grass relates to the fact that it is a C_4 species and thus does not show variations in $\delta^{13}C$ as a function of water stress, in that the enzyme pep-carboxylase concentrates CO_2 inside the leaf, avoiding stomatal diffusion as a limit to CO_2 entry (Evans *et al.*, 1986).

The $\delta^{15}N$ results for the 1995 creosotebush samples show consistently higher values ($t = -2{\cdot}80$, $p = 0{\cdot}0033$) for the bead samples (mean 2·38%, standard deviation 1·10‰) compared to those taken outwith the bead (mean 1.28‰, standard deviation 1·31‰). The isotopic measurement was not repeated in 1999. For the 1995 samples, there was no significant difference in nitrogen content between the samples (Table 4). In 1999, there was a marginally significant difference, with higher values outwith the bead ($p = 0{\cdot}048$). In the case of the muhley grass sampled in 1995, $\delta^{15}N$ values were significantly higher ($t = 2{\cdot}73$, $p = 0{\cdot}017$) within the bead (mean 1·53%, standard deviation 0·56‰) compared to those outwith the bead (mean 0·51%, standard deviation 0·83%). Higher $\delta^{15}N$ for plants growing in the bead reflects a higher rate of soil–nitrogen transformations in these soils (Garten & van Miegroet, 1994), and perhaps greater losses of nitrogen to the atmosphere by denitrification, which leaves soils enriched by $\delta^{15}N$ (Sutherland *et al.*, 1993). Both processes should occur more rapidly in desert soils of higher moisture content (e.g. Peterjohn & Schlesinger, 1991).

Soils

Results from the CHN analyses on the soils are shown in Table 5. For all three elements, it can be seen that there is a significantly higher content in the soils of the bead compared to the soils outwith the bead area. This result implies that the soils of

Table 3. *Summary of $\delta^{13}C$ isotope analyses on creosotebush twigs*

	North Watershed				Bead 2		Bead 3		Bead 4	
	1995		1999							
	δ^{13}C%		δ^{13}C%		δ^{13}C%		δ^{13}C%		δ^{13}C%	
	Bead	Outwith	Bead	Outwith	Bead	Outwith	Bead	Outwith	Bead	Outwith
Mean	−24·14	−23·79	−24·22	−23·70	−26·24	−25·03	−26·11	−24·88	−24·86	−24·27
S.D.	0·62	0·58	0·47	0·39	0·32	0·51	0·65	0·81	0·48	0·52
t	1·91		2·41		5·68		3·36		0·238	
p	0·030		0·015		$< 5 \times 10^{-5}$		0·002		0·016	

Table 4. *Summary of C and N analyses on creosotebush and muhley grass in the North Watershed*

	1995				1999			
	%C		% N		% C		%N	
	Bead	Outwith	Bead	Outwith	Bead	Outwith	Bead	Outwith
Mean	46·82	47·18	0·95	0·99	47·50	47·32	0·86	1·04
S.D.	1·39	0·714	0·19	0·18	0·42	1·07	0·13	0·20
t	1·32		0·81		−0·45		2·17	
p	0·19		0·42		0·66		0·048	

the bead are essentially acting as sinks for nutrients. There are also some very high peaks in these values within the bead, which are reflected by the much higher standard deviations in these samples. Thus, there is a high spatial variability in the pattern of these sinks.

Particle-size analyses show the high proportions of sand making up the soils of the bajada (Table 6), reflecting their source as grus from Summerford Mountain. The clay contents are low, making up only 6·6% of the bead samples and 6·2% of the samples outwith the bead. The median particle size falls in the upper part of the fine sand class, and the d_{95} lies in the lower range of the granule class in both cases. In any of these variables, no significant difference is found between the mean values for the bead and non-bead samples. However, it should be noted that the bead samples show considerably more variability, as reflected by their much higher coefficient of variability. An *F* test was carried out to test whether the variance in each case was significantly different. In all cases apart from clay content, a highly significant difference is found. It is likely that the low values for clay content explain the lack of significant variability. Thus, the variability in the spatial patterns of erosion and deposition within the bead may be reflected by greater variability in the soil texture.

Plant hydrology

The results of the xylem-pressure-potential measurements showed that at the height of the drought period, the creosotebush were significantly more highly stressed in the bead compared to those in the adjacent area (Table 7). However, those plants in the bead show a smaller increase in pressure potential between the predawn and midday cases, albeit marginally not significant at the 95% confidence level. The coefficient of variation shows greater variability again in the measurements taken within the bead.

Table 5. *Summary of C, H and N analyses on soils in the North Watershed*

	% C		% H		% N	
	Bead	Outwith	Bead	Outwith	Bead	Outwith
Mean	0·79	0·32	0·24	0·18	0·07	0·03
S.D.	1·01	0·16	0·17	0·03	0·10	0·01
t	−3·31		−2·53		−3·28	
p	0·0015		0·014		0·0017	

Table 6. *Summary of particle–size analyses of soils sampled in the North Watershed*

	Bead samples			Outwith bead samples			Comparison			
							Mean		Variance	
	Mean	S.D.	CV%	Mean	S.D.	CV%	t	p	F	p
Sand (%)	74·6	17·1	22·9	80·4	2·3	2·9	−0·95	0·373	53·63	$2{\cdot}86 \times 10^{-6}$
Silt (%)	18·7	14·9	79·4	13·4	2·2	16·5	0·99	0·354	45·08	$5{\cdot}24 \times 10^{-6}$
Clay (%)	6·6	2·3	35·0	6·2	1·7	28·3	0·41	0·688	1·75	0·252
d_{50} (mm)	0·236	0·183	77·7	0·218	0·024	11·0	0·27	0·797	58·13	$2{\cdot}16 \times 10^{-6}$
d_{95} (mm)	2·242	0·667	29·8	2·464	0·279	11·3	−0·87	0·408	5·72	$6{\cdot}17 \times 10^{-3}$
K_s (mm h^{-1})*	2·018	0·978	48·5	1·598	0·286	17·9	1·17	0·276	11·68	$5{\cdot}56 \times 10^{-4}$
b (−)†	6·745	13·981	207·3	1·117	0·370	33·1	1·14	0·292	1431·60	$2{\cdot}96 \times 10^{-11}$
β (−)‡	2·184	0·940	43·0	1·896	0·135	7·1	0·86	0·420	48·76	$3{\cdot}99 \times 10^{-6}$

CV is the coefficient of variation.
*K_s is the saturated hydraulic conductivity, and is estimated using particle size data following the method of Campbell (1974).
† b is the suction–moisture parameter of Campbell (1974), estimated using sand and silt fractions.
‡β is the modified version of the Campbell b parameter, estimated using sand, silt and clay fractions using the method of Ghosh (1980).

Table 7. *Summary of xylem–pressure potentials measured on eight creosotebush in the bead and eight creosotebush outwith the bead in the North Watershed both immediately before and immediately after the summer monsoon (early July and late September, respectively)· The difference column reflects the increase in suction in each plant between the predawn and the midday measurements*

	Pre–monsoon measurements						Post–monsoon measurements					
	predawn xylem–pressure potential MPa		Midday xylem–pressure potential (Mpa)		Difference (Mpa)		Predawn xylem–pressure potential (Mpa)		Midday xylem–pressure potential (Mpa)		Difference (Mpa)	
	Bead	Outwith	Bead	Outwith	Bead	Outwith	Bead	Outwith	Bead	Outwith	Bead	Outwith
Mean	−3·52	−2·78	−3·99	−3·56	0·48	0·79	−1·67	−1·33	−2·63	−2·27	0·95	0·94
S.D.	0·50	0·29	0·51	0·41	0·27	0·48	0·26	0·19	0·28	0·39	0·31	0·31
CV (%)	14·1	10·3	12·7	11·6	57·7	61·3	15·7	13·9	10·8	17·1	32·6	33·2
t	−3·666		−1·858		−1·593		−3·012		−2·095		0·089	
p	0·001		0·042		0·067		0·005		0·027		0·465	
F	3·043		1·505		0·322		2·022		0·536		0·990	
p	0·048		0·381		0·045		0·376		0·434		0·966	

These results apparently contradict the results obtained thus far that the bead is an area of net deposition of water. A simple interpretation would suggest that the creosotebush in the bead should be less stressed. There are several potential explanations for this discrepancy. First, the fact that there is a greater overall plant cover and that there are bigger plants in the bead might suggest that the drought condition is enhanced at the onset of the monsoon because the plants extract more available moisture from the soil during periods without rain. Schlesinger *et al.* (1989) showed a relationship between greater biomass and lower xylem-pressure potential at the time of drought onset in creosotebush in the Mojave desert. Although the mean volume of the creosotebush measured along the transects does not differ significantly between the bead and the adjacent area ($t = -0{\cdot}82$, $p = -0{\cdot}42$), there are several much larger plants in the bead. The largest creosotebush in the bead has a volume of $16{\cdot}25\,m^3$, compared to a maximum of $8{\cdot}42\,m^3$ in the immediately adjacent areas. Secondly, the texture of the soils in the bead may mean that less moisture is retained in soil of the bead than elsewhere. To test this hypothesis, the particle-size data were used to estimate the saturated hydraulic conductivity and suction–moisture characteristics of the soils using the methods of Campbell (1974) and Ghosh (1980). Although the results show no significant difference between the average values for the two areas, the bead is again characterized by significantly greater variability (Table 6). Estimated suction–moisture curves (Fig. 4) suggest that although some areas of the bead are capable of retaining more moisture than elsewhere, there are also a number of samples which suggest that some areas are much less capable. This variability is again statistically highly significant (Table 6). Thirdly, the fact that the bead has a higher proportion of other species, notably grasses (38·2% compared to 13·8%), may mean that much of the additional water entering the bead is used by plants whose roots are concentrated in the upper part of the soil profile. Thus, the additional water is not available to the creosotebush. Fourthly, in the Mojave Desert, Schlesinger *et al.* (1989) demonstrated that the small numbers of creosotebush in areas that were deprived of overland flows tended to do better in times of drought, apparently due to lower competition. The greater density and range of species in the bead would, therefore, account for the greater stress in the creosotebush in the bead. When drought was not a significant feature, this difference would no longer be present. To test this idea, a second set of xylem-pressure-potential measurements were taken immediately following the monsoon season, in late September. The results again demonstrate that plants within the bead are significantly more stressed, although the change through the day is now very similar in both cases (Table 7). Therefore, this fourth hypothesis seems unlikely based on these figures.

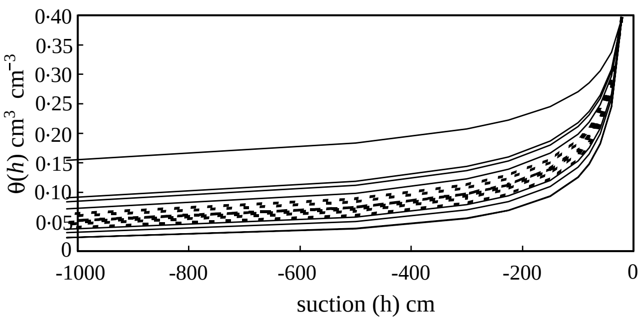


Figure 4. Estimated soil suction–moisture curves for samples taken from the North Watershed. Continuous lines are samples from the bead; the dashed lines are samples from outwith the bead. The curves were estimated using the technique of Ghosh (1980) and the parameters are given in Table 6.

Discussion and conclusions

The hydrology and $\delta^{13}C$ isotopic data suggest that the beads on the Summerford Mountain bajada are indeed areas of seasonal net accumulations of water, leading to the preferential growth of some creosotebush, and particularly some grass species, especially muhley grass. The net accumulation of water is a function of transmission loss along rills, accentuated by locally decreased slopes leading to deposition. Deposition of some areas of coarser sediment accounts in part for the increased infiltration on the beads. The higher vegetation cover generated once this process in set in motion accounts for a further increase in infiltration. The erosion-pin data suggest that the beads are still dynamic environments, and field evidence suggests that they can be headcut by oversteepening due to continuing deposition of sediment. The hydrologic and erosion data both suggest that the beads are most effective at trapping water and sediments during relatively small events, or relatively dry conditions. Larger storms will tend to move the locus of deposition and lead to the destruction or migration of the bead. The fact that large numbers of creosotebush can be established on the beads during seasonal periods when water accumulates appears to lead to greater stress during subsequent periods of drought. Concentrations of grasses may be enhanced in the bead by the preferential deposition of seeds carried in overland and rill flows. The flows also carry significant quantities of nutrients (Schlesinger *et al.*, 1999), leading to their concentration in the soils of the bead as seen from the CHN analyses. These conditions would further increase the competitive advantage of plants in the bead.

In one sense, the presence of beads in the Jornada landscape can be seen as a larger-scale instance of the island of fertility model for desertification. The continuum of resource redistribution to provide patchy resources, favouring the growth of shrubs, seems to occur on a larger scale where rills and washes are present to provide longer distance transport of water and nutrient resources. The beads provide localized instances of even greater resource accumulations than those occurring with individual 'islands' of bushes.

Conversely, the beads seem to provide much more significant expanses of grass than are possible anywhere else on the degraded landscape. Under drought conditions, it is even possible that the grasses may be out-competing the creosotebush. In practical terms, therefore, it may be possible to exploit the properties of the beads as natural accumulations of resources to reverse the process of human-induced land degradation. It is possible that deliberate seeding of these areas with grasses might enhance the chances of providing a vegetation cover that can out-compete the creosotebush. For this method to succeed, conditions need to be generated so that the grasses could spread away from the bead in all directions. In the downstream direction, this process may be encouraged by the occasional flushing of water through the bead in the higher intensity rainfall events. Positive feedbacks could also enhance the upstream migration of plants, essentially by shifting the focus of deposition upslope.

Packard (1974) investigated the hydraulic geometry of discontinuous flows on a bajada surface in southern Arizona. The Dead Mesquite wash channel described by Packard was composed of multiple headcuts feeding into a main channel stem, which was periodically interrupted by braided sections, before dispersing into a fan zone. The formation of the braid zones at Dead Mesquite wash was attributed to three factors: first, the local decrease of the slope angle; secondly, the position of riffles in the pre-existing channel flows; and thirdly, the distribution of vegetation in the floor of the wash. Slopes and stream power were suggested to oscillate along the profile, leading to discontinuous patterns of erosion and deposition, and localized accumulations of sediment towards the end of a storm event. These mechanisms provided a cycle of aggradation moving upslope, that could subsequently be eroded under conditions of localized steepening or vegetation disturbance.

On the other hand, the erosion-pin data and field observations suggest that the beads can also be eroded. These observations of dynamic erosion are compatible with discussions of discontinuous flows which have been discussed in relation to the morphology of semi-arid channel systems in the work of Schumm & Hadley (1957). With reference to arroyos in New Mexico and Wyoming, Schumm and Hadley defined a cycle of erosion, due to a building up of sediment by alluviation that then became oversteepened relative to a critical erosion threshold and thus started to erode. At any one point in time, therefore, a particular channel system may alternate between aggrading and degrading areas due to internal oscillations in the functioning of the erosional system. As the catchment area became larger, Schumm and Hadley suggested that progressively shallower slopes would be subjected to erosion because the erosion threshold could be more easily overcome. This relationship was subsequently used to infer the presence of threshold conditions required for incision (Schumm, 1973).

The question of stability of the beads through time depends on two factors. First, the downslope edge of the bead must not become sufficiently steep for headcutting to take place. This location is the most vulnerable, because it is the part of the bead least likely to receive larger quantities of water, and thus most likely to have a lower vegetation cover to protect the surface from erosion (see Table 2). Secondly, erosion of the beads seems to be most marked in years of relatively low rainfall. Long-term rainfall data are not available for the Summerford Mountain bajada, but the Jornada Experimental Range Headquarters weather station, 17-km distant, provides a reasonably similar record back to 1914. Between 1914 and 1995, 11 years had annual rainfall totals of less than one standard deviation below the mean (i.e. 158.8 mm). Of these 11 years, three had maximum rainfall events of >20 mm, a threshold value which generally provided sufficient runoff to allow flow to continue through the bead. Thus, an event that could cause significant erosion of a bead might occur once every 30 years or so. Such a value would be broadly consistent with the occurrence of eroding beads observed on the bajada, given the time-scale since the onset of shrubland at the Jornada. This periodicity would suggest that there may be sufficient time between destructive events to use the beads as areas for initiation of remediation measures.

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