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Plot-scale studies of vegetation, overland flow and erosion interactions: case studies from Arizona and New Mexico

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Abstract:

Rainfall-simulation experiments have been carried out on a series of plots ranging in size from 1 m^2 to *c* 500 m^2 in order to observe process and flux-rate changes resulting from the replacement of the dominant vegetation type from grassland to shrubland in the American South-west. Results have demonstrated variations in infiltration rates, flow hydraulics, splash and interrill erosion rates and nutrient transport rates. Furthermore, the shrubland areas develop rills, which are responsible for significant increases in overall erosion rates. The small-plot experiments allow the definition of controlling factors on the processes, and highlight the importance of vegetation controls. Although the small-plot approach has a number of significant advantages, it also has a number of disadvantages, which are discussed in detail. Some of these problems can be overcome with a careful consideration of experimental design. It is argued that plot-scale studies play an important part in improving our understanding of complex, open systems, but need to be integrated with other approaches such as the monitoring of natural events and computer modelling so that mutually consistent understandings of complex ecohydrological systems can be achieved. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS rainfall simulation; plot experiments; infiltration; runoff; overland-flow hydraulics; raindrop processes; splash erosion; interrill erosion; rill erosion; nutrient transport; experimental design; Sonoran Desert; Chihuahuan Desert

INTRODUCTION

Plot-scale studies have become increasingly important in a range of overlapping disciplines broadly covering hydrology, ecology and geomorphology, as it has been realized that a greater focus is necessary on the processes at work within landscapes. The aims of this paper are:

(1) to exemplify the ways in which plot-scale studies have been used to characterize such processes in semi-arid grassland and shrubland habitats in the American South-west;
(2) from this base to generate a discussion of the advantages and limitations of using small-scale plots in the study of hillslope runoff and erosion.

INTERACTIONS BETWEEN VEGETATION, WATER REDISTRIBUTION AND EROSION

The basic interactions between vegetation, water movement and erosion on hillslopes are illustrated in Figure 1. Because vegetation cover is relatively sparse in semi-arid areas, rain falling during a storm event may fall directly on to the ground surface or be intercepted by the vegetation canopy. The intercepted rain

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may be stored on the plant and ultimately be evaporated back into the atmosphere. Once the storage component is filled, however, water will either start to drip off the leaves and branches and reach the ground (or cascade on to lower leaves or branches), or it will flow along the branches and down the plant stems as stemflow, ultimately reaching the ground in some concentrated form around the base of the vegetation. Any water arriving at the surface may infiltrate, but if the infiltration capacity of the soil is satisfied, runoff will be generated at the surface. This runoff will then start to flow down the slope at a velocity controlled by the slope angle and the surface roughness. In a number of cases, as will be discussed below, the surface roughness is controlled either directly or indirectly by the vegetation cover, type and distribution.

Erosion on hillslopes is controlled essentially by the interactions between raindrop processes and surface flow processes. Before runoff commences, splash will be the dominant erosion process wherein particles are dislodged by rainfall impact and displaced by rebounding water droplets. The energy of rainfall arriving at the surface is the most critical factor in controlling raindrop detachment rates. Thus raindrops intercepted by the vegetation canopy typically will give rise to less splash than those that fall directly on the soil surface.

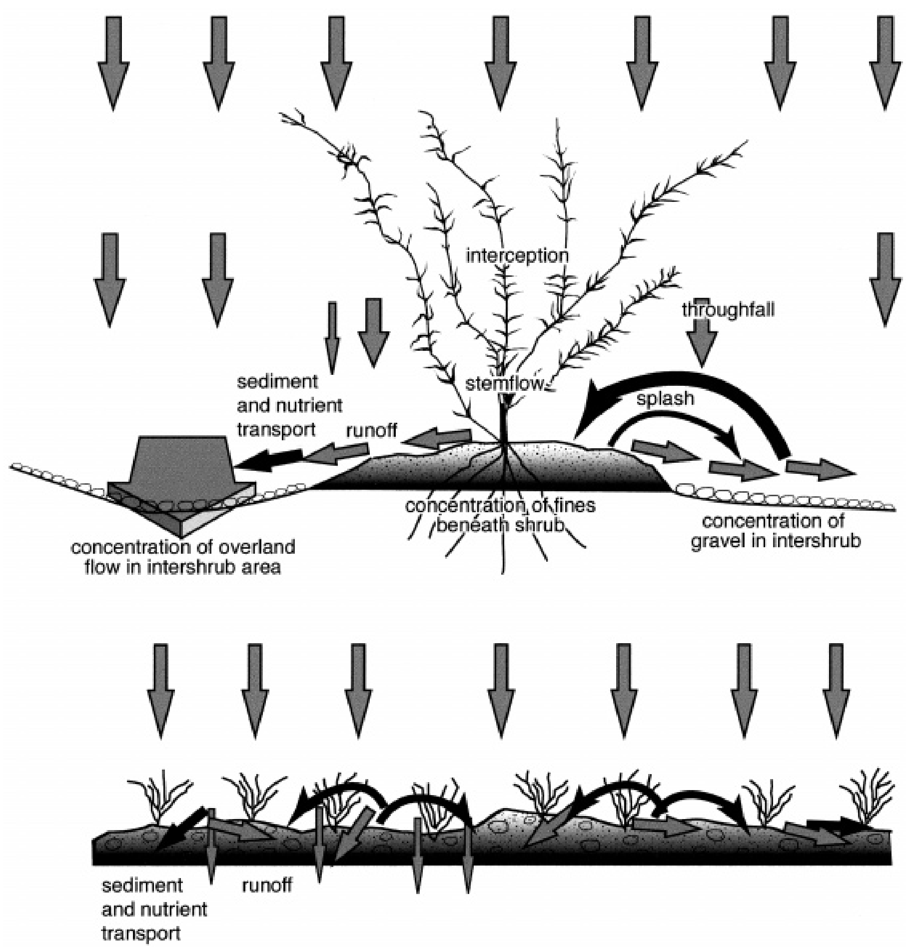


Figure 1. The basic interactions between vegetation, water movements and erosion on hillslopes, showing differences between shrub-dominated landscapes (upper) on grass-dominated landscapes (below)

After the onset of runoff, erosion typically takes on an initially diffuse form because flow rates are usually still too low to allow entrainment of soil particles by the flow. Thus, raindrop detachment of particles is still the critical, controlling factor of erosion rates, although the flow hydraulics may cause the erosion to be transport limited. Once sufficient flow has accumulated, flow entrainment may occur and flow concentrations in rills became the dominant pathways for water and sediment.

Nutrient transfers are also a significant part of the interactions between water and sediment flows and vegetation on semi-arid hillslopes. Movements of nutrients may thus affect the spatial sustainability of plant growth. Indeed, a number of authors have argued that semi-arid vegetation often forms a self-sustaining system to concentrate water and nutrients in 'islands of fertility' (Charley and West, 1975; Virginia and Jarrell, 1983; Goldberg and Turner, 1986; Schlesinger *et al*., 1990).

Plot-scale studies have been used to try to elucidate the character of the above interactions in different environments in the semi-arid American South-west. Rainfall-simulation techniques have been used over a range of plot sizes in order to produce quantifiable results with good levels of experimental control. The rainfall-simulation techniques involved have been discussed previously in detail by Luk *et al*. (1986) and Parsons *et al*. (1991). In each case below, the specific modifications to the techniques required to measure different parameters will be assessed. Following a discussion of the principal results from these studies, there will be a discussion of some of the potential advantages and limitations of small-plot experiments.

FIELD AREAS

The experimental results to be described here are derived from two field areas in the American South-west. Walnut Gulch Experimental Watershed is located in Tombstone, Arizona (31°4′N, 110°41′W), and has a warm, semi-arid climate with a mean annual precipitation of 288 mm, 67% of which falls between May and September, and a mean monthly temperature ranging from 8° to 27°C (Osborn, 1983). The Jornada Long-term Ecological Research Site (32°31′N, 106°47′W) is situated 40 km NNE of Las Cruces, New Mexico. 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). In both areas, vegetation change has been an important process over the past 100 years or so, with a conversion from a landscape largely dominated by grasses to one dominated by shrub species (Glendening, 1952; Humphrey, 1958; Hastings and Turner, 1965; Cox *et al*., 1983). At Walnut Gulch, the major grass species still present include *Bouteloua* spp., *Andropogon bardinodis* and *Hilaria belangeri*, whereas the grassland investigated at Jornada is dominated by *Bouteloua eriopoda*. Both shrublands investigated are dominated by creosotebush (*Larrea tridentata*), although the Walnut Gulch site has a greater variety of other species, including *Acacia constricta*, *Dasylirion wheeleri*, *Rhus microphylla* and *Yucca elata*, with a ground layer dominated by *Dyssodia acerosa* and *Zinnia pumila*. Typical vegetation covers for the grassland are 33% at Walnut Gulch and 50% at Jornada, whereas the respective figures for the shrubland are 44% and 27%. A further difference between the two locations lies in the soils. At Walnut Gulch, gravelly or gravelly loam soils are developed on Quaternary alluvium (Gelderman, 1970). The shrubland site is located on a loamy skeletal, carbonatic, thermic, shallow, Ustollic Palaeorthid, whereas the grassland site in on a coarse-loamy, mixed, themic, Ustollic Calciorthid (Breckenfield *et al*., 1995). The Jornada soils are granite grus with varying quantities of igneous rock fragments, dependent on location. These soils are classified as Typic Haplargids and Torriorthentic Haplustolls with localized Typic Haplocalcids (Gile *et al*., 1981; Monger, in press). In both field areas, calcareous accumulation horizons occur below the surface, although in some places these horizons are being exhumed owing to erosion (Gile *et al*., 1981; Marion *et al*., 1990).

RAINFALL–RUNOFF PROCESSES

Interception and stemflow

The processes of interception, leaf-drip and stemflow have been studied under creosotebush at the Jornada site. Seven bushes were selected, which encompassed the range of shapes occurring naturally (Whitford *et al.*, 1996). A two-part experiment was conducted which first measured the runoff generated from the stemflow only. First, a metal collar was inserted into the ground immediately around the shrub base so that the stemflow water running off the surface was trapped and passed along a tube from which it was collected and measured. Secondly, the leaf-drip, interception and stemflow components were distinguished. The bushes were cut off at ground level and secured in a clamp above a 20-l bucket into which all the stemflow drained (Abrahams *et al.*, forthcoming). The relative amounts of water being intercepted, falling through the canopy and falling as leaf-drip were also estimated. Data on the effects of the canopy on rainfall drop-size characteristics were also collected using the flour-pellet method (Bentley, 1904). These data were then used to calculate the energies of different rainfall components (Wainwright *et al.*, 1999c).

For the experiments that had a mean rainfall intensity of 147·7 mm h^{-1} ($\sigma = 19{\cdot}1$ mm h^{-1}), the canopy significantly reduced the mean rainfall intensity arriving at the surface to 132·3 mm h^{-1} ($\sigma = 19{\cdot}3$ mm h^{-1}, $p = 1{\cdot}36 \times 10^{-4}$, $n = 7$). The subcanopy rainfall was composed on average of 89·5 mm h^{-1} ($\sigma = 21{\cdot}8$ mm h^{-1}) of drops falling through the canopy and 37·2 mm h^{-1} ($\sigma = 15{\cdot}7$ mm h^{-1}) of leaf-drip. The median drop size of the rainfall outside the canopy was 1·76 mm, compared with 1·61 mm for the subcanopy rainfall as a whole and 1·31 mm for the leaf-drip. Because of the reduction in both fall height and drop size of the leaf-drips, the kinetic energy arriving at the surface beneath the shrubs is reduced by a greater proportion than is the rainfall intensity. Subcanopy rainfall intensity is 90% of that outwith the canopy, whereas the kinetic energy is only 70%. The relative figures for kinetic energy were 0·97 J m^{-2} s^{-1} for the rainfall outside the canopy compared with 0·68 J m^{-2} s^{-1} beneath the canopy, of which by far the larger proportion (0·62 J m^{-2} s^{-1} compared with 0·06 J m^{-2} s^{-1}) came from the throughfall drops. There may be a further feedback in this process, in that the reduction of energy at the surface would slow the surface sealing or crusting process during a rainfall event, which would tend to increase the infiltration rates beneath the shrubs, and promote the concentration of soil water in these areas. It was found that on average stemflow was equivalent to 10·2% of the total rain falling within the area covered by the shrub canopy. Accounting for the sparse nature of the canopy, this figure is equivalent to 27% of the intercepted rainfall. This difference calls into question the physical meaning of using simple measures of canopy area to describe desert shrubs with sparse canopies. Bias can be produced in any resulting measurements if the gaps in the canopy area are not accounted for. Because the stemflow arrives in a concentrated form at the shrub base, a large proportion of it produces runoff (nearly 80% on average: Abrahams *et al.*, forthcoming).

These figures can be compared with those of Martinez Mesa and Whitford (1996) who monitored 13 creosotebushes at Jornada over a period of three years under natural rainfall. They found that on average, 34% of the rainfall was intercepted by the bushes, with a further 10% occurring as stemflow that reached the base of the shrub. The remaining 56% of rainfall reached the surface as throughfall. The higher proportion of interception compared with the experimental results can be explained by the lower average rainfall intensities in the natural rainfall.

Infiltration

As reported by Parsons *et al.* (1996), two sets of experiments have been carried out on both grassland and shrubland sites at Walnut Gulch in order to define the controls on infiltration rates. The experiments differed in the method by which runoff was collected from 1-m^2 plots. In the first experiments, the plot had closed boundaries on all four sides, and runoff was collected by pumping the water off the lower part of the plot using two 20–30 cm sections of 1/4-inch copper pipe connected via plastic tubing to peristaltic pumps. From the pumps, the tubing was directed to calibrated buckets where the runoff rates could be measured. The weakness in this design is the fact that when runoff volumes are low or change quickly, as usually occurs in the early stages of the runoff process, the time delay between water leaving the plot and being measured can lead to significant inaccuracies (see also Smith (1979, 1996) and Mohamoud *et al.* (1990) for a discussion of the implications of similar problems). Thus, a second set of experiments was carried out in an attempt to overcome this problem. Here, plots were constructed with boundary walls on the upslope and lateral boundaries of the plot, while a covered trough on the downslope boundary permitted timed samples to be collected without a significant time delay. Infiltration rates through time were then calculated for each set of experiments by subtracting the measured runoff rates from the constant rainfall rates. However, it should be noted that this approach still lumps other factors such as interception, detention and depression storage with the infiltration term (Mohamoud *et al.*, 1990). The simplified Green and Ampt equation

$$i = a + \frac{b}{t} \tag{1}$$

was then fitted to the data from the experiment, where i is the infiltration rate (mm min^{-1}), a equals the final infiltration rate (mm min^{-1}), b reflects the initial changes in infiltration rate (mm) and t is the time since the onset of rain (min).

A number of significant results are obtained by comparing the parameter distributions for the two sets of experiments (Table I). The final infiltration rate for the grassland in the first set of experiments (a_{g1}) is significantly higher than that for the shrubland (a_{s1}, $t = 3{\cdot}48$, $p = 0{\cdot}001$, $n_{g1} = 27$, $n_{s1} = 21$). This result would imply that for the same rainfall input, the grassland should produce less runoff. However, the same comparison using the second method suggests that a_{g2} and a_{s2} are not significantly different ($t = 0{\cdot}290$, $p = 0{\cdot}387$, $n_{g2} = 18$, $n_{s2} = 24$). The different methods produce similar values for a_{s1} and a_{s2} ($t = 0{\cdot}023$, $p = 0{\cdot}49$), but significantly different values for a_{g1} and a_{g2} ($t = 4{\cdot}064$, $p = 9{\cdot}55 \times 10^{-5}$).

After each experiment, the ground-surface characteristics of the plots were measured and used to try to predict the values of the infiltration parameters for the purposes of modelling runoff from larger plots (see Scoging *et al.*, 1992; Parsons *et al.*, 1997). The following predictive equations were produced

$$a_{g1} = 0 \cdot 333 + 0 \cdot 008 \text{ rain} + 0 \cdot 006\ F\% \tag{2a}$$

$$a_{s1} = 1 \cdot 63 - 0 \cdot 014\ P\% \tag{2b}$$

$$a_{g2} = 0 \cdot 043\ L\% \tag{2c}$$

$$a_{s2} = 0 \cdot 351 + 0 \cdot 010 \text{ rain} - 0 \cdot 006\ P\% \tag{2d}$$

where rain is the rainfall intensity (mm h^{-1}), $F\%$ is the percentage of the plot surface covered by particles < 2 mm , $L\%$ is the percentage of the plot surface covered by vegetation litter, and $P\%$ is the percentage of

Table I. Comparison of values of the final infiltration rate a measured using various techniques at Walnut Gulch. The subscripts g and s refer to the grassland and shrubland respectively, the subscript 1 refers to the technique of pumping runoff from the plot, whereas 2 refers to the collection of flow from the downstream boundary

Parameter	Mean (mm min^{-1})	Standard deviation (mm min^{-1})
a_{g1}	0·967	0·264
a_{g2}	0·661	0·245
a_{s1}	0·683	0·307
a_{s2}	0·685	0·306

the plot surface covered by gravel pavement. Not only do the predictor variables change between the different methods, but the goodness of fit also decreased dramatically for Equations (2c) and (2d) ($r^2 = 0{\cdot}08$ and 0·44, respectively) compared with (2a) and (2b) ($r^2 = 0{\cdot}57$ and 0·90, respectively).

Four hypotheses were put forward by Parsons *et al.* (1996) in order to explain these differences. First, the plot boundaries in the first set of experiments were driven up to 10 cm into the ground, whereas those in the second set of experiments were inserted to a shallower depth, albeit with other precautions taken to prevent water diffusion across the boundary. It was thought that this explanation was implausible because it did not affect the grassland and shrubland surfaces differently. Secondly, although the data sets were collected at the same time of year with comparable antecedent moisture conditions, they were collected over a period of four years, so that interannual variation of surface conditions may account for some of the differences. Vegetation growth may have been affected not only by interannual climate variability (which is high in drylands: e.g. Wainwright *et al.*, 1999a), but potentially also by the effects of prior experiments increasing local water availability and thus vegetation growth, although attempts were made to avoid repeating experiments in the same locations as far as possible. Thirdly, the four data sets may not be unbiased estimates because they were collected to cover as wide a range of surface conditions as possible, because of their use in model parameterization. The gravel-pavement covers on the shrubland were relatively similar between the experiments, which might explain the lack of a significant difference between a_{s1} and a_{s2}. However, the mean fine particle and surface litter covers on the grassland changed significantly, which either demonstrates sampling bias or interannual variations as suggested above. Fourthly, the differences in the predictive equations suggest that such surface characteristics are unreliable estimators of infiltration, probably because of the relationship between infiltration and the three-dimensional properties of the soil (Youngs, 1991).

A series of experiments was carried out to characterize the infiltration rates of the Jornada sites, using the second method for collecting the runoff produced. The first set of experiments was used to examine nutrient losses from different sites (see below), so sites were sampled according to location on grassland and shrubland, with the shrubland sites being further divided into shrub and intershrub samples. The average final infiltration rate on the grassland was 1·8 mm min^{-1} ($\sigma = 0{\cdot}58$ mm min^{-1}, $n = 8$), compared with 1·2 mm min^{-1} ($\sigma = 0{\cdot}3$ mm min^{-1}, $n = 10$) for the intershrub areas and 1·4 mm min^{-1} ($\sigma = 0{\cdot}5$ mm min^{-1}, $n = 8$) for the shrubs. Analysis of variance suggests that these values are significantly different ($p = 0{\cdot}027$). The different canopy height and structure between the grasses and shrubs leads to the development of different infiltration characteristics, probably as a result of the differential development of surface sealing. The total volume of water produced in 30 min, expressed as a runoff coefficient, was also significantly different ($p = 0{\cdot}04$) according to the surface type, with mean values of 24·2% for the grassland, 52·3% for the intershrub areas and 29·9% for the shrubs. Assuming the runoff coefficient is distributed on the shrubland as a whole according to the proportion of shrub cover, this implies that the weighted average runoff coefficient on the shrubland is 46·3%. In other words, the shrubland at Jornada produces nearly twice as much runoff as the grassland, which is compatible with the large plot simulations at Walnut Gulch (see below), although the small plot experiments at Walnut Gulch show a smaller difference. A further difference between the infiltration characteristics is that the grassland and intershrub infiltration rates vary through time in close agreement with Equation 1. However, the shrub infiltration curves are divided into two types: those that follow Equation 1 and those that show an initially rapidly declining infiltration rate followed by a subsequent increase, in some cases almost returning to the value at the beginning of the experiment (Figure 2). The latter also tend to produce runoff more rapidly (after an average of 1·7 min compared with an average of 2·3 min, $p = 0{\cdot}06$). Indeed, this runoff production was often more rapid than that on the bare intershrub areas, which averaged two minutes before the production of runoff. In a second set of experiments (Howes, 1999), this difference in time to runoff production between shrub and intershrub plots was more marked (2·7 min on the shrubs compared with 4·5 min on the intershrub area, $p = 0{\cdot}05$, $n = 16$), although again the shrub plots tended to have much lower runoff coefficients. Abrahams *et al.* (forthcoming) attributed this difference to the early production of runoff derived from stemflow arriving at the base of shrubs more rapidly than surface infiltration could accommodate it. Over longer time periods, the stemflow remains constant, whereas the infiltration rate in the intershrub areas continues to decrease, so that the intershrub areas eventually produce more surface runoff than the shrubs.

The concentration of interrill flow between shrubs eventually leads to the formation of rills. As these widen, they develop sandy beds, which have different infiltration characteristics from the interrill areas. Rill infiltration rates can be compared with the transmission losses in ephemeral channels (Parsons *et al.*, 1999). Because of the soil-surface differences between Walnut Gulch and Jornada, there tend to be differences in the morphology of the rills in the two locations. At Walnut Gulch, the rills are continuous and single-channelled, except in a few places where they divide around shrubs. In contrast, the Jornada rills have alternating sections of well and poorly defined channels. The well-defined sections are usually less than 2 m wide and 0·8 m deep and are fairly straight, whereas the poorly defined sections have either numerous, shallow, anastomosing threads over an area of up to 10 m wide, or no flow concentration at all. Only the well-defined sections have been studied with plot experiments. Ten straight-sectioned reaches were selected at both Walnut Gulch and Jornada, and water was applied from a trickle trough at the upper end of the reach by means of a calibrated pipe. Flow depths were measured in the downstream direction to allow changes of discharge to be estimated, and discharge was measured at the reach outflow.

In both cases, equilibrium discharge at the outflow is obtained relatively quickly, in the order of one to two minutes. At equilibrium, the Walnut Gulch rill transmission losses range from 9·7% to 32·0%, with an average rate of 5·10 mm min^{-1}. This value may be compared with the mean final interrill infiltration rate of 0·52 mm min^{-1}. Transmission losses at Jornada range from 22·5% to 50·7%, and average 9·24 mm min^{-1}. Final infiltration rates in interrill areas by contrast vary between 1·93 and 2·32 mm min^{-1}. Thus, at both Walnut Gulch and Jornada, the rill transmission loss is about an order of magnitude greater than the final infiltration rate in the interrill zone. This difference may be due to several factors, including the presence of sealing in the interrill areas and the more deeply ponded conditions in the rills, which thus generate a greater hydraulic head than the diffuse ponds under rainfall simulation in the interrill zone, and can more completely satisfy spatially variable infiltration rates (see Hawkins, 1992). Indeed, similar differences are reported for interrill infiltration using rainfall simulation and cylinder infiltration (e.g. Wainwright, 1996). The values in the sand-bedded rills at Jornada were typically 66% higher than those in the gravel-bedded rills at Walnut Gulch, reflecting the difference in the surface characteristics. The Jornada rills also show a relatively strong relationship between discharge and transmission loss, supporting the suggestion of a control by the greater hydraulic head, whereas those at Walnut Gulch do not. This difference may be related to the buffering effect of the gravel surface.

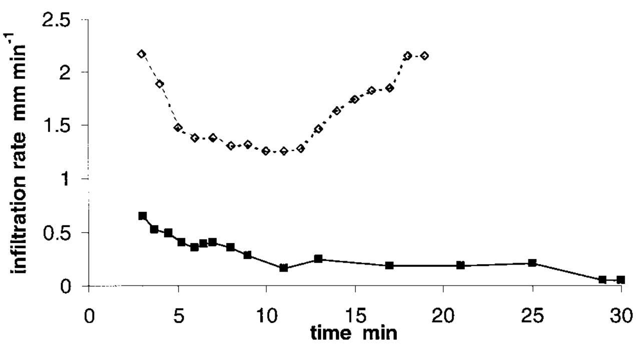


Figure 2. Examples of shrubland infiltration curves

Runoff hydraulics

Both interrill and rill hydraulics have been studied in detail at Walnut Gulch. Parsons *et al.* (1994a) looked at the effects of different experimental designs for obtaining the Darcy–Weisbach friction factor

$$ff = \frac{8gds}{v^2} \tag{3}$$

for the grassland surface (where g is acceleration due to gravity (m s^{-2}), d is flow depth (m), s is surface slope (m m^{-1}) and v is flow velocity (m s^{-1})). An earlier set of experiments had produced values ranging from 0·05 to 18·81, with a median of 8·30 for the grassland and 0·81 and 12·37, with a median of 1·91, for the shrubland (Abrahams *et al.*, 1994). Vegetation and litter cover were found to be important controls on the grassland hydraulics, whereas stone cover and stone size were the dominant controls of *ff* on the shrubland. In both cases, the flow Reynolds number had a relatively minor effect on the friction factor. These experiments used plots that were 0·5 m wide in the grassland and 0·61 m wide in the shrubland, by 1·5 m long. Overland flow was simulated simply by the use of an overflow trough at the upslope boundary (Abrahams and Parsons, 1991). Depths were measured at transects across the lower part of each plot. Knowing the inflow and outflow discharges, flow velocities at the transects could be calculated. However, at nearby sites, Weltz *et al.* (1992) had obtained *ff* estimates of 114·16 for the grassland and 16·17 for the shrubland. Weltz *et al.* used plots 3·05 m wide by 10·70 m long, on which rainfall was simulated using a rotating boom simulator, and outflows were monitored continuously at a flume. Optimization of the kinematic wave equations was used to produce estimates of *ff* from the hydrographs recorded at the flume. Parsons *et al.* (1994a) identified the three main differences between the experimental techniques as being the size of the plot, the method of flow generation and the method of determining the friction factor. Therefore, they carried out a set of comparative experiments to examine the different effects of these differences. Plots were constructed varying in size from 3 m wide by 6 m long to 0·5 m wide by 1 m long. To minimize any effect of spatial variability, the smaller plots were constructed inside the largest plot (two intermediate sizes were used, of 2 m wide by 4 m long and 1 m wide by 2 m long). All flows were generated using rainfall simulation. For each plot size *ff* was estimated from direct measurement of d and q (to estimate v) and by the hydrograph-optimization method.

The results suggested no significant difference between the values of *ff* obtained by the two methods. Furthermore, there appeared to be no relationship between the plot length and the value of *ff* obtained by either method (Figure 3). In addition, there was no consistent relationship between the values of *ff* calculated by the two methods. The previous estimates of Abrahams *et al.* (1994) were generally an order of magnitude lower than those found in the new set of experiments. Thus it was concluded that the major difference in the values was due to the method of application of water to the plot. However, this difference is unlikely to be simply due to the addition of rainfall resistance, and probably relates to the fact that water trickled on to the upper part of the plot typically organizes itself into deeper threads of flow due to the presence of obstacles, and thus becomes more hydraulically efficient owing to the persistence of these flow threads further down the plot. Comparison of mean flow depths predicted using hydrograph optimization with those measured in the field suggests that the optimization method can introduce relatively large errors into the prediction of *ff*. Therefore, Parsons *et al.* (1994a) concluded that the optimal technique for the measurement of friction factors involved the use of rainfall simulation and the direct measurement of depths and discharge, with plot size being a relatively unimportant consideration for the grassland surface investigated.

Runoff hydraulics were also investigated at Walnut Gulch at a much larger scale on plots of approximately 500 m^2. On the grassland the plot was 18 m wide by 29 m long, whereas on the shrubland it was 18 m wide by 35 m long (Parsons *et al.*, 1996). Flow hydraulics were measured at cross-sections 6 m, 12 m and 20·5 m from the top of the grassland plot and at 12·5 m and 21 m on the shrubland plot. Depths and discharges were sampled at 0·5-m intervals, and from these measurements, values for width and velocity of flow were obtained. To analyze these data, hydraulic geometry relationships were used, rather than the Reynolds-number approach of Emmett (1970). The latter ignores the effects of flow width, which Abrahams and

Figure 3. Relationships between the plot length and the value of the Darcy–Weisbach friction factor obtained by direct measurement of the hydraulics (f_d) and by optimization of the runoff hydrograph (f_h: A, B, C refer to the three different experimental plots used: redrawn after Parsons *et al*., 1994a. Parsons AJ, Abrahams AD, Wainwright J. *Water Resources Research* **30**, 3515–3521, 1994, copyright by the American Geophysical Union.)

Parsons (1990) demonstrated is highly variable in overland flows. Following standard practice, the hydraulic geometry relationships (Leopold and Maddock, 1953)

$$w \propto Q^b \tag{4a}$$

$$d \propto Q^f \tag{4b}$$

$$v \propto Q^m \tag{4c}$$

were determined and changes in the exponents b, f and m were investigated.

At-a-section increases in discharge appear to be accommodated more or less equally by depth and inundated width in both the shrubland ($b = 0{\cdot}492, f = 0{\cdot}432$) and in the grassland ($b = 0{\cdot}578, f = 0{\cdot}568$), whereas changes in the velocity are minimal and increase with discharge on the shrubland ($m = 0{\cdot}132$) but decrease on the grassland ($m = 0{\cdot}103$; Figure 4). These differences can be attributed to the differences in microtopography on the two sites (Figure 5), which is in turn a function of the vegetation types. The broad swales between shrubs on the shrubland promote the concentration of interrill flows in these locations, so that increases in depth tend to occur in areas already inundated, causing the flows to become hydraulically more efficient and the flow velocities to increase. Conversely, on the grassland, the microtopography is less pronounced and the inundated areas are scattered across the plot. Vegetation stems and stones protrude through the flow, so that increases in discharge are offset by the greater cross-sectional area of roughness elements at greater depths, causing the observed reduction in velocity. Thus, for equivalent discharges, the more concentrated flows in the shrubland travel at greater velocities than the dispersed flows in the grassland.

Downslope changes in discharge on the shrubland are dominantly accommodated by increases in velocity with a small increase in width and minor changes in mean depth. The grassland shows equal rates of increase

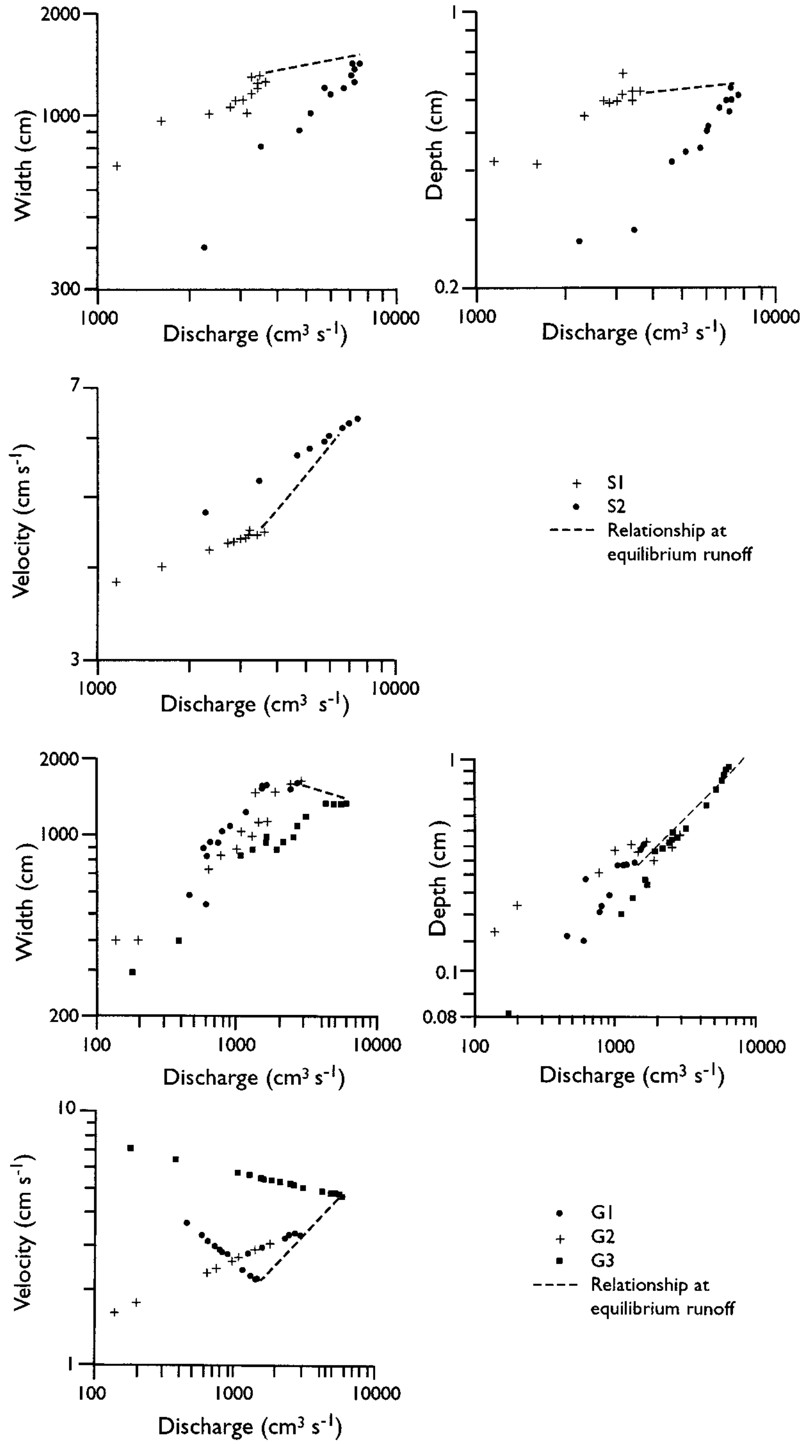


Figure 4. At-a-section hydraulic geometry relationships on the shrubland and the grassland at Walnut Gulch (redrawn after Parsons *et al.*, 1996b. Reproduced by permission of John Wiley & Sons Ltd.)

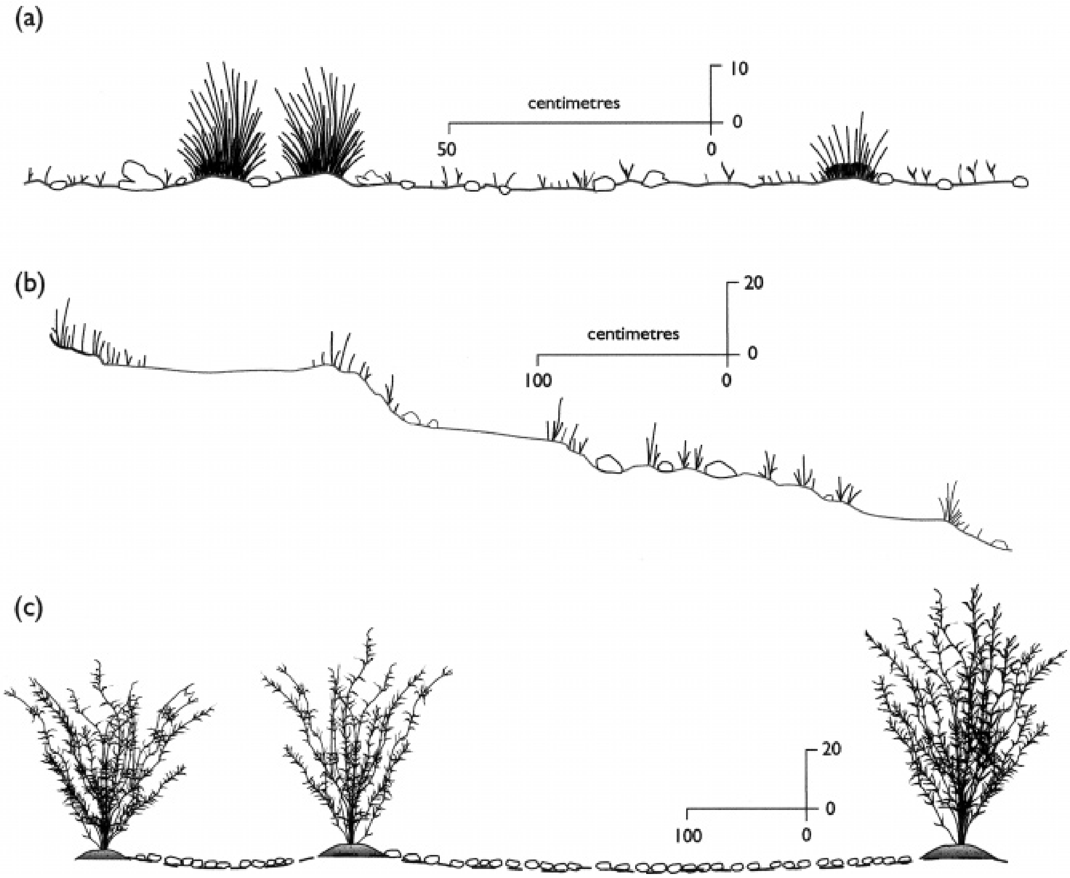


Figure 5. Microtopography of the Walnut Gulch grassland and shrubland sites defined by surveys carried out at 1-cm intervals (redrawn after Parsons *et al.*, 1996a. Reproduced by permission of John Wiley & Sons, Ltd.)

in depth and velocity but a small rate of decrease in inundated width downslope. Although the mean flow depths are similar on the grassland and shrubland, the distributions of depth vary. In particular, there are more extreme values in the shrubland, reflecting the concentration into deeper, more hydraulically efficient threads of flow. This downslope increase in maximum depths probably explains the existence of rills in the shrubland, which typically occur around 30 m from the divide, and their absence from the grassland. The use of mean flow shear stresses derived from mean flow depths would suggest that the opposite should occur. There may be a partial explanation in terms of differences in soil resistance, although this factor is still under investigation.

Once these rills have formed in the shrubland, their hydraulics are controlled by a different set of factors (Abrahams *et al.*, 1996). At-a-section changes in discharge are accommodated almost equally by changes in depth, velocity and inundated width ($b = 0{\cdot}33$, $f = 0{\cdot}34$, $m = 0{\cdot}33$). In comparison to cropland rills, the ratios of b/f and m/f are higher for the Walnut Gulch rills (0·97 compared with 0·75). This difference is thought to reflect the broad, shallow cross-section of the latter rills compared with the usually rectangular cross-section of the former. At Walnut Gulch, the median grain size of the surface exerts the major control on the friction factor of the rills, with the flow discharge only explaining 2·9% of the variance in *ff*. Vegetation is usually absent from these rills because of their unstable nature.

EROSION PROCESSES

Raindrop-erosion processes

Parsons *et al.* (1994b) carried out a series of measurements of splash rates on the same large grassland plots described above. The technique consisted of using a 'splash kite' placed at five locations down the slope on the surface of the plot (Parsons *et al.*, 1991, 1994b) and replaced at intervals of five minutes, so that both spatial and temporal variability were sampled. In the first experiment on the large plot, the splash rates gradually increase until around 15 to 20 min into the experiment, and then decline. The rates measured during a second experiment carried out two days later continued to decline (Figure 6). This pattern was attributed to an initial increase in detachment rates due to the continued saturation of the surface, followed by an exhaustion of available material which is detachable by raindrop impact. The splash rates measured in this was were 0·012 g m^{-2} min^{-1} at the start of the first experiment rising to a peak of 0·054 g m^{-2} min^{-1} and then falling to around 0·006 g m^{-2} min^{-1} during most of the second experiment. Correcting for collector size according to the method of Torri and Poesen (1988), these values become 0·010 g m^{-2} min^{-1}, 0·043 g m^{-2} min^{-1} and 0·005 g m^{-2} min^{-1}, respectively. Variability between locations can be explained as a function of local variability in grass cover and of interrelated variations in the flow depth.

Parsons *et al.* (1991) used the same method to estimate a mean rate of splash for the shrubland. Their value of 0·432 g m^{-2} min^{-1} corresponds to a corrected value of 0·342 g m^{-2} min^{-1} (Torri and Poesen, 1988). Parsons *et al.* (1992) undertook a study of rates of splash towards and away from shrub canopies. They found that about 1·6 times more sediment splashed towards shrub canopies than splashed outwards, leading to a net accumulation of fine material beneath shrubs. They argued that shrubs, therefore, play a significant role in creating microtopography and in sorting surface materials on these hillslopes and, consequently, in affecting runoff and erosion. Results of experiments on creosotebush at Jornada suggest that although kinetic energy is reduced by 30%, the effective kinetic energy is reduced by 55% (Wainwright *et al.*, 1999c). In a separate modelling study, Wainwright *et al.* (1995) demonstrated that such differences in energy hitting the surface underneath shrubs and in the intershrub areas could explain the build up of mounds and the development of microtopography on the shrubland, of the sort responsible for controlling the flow hydraulics described above.

Interrill erosion

Abrahams *et al.* (1988a) measured interrill erosion rates on six 1·8-m wide by 5·5-m long plots on the shrubland, under simulated rainfall with an intensity of 145 mm h^{-1}. Slope gradient varied from 6° to 33°, vegetation cover from 2·0% to 9·8%. Sediment concentrations generally showed negative correlations with flow discharge, suggesting again that exhaustion of available material from raindrop detachment and weathering is an important control on interrill transport. Sediment yields measured over a 30-min period varied from 4·2 g m^{-2} min^{-1} to 137·6 g m^{-2} min^{-1}, with a strong control by the surface gradient. The yield increased up to a slope angle of 12° and decreased thereafter (Figure 7). This decrease resulted from a decrease in runoff rates in response to an increase in infiltration rates, as surface particle size and roughness increased with gradient. There was also a relatively strong negative correlation between sediment yield and vegetation cover. Sediment yield decreases as vegetation cover increases as there is (i) an increase in the interception of raindrops, (ii) an increase in hydraulic roughness due to plant stems (see above), and (iii) an increase in plant roots, which bind the soil and reduce its erodibility. In a further study, Abrahams *et al.* (1988b) looked at particle sizes of entrained material to investigate threshold conditions of motion in overland flow. The largest particles moved varied from 4·7 mm to 14·7 mm on a 7° slope to 10·8 mm to 52·6 mm on a 35° slope. The study demonstrated that the Shields parameter is an inappropriate predictor of flow competence in interrill flows, and that critical shear stress is a function of particle diameter and relative submergence. The size characteristics of transported material suggest that larger particles are often detached by splash rather than by the overland flow (Parsons *et al.*, 1991).

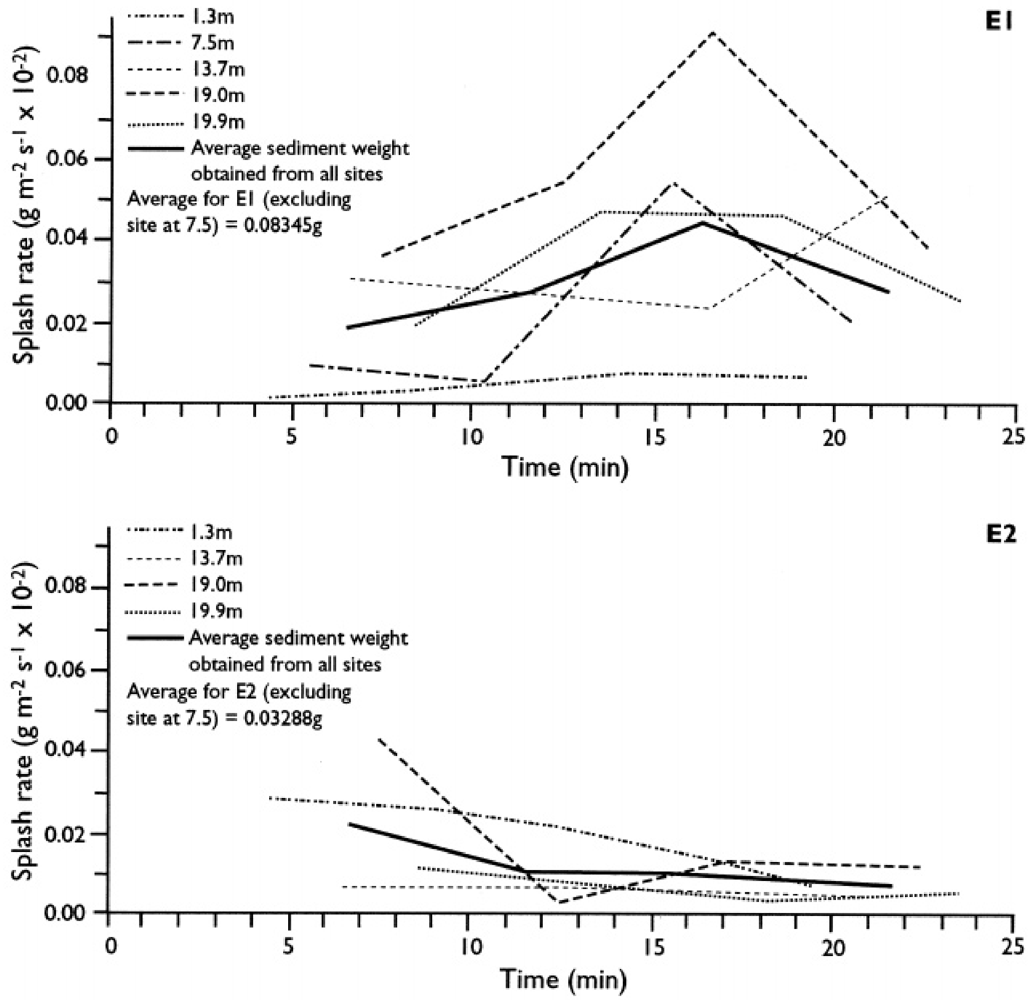


Figure 6. Splash erosion rates on the large grassland plot at Walnut Gulch (redrawn after Parsons *et al.*, 1994b. Modified and reprinted from *Catena*, **22**, Parsons AJ, Abrahams AD, Wainwright J, 'Rainsplash and erosion rates in an interill area on semi-arid grassland, southern Arizona', 215–226, 1994, with permission from Elsevier Science.)

Shrubland sediment-transport rates were also measured on the large plot described above (Abrahams *et al.*, 1991, 1995; Parsons *et al.*, 1996a,b). Partial cross-sectional measures of sediment load were carried out at distances of 3 m, 12·5 m and 21 m down the 35 m-long plot and extrapolated to the entire 18-m width of the plot. Sediment loads varied from 5·13 g m^{-1} min^{-1} to 17·97 g m^{-1} min^{-1} on the section 12·5 m from the top of the plot and from 11·4 g m^{-1} min^{-1} to 31·73 g m^{-1} min^{-1} on the section 21 m from the top (Figure 8). The respective average soil losses range from 0·41 g m^{-2} min^{-1} to 1·44 g m^{-2} min^{-1} on the upper section and from 0·54 g m^{-2} min^{-1} to 1·51 g m^{-2} min^{-1} on the lower. However, dividing by the distance downslope to produce an average soil loss shows that the erosion rate first increases downslope and then decreases. This pattern can be explained in terms of the downslope changes in the distributions of flow depths and velocities (see discussion above), rather than changes in their mean values (Abrahams *et al.*, 1991).

Similar measurements of erosion rates were made on the large grassland plot at cross-sections that were 6 m, 12 m and 21 m from the top of the plot. The sediment loads for these cross-sections varied from 1·14 g

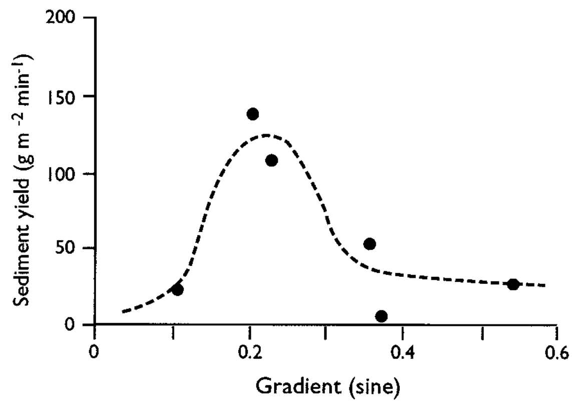
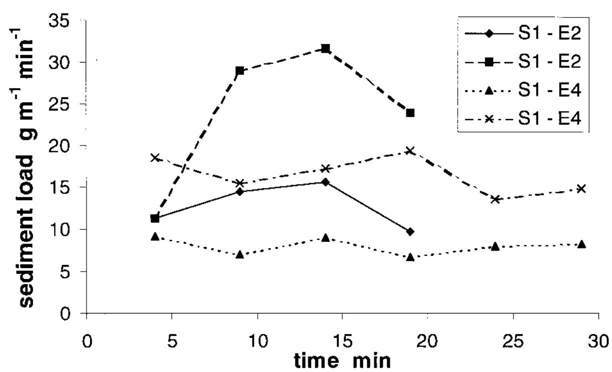


Figure 7. Relationship between sediment yield and slope gradient for a series of small-plot experiments on shrubland sites at Walnut Gulch (redrawn after Abrahams *et al.*, 1988a. Modified and reprinted from *Catena*, **15**, Abrahams AO, Parsons AJ, Luk S-H, 'Hydrologic and sediment responses to simulated rainfall on desert hillslopes in southern Arizona', 103–117, 1988, with permission from Elsevier Science.)

a.



b.

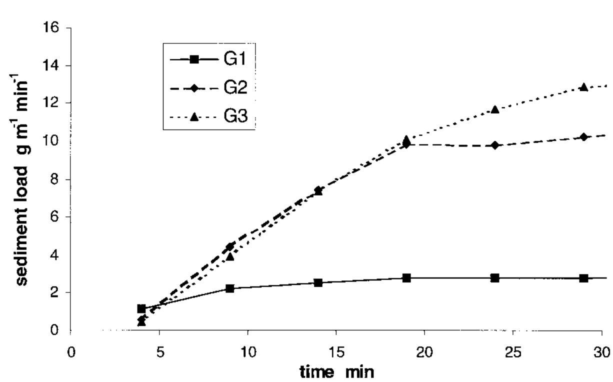


Figure 8. Sediment load at cross-sections on the large plot experiments: (a) at cross-sections 12·5 m (S1) and 21 m (S2) from the upslope boundary on the shrubland during experiments 2 and 4 (E2 and E4); and (b) at cross-sections 6 m (G1), 12 m (G2) and 20·5 m (G3) from the upslope boundary on the grassland plot during experiment 2

m^{-1} min^{-1} to 2·98 g m^{-1} min^{-1}, from 0·57 g m^{-1} min^{-1} to 11·50 g m^{-1} min^{-1}, and from 0·42 g m^{-1} min^{-1} to 14·01 g m^{-1} min^{-1}, respectively. Average soil losses were 0·72 g m^{-2} min^{-1} at 6 m downslope, 1·83 g m^{-1} min^{-1} at 12 m downslope and $-$ 1·37 g m^{-1} min^{-1} at 21 m downslope. This pattern reflects that seen on the shrubland, with first an increase and then a decrease in average soil losses. The negative value at 21 m reflects the fact that deposition is dominant owing to the lack of transport capacity of the overland flow. Parsons *et al.* (1993) also investigated the travel distance of individual soil particles on the grassland during these experiments, by placing a line of magnetite tracer on the surface, and observing the dispersal of the magnetite both on the surface, using a hand-held magnetometer, and in samples collected in overland flow through the three cross-sections. Most sediment seems to travel very short distances: 29·7% is deposited within 0·25 m of its source and only 2·2% travels 2·95 m. Although temporal and spatial variability in transport distances are large, the data suggest a negative exponential relationship between sediment amount and transport distance.

Comparison of the overall erosion rates in the shrubland and grassland at Walnut Gulch shows a major difference between the two vegetation types (Figure 9). Rates in the first two 80-mm-h^{-1} experiments in the shrubland were higher than achieved in the grassland, even during events that were twice as long. In part this difference is related to the hydrological behaviour of the shrubland, which produces more runoff faster, and concentrates this runoff more rapidly as it proceeds downslope. The difference in erosion rate also can be attributed to the higher raindrop detachment rate in the shrubland, which is thought to be due, at least in part, to the greater effect of frost action on the bare surface (Parsons *et al.*, 1996a). Erosion rates in the grassland continue to increase after the second experiment, probably as a result of the continuing increase in the area contributing to overland flow, whereas exhaustion effects are clearly visible in the second experiment in the shrubland.

Rill erosion

Rates of rill erosion are perhaps the most difficult of slope processes to measure effectively in a field setting using small plot experiments because of the major difficulties of supplying sufficient water into a rill and surrounding interrill areas to simulate the processes in a reasonable way. Obviously as rill size grows and

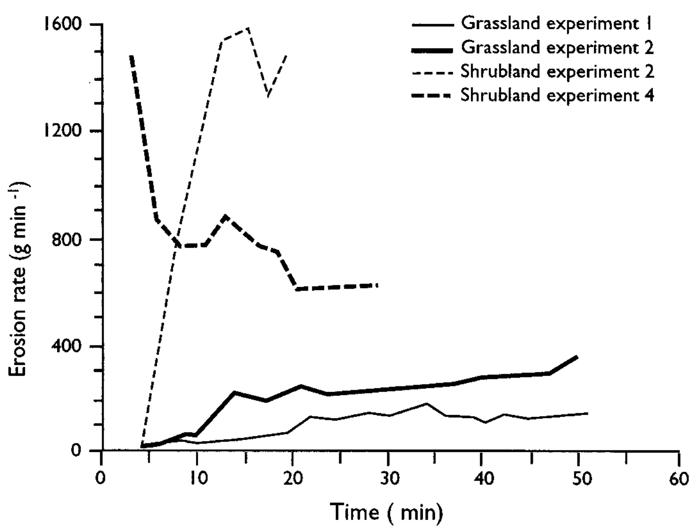


Figure 9. Comparison of the overall erosion rates in the large plot experiments on the shrubland and grassland at Walnut Gulch (redrawn after Parsons *et al.*, 1996a. Modified and reprinted from *Geomorphology*, **14**, Parsons AJ, Abrahams AD, Wainwright J, 'Responses of interill runoff and erosion rates to vegetation change in southern Arizona', 311–317, 1996, with permission from Elsevier Science.)

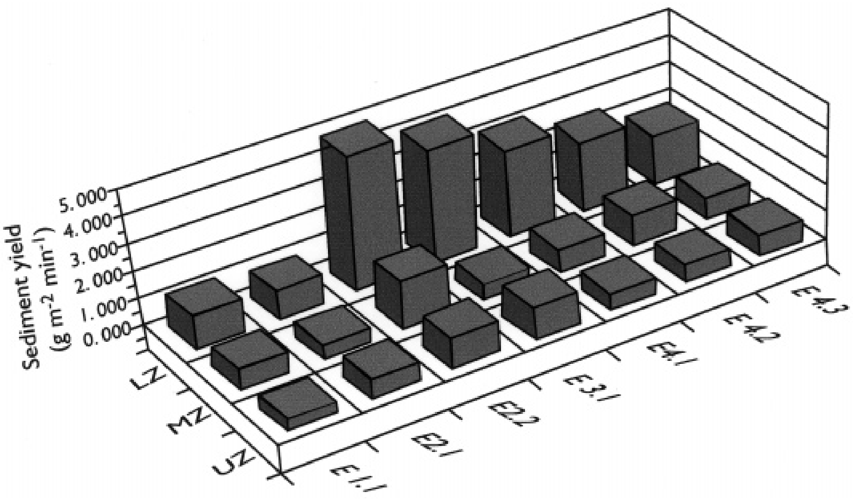


Figure 10. Rill erosion rates derived from repeated cross-sectional surveys during the large shrubland plot experiment at Walnut Gulch (redrawn after Luk *et al*., 1993. Modified and reprinted from *Catena*, **20**, Luk S-H, Abrahams AD, Parsons AJ, 'Sediment sources and sediment transport by rill flow and interill flow on a semi-arid piedmont hillslope, southern Arizona', 93–111, 1993, with permission from Elsevier Science.)

permanent gullies develop, such measurements become increasingly difficult when using controlled experiments, and the monitoring of natural events is usually the most effective way to proceed. However, at the base of the large shrubland plot, a bifurcated rill had formed, and it was possible to make some measurements of erosion rates (Luk *et al*., 1993). Three flumes were positioned so as to capture the rill and interrill contributions separately, and five rill cross-sections were repeatedly surveyed to observe patterns of scour and fill. In all cases, the rate of rill erosion was significantly higher than the rate of interrill erosion. During the second part of the second experiment, this rate peaked at a value of just under 5 g m^{-2} min^{-1}, and then remained at a constant value of around 1·8 g m^{-2} min^{-1} until the end of the fourth experiment. The sediment transport rate in the second experiment remained relatively high throughout the experiment, whereas in the fourth experiment, it peaked early and then declined (Figure 10). This decline probably reflects the exhaustion of transportable sediments. This explanation is also consistent with the decline in coarser sediment transport during the fourth experiment. Microrelief measurements permitted the calculation of net scour and fill in different parts of the rill system. These results demonstrated that there is significant spatial and temporal variability in the erosion rate of rills (Table II), although in general there was net scour after the first experiment everywhere except in the most upslope section on the left rill. Overall, it was found that there was a negligible sediment supply from the rill system during the first experiment, but that in the three successive experiments, the rills supplied approximately 30%, 42% and 34%, respectively, of the total plot sediment loss. The importance of these figures is reflected in the fact that the rills represent approximately 3% of the total plot area.

NUTRIENT TRANSPORT

Transport of nutrients has been investigated recently at the Jornada site by Schlesinger *et al*. (1999). Rainfall simulations were carried out on six grassland plots, and on eight shrub and ten intershrub plots in the shrubland. The grass and intershrub plots were 1 m wide by 2 m long, whereas the shrub plots were 1 m^2 so as to minimize the inclusion of intershrub areas. Outflow samples were collected and measured using a Traacs 800 Autoanalyzer. Mean concentrations of total dissolved nitrogen in runoff waters were 1·72 mg l^{-1} on the grassland, 1·44 mg l^{-1} on the shrub and 0·55 mg l^{-1} on the intershrub areas, giving a mean weighted

Table II. Rates of rill scour and fill during a series of four experiments (E1–E4) on the large shrubland plot at Walnut Gulch. All values are cumulative height loss in centimetres measured at centimetre intervals using a 1-m-wide microtopography meter (after Luk *et al.*, 1993. Modified and reprinted from *Catena*, **20**, Luk S-H, Abrahams AD, Parsons AJ, 'Sediment sources and sediment transport by rill flow and interill flow on a semi-arid piedmont hillslope, southern Arizona', 93–111, 1993, with permission from Elsevier Science.)

	E1		E2		E3		E4		
Location	Scour	Fill	Scour	Fill	Scour	Fill	Scour	Fill	Net scour/fill
Right rill upper	2·15	7·82	19·01	2·30	12·47	4·08	7·38	7·76	19·05
Right rill lower	4·00	8·52	11·99	0·00	5·76	0·60	3·20	7·02	8·81
Left rill upper	0·00	6·75	0·00	8·43	0·00	8·55	6·64	2·40	– 19·49
Left rill lower	3·60	3·05	5·35	3·05	4·03	8·08	12·05	1·85	9·00
Main rill	8·35	0·00	13·89	22·19	10·78	2·78	34·47	1·80	40·72
Mean	3·62	5·23	10·05	7·19	6·61	4·82	12·75	4·17	11·62

shrubland concentration of 0·77 mg l^{-1}. Total N yields in a 30-min experiment for the three sites averaged 0·0294 g m^{-2}, 0·0227 g m^{-2} and 0·0176 g m^{-2}, respectively, with the weighted mean for the shrubland being 0·0195 g m^{-2}. Thus, the grasslands produce greater nutrient losses to runoff despite their producing smaller quantities of runoff. Comparison of the organic and inorganic fractions of N suggested that extra yield came dominantly from the inorganic fraction in the soil. Total phosphorus loss was much lower, and dominated by inorganic fractions (up to 98% of the total on the grassland and 64% on the shrubland). The 30-min yields were $3{\cdot}999 \times 10^{-3}$ g m^{-2} on the grassland, $1{\cdot}681 \times 10^{-4}$ g m^{-2} on the intershrub and $1{\cdot}374 \times 10^{-3}$ g m^{-2} on the shrub plots, giving a weighted mean for the shrubland of $6{\cdot}264 \times 10^{-4}$ g m^{-2}. These results suggest that runoff is an important contributor to the loss of organic N. Further experiments are underway to investigate the longer distance transport of these solutes.

IMPACTS OF THE CHANGE FROM GRASSLAND TO SHRUBLAND

The impacts of the change from grassland to shrubland vegetation at the field sites can be seen in various ways from the foregoing discussion (a summary of the results is presented in Table III). In most, but not all cases, more runoff is produced from shrubland surfaces than from grassland surfaces. Interactions between the rainfall, vegetation canopy, surface litter and surface crust are important factors that have been isolated by the experiments. Flows on the shrubland are also faster for the same discharge, and also tend to contain more extreme values, because of the form of the microtopography. These flows therefore tend to lead to the development of rills, which reinforce the development of the microtopography. Shrubs also tend to develop mounds of fine sediment beneath them due to the erosion process, as more material is splashed beneath them than is able to escape. This process tends to accentuate further the swale topography of the shrubland. In contrast, erosion rates are typically lower and more diffuse on the grassland due to the nature of the canopy, and sediment tends to accumulate by grass clumps and obstacles such as large stones. The erosion process on the grassland therefore tends to develop a tread-and-riser microtopography, which acts to minimize the effects of erosion, and further slows the overland flows on the grassland. Once rilling starts, as occurs on the shrubland at Walnut Gulch, but is also seen in some of the grassland areas at Jornada, it leads to a significant acceleration of the rate of erosion. Nutrient losses are important components of the runoff from both the grassland and the shrubland. As discussed previously (Abrahams *et al.*, 1995; Parsons *et al.*, 1996a,b), there is a feedback between the introduction of shrubs and the maintenance of conditions that are likely to encourage the development of a shrubland habitat. This feedback largely promotes the development of islands of fertility (Schlesinger *et al.*, 1990), although the experiments on the disposition of stemflow, infiltration and runoff, splash and nutrient transport suggest that these islands are to a certain extent 'leaky'.

Table III. Summary of rates and fluxes of water, sediments nutrients based on rainfall-simulation experiments at Walnut Gulch and Jornada, together with an outline of the main controls that are either directly or indirectly affected by biotic processes on the slope. Where a cell in the table is left blank, no measurements have been made reflecting those specific conditions; n/a indicates that such measures are not applicable for the specific conditions. Most of the measurements reflect a single set of measurement conditions or ranges of resulting values, and should thus be taken only as a general indication of the relevant rates — see text for further discussion

		Grass		Intershrub		Shrub		Shrubland weighted	
Process	Location	Value	Controls	Value	Controls	Value	Controls	Value	Controls
Interception[a]	Jornada	?		n/a	n/a	10%	Canopy cover[e] and shape	n/a	
Stemflow[a]	Jornada	Minimal		n/a	n/a	10·2%	As above	n/a	
Infiltration[a]	Walnut Gulch — small plots	73·1%	Vegetation cover[e], rainfall intensity, litter cover?, surface fines?	41·3%	Rainfall intensity, pavement cover	86·3%	Rainfall intensity, canopy cover[e]	65·2%	Vegetation and subcanopy cover[e]
Infiltration[a]	Walnut Gulch — large plots	79·5%	As above	n/a	n/a	n/a	n/a	17·3%	Vegetation and subcanopy cover[e]
Infiltration[a]	Jornada	75·8%	As above	47·7%	As above	70·1%	As above	53·7%	Vegetation and subcanopy cover[e]
Rill transmission loss[b]	Walnut Gulch	n/a		9·7–32%	Stone cover	n/a		n/a	
Rill transmission loss[b]	Jornada	n/a		22·5–50·7%	Sand fraction?	n/a		n/a	
Interrill runoff hydraulics[c]	Walnut Gulch — at a section	$b = 0{\cdot}578$, $f = 0{\cdot}568$, $m = -0{\cdot}103$	Vegetation cover[e], stone cover, microtopography[f]					$b = 492$, $f = 0{\cdot}432$, $m = 0{\cdot}132$	Vegetation cover[e], stone cover and size[g], microtopography[f]
	— downslope	$b = 0{\cdot}162$, $f = 0{\cdot}585$, $m = -0{\cdot}586$	As above					$b = 164$, $f = 0{\cdot}080$, $m = 0{\cdot}785$	As above
Rill runoff hydraulics[c]	Walnut Gulch — at a section	n/a		$b = 0{\cdot}33$, $f = 0{\cdot}34$, $m = 0{\cdot}33$	Surface grain size[g]	n/a		n/a	
Raindrop erosion[d]	Walnut Gulch	0·005–0·043	Vegetation cover[e], surface grain size[g]	0·342	Vegetation cover[e], surface grain size[g]	?0·150	Vegetation cover[e], surface grain size[g]	?0·249	Vegetation cover[e], surface grain size[g]
Interill erosion[d]	Walnut Gulch — small plots			4·2–137·6	Sediment supply[h], surface grain size[g]			2·8–90·8	Sediment supply[h], vegetation cover[e], surface grain size[g]
	— large plots	0·21–0·65	Sediment supply[h], vegetation cover[e], surface grain size[g]					1·5–1·7	As above
Rill erosion[d]	Walnut Gulch	n/a				n/a		1·8–5·0	Sediment supply[h], surface grain size[g]
Nutrients — TDN[d]	Jornada	$9{\cdot}8 \times 10^{-4}$	Availability in soils, vegetation and litter, flow amount and velocity	$7{\cdot}6 \times 10^{-4}$	Availability in soils, vegetation and litter, flow amount and velocity	$5{\cdot}9 \times 10^{-4}$	Availability in soils, vegetation and litter, flow amount and velocity	$6{\cdot}5 \times 10^{-4}$	Availability in soils, vegetation and litter, flow amount and velocity
— %ON	Jornada	56·3%	As above	74·9%	As above	56·3%	As above	65·7%	As above
— TDP[d]	Jornada	$3{\cdot}2 \times 10^{-6}$	As above	$1{\cdot}8 \times 10^{-6}$	As above	$3{\cdot}2 \times 10^{-5}$	As above	$1{\cdot}3 \times 10^{-5}$	As above
— %OP	Jornada	2·3%	As above	32·2%	As above	70·6%	As above	64·2%	As above

[a]Values are proportions of rainfall.
[b]Values are proportion of water in rill.
[c]b is the proportionality coefficient for inundated width, f for flow depth and m for flow velocity: see equation 4.
[d]Units are g m^{-2} min^{-1}.
[e]A distinction is drawn between the canopy cover — i.e. the proportion of the canopy area excluding gaps — and the vegetation cover — i.e. the ground surface covered by vegetation.
[f]Microtopography can be considered to be an indirect consequence of the vegetation properties (see Parsons *et al*., 1996a).
[g]Surface stone size on the shrubland can be considered to be an indirect consequence of the vegetation cover (see Parsons *et al*., 1992; Wainwright *et al*., 1995).
[h]As well as detachment by raindrop processes, sediment supply for interrill and rill erosion may be controlled by a number of other factors, including surface distribution by animal activity.

ADVANTAGES AND LIMITATIONS OF PLOT-SCALE STUDIES

The most significant advantage of plot-scale rainfall-simulation studies such as those described above are in the way that they can allow the definition of the major fluxes of water, sediments and nutrients. By integrating the plot-scale rainfall-simulation studies at a range of scales with a range of relatively simple measurement techniques, it is possible to define the most important direct and indirect impacts of vegetation on surface processes, together with the potential feedbacks of those processes on vegetation growth. In an area where vegetation change has been one of the dominant environmental changes over the past 100 years, understanding these impacts and feedbacks is vital both in comprehending landscape changes and for managing landscapes. Such management is important because of direct hazards such as flooding and reservoir siltation, and also because of the impacts on rangeland resources in general. The plot-scale approach provides a flexible approach to obtaining such data, which is both cost- and time-effective.

However, the plot-scale approach also has a number of disadvantages or potential problems, which must be accounted for at each stage of the experimental design. Perhaps the most important of these is the way in which, and extent to which, such experiments can capture 'reality'. As with other experimental approaches, plot-scale rainfall simulations impose a necessary restriction on the degree of variability present in the system under study. Most rainfall simulators produce a restricted range of fixed rainfall intensities, with statistically constant raindrop size distributions and kinetic energies (see Bubenzer (1979) and Meyer (1979) for a review of desirable characteristics of simulated rainfall). However, studies into the properties of natural rainfall have demonstrated that such properties are continuously variable, both within and between storms (Mutchler and McGregor, 1979; Parsons and Gadian, in press) and thus have a complex spatial and temporal structure. Experiments and numerical simulations need to be carried out to investigate the impacts of such variability, so that the approximations made at the present time can be evaluated. There is a consequent problem, though, in utilizing such information, in that data requirements for extrapolation or modelling would be unfeasibly large.

Surface conditions and vegetation covers are also continuously variable. In the studies described above, these properties are treated as discrete entities, for example shrubland versus grassland or the proportions of a plot covered by vegetation or stones, which may not necessarily be the best ways of generating general models of processes, particularly at transitions between zones in space or time. Differences between repeated experiments to derive the same measurement (e.g. infiltration rate discussed above) in terms of the controlling variables that are identified suggests that this is a real problem. Indeed, although 'natural' processes are explicitly the topic of study, what is actually being investigated most of the time are the *effects* of an artificially generated and controlled set of conditions, which may or may not approximate to those processes. The examples described above of different results for both infiltration rates and friction factors using different experimental designs illustrates this point very clearly. The experimental results obtained can be seen to be related very closely to the extent to which the experimental conditions reflect the reality of a complex, open system (Richards, 1990). Defining this relationship is not always as self-evident as it first appears. As in these cases, it was only when the first results produced explanatory inconsistencies that further studies were undertaken. In a broader sense, this relationship also affects which processes can be captured by this type of approach. The clearest example described above is that of the processes active in the formation, maintenance and destruction of rills and gullies. Although rills and gullies are the most important sources of sediment from hillslopes, less is known about them than raindrop and interrill processes because of the practical difficulties with producing effective experiments. Such experiments would usually require tens of thousands of litres of water, and simulations to be carried out over areas equal to, but preferably larger than the 500 m^2 discussed here. Otherwise, the boundary effects become an increasingly significant component of the experimental design, and the results become more an artefact of these effects. As noted above, it is probably most appropriate to use monitored natural events in the consideration of these processes, although this approach can require several years to obtain sufficient data.

The consideration of boundary effects is also significant with smaller sizes of plot. For example, in infiltration studies, it is necessary to rain outside the plot area itself to prevent more rapid diffusion of water across boundaries. In the case of erosion rates, the sediment supply may be dominated by the effects of disturbance in the construction of the plot itself. If a boundary is constructed, however, the fluxes of sediment by splash will be affected in the peripheral zone. If this zone is large compared with the overall size of the plot (e.g. if splashed material is travelling over a 5-cm distance, the boundary zone will make up nearly 20% of a 1-m^2 plot), then the results will say more about the boundary than the process under investigation. In some cases, it may be better to design experiments without boundaries, at the expense of not being able to collect every single piece of data that might be useful (e.g. Wainwright *et al.* (1999b) used a plot without boundaries in their study of desert-pavement formation).

Not only is rainfall highly variable in space and time, but so too is vegetation. Vegetation changes are seasonal, relating to cycles of growth and die-back (more markedly in the case of grass), and to longer term fluctuations in climate and other controls. Indeed this is self-evident in the focus on the widespread historical changes from grassland to shrubland. Such changes have characterized the American South-west over much of the Holocene (see Wainwright (in press) for a specific review relating to the field areas). However, the studies presented above largely represent a 'snapshot' of a specific set of conditions at a specific time. Simanton *et al.* (1992) have demonstrated the extent to which infiltration and erosion properties vary seasonally at Walnut Gulch. Because shrub species in particular have complex responses to seasonal water availability (Reynolds *et al.*, 1999), the implications of understanding this availability are important. Although the obvious answer is to carry out all experiments during every season over an extended period to investigate the extent to which such changes are important, this approach is not usually feasible or practical (or necessary in all cases). In many cases it may still be more important to make the basic characterizations of processes discussed above so that key controls or feedbacks can be highlighted for further study. Limits are also posed on such an approach from the perspective of research infrastructure. Few funding bodies will countenance continued funding of repeated measurements (although the National Science Foundation Long Term Ecological Research programme, which funds the Jornada field site, is a notable exception), and the career and promotion prospects of individual researchers are usually damaged if they are perceived to be doing the 'same old thing'.

Another issue already hinted at is that of scaling of measurements and interconnectivity between elements within a large, open system. Examples of complex scaling patterns are illustrated by the study on grassland friction factors at Walnut Gulch discussed above, and by differences in the infiltration and erosion rates measured on small and large plots on the Walnut Gulch shrubland (Abrahams *et al.*, 1995; Table III). Because they are controlled by different sets of factors, different parameters are likely to scale in fundamentally different ways. Plot-scale studies are usually incorporated either implicitly or explicitly within a broader research framework, which may, for example, be to understand hydrological cycles, ecosystem functioning or landscape development. The important issue is how necessarily small-scale studies can be used to investigate properties at much larger spatial and temporal scales. The answer may lie in the scaling of measures of landscape properties (e.g. McBratney, 1998) or in explicit spatial and temporal representations of the process description (Zhang *et al.*, 1999). However, such approaches may be unrealistic because of the boundaries drawn in the initial field measurements. An important focus for future work will lie in the investigation of the interconnectivity of what is essentially a large, open system, and the extent to which current approximations capture these linkages (e.g. Michaelides, 2000). Future work may be required at a plot scale, but with an entirely unforeseen focus on the types of measurement that are required. Whatever these may be, it is likely that numerical simulations will be necessary to allow the integration of different measurements.

Further methodological issues relating to consistency and reporting of results are presented in Agassi and Bradford (1999). They stress the need for a full discussion of the methods used and the information presented in publications, so that effective comparisons between studies can be made.

CONCLUSIONS

From this discussion, it is clear that plot-scale studies have provided significant insights into the understanding of the ecohydrology of the grassland and shrubland biotas of the American South-west. Furthermore, it is clear that such studies play an important part in a continuum of methodological approaches, in which a variety of other techniques must be used. Laboratory experiments provide us with exceptional control on the processes (e.g. Abrahams *et al.*, 1998; Parsons *et al.*, 1998), albeit with a significant loss of 'reality' and representation of the connectedness of the real system. However, this type of work gives us clear ideas of the fundamental actions and reactions between processes, and can point the way in terms of the requirements of what can and should be looked at in the field. The approach also can be used for elucidating some of the more complex interactions that it is impossible to untangle from the residuals of a set of relationships measured in the field. Monitoring studies are also required because they can better capture much larger scales and as a consequence generally will incorporate a greater level of complexity and interconnectedness — albeit again perhaps at the expense of initial understanding — and the probability that boundary effects will have a much smaller impact on the results obtained, if the monitoring scheme is designed effectively. Numerical modelling is the final major methodological consideration. It provides a means of extrapolating between temporal and spatial scales and of testing the results of plot studies against monitored data (e.g. Kirkby, 1987; but cf. Oreskes *et al.*, 1994). For example, Parsons *et al.* (1997) discuss in detail the way in which an iterative approach may be used involving modelling and plot studies of different scales to approach a more internally consistent understanding of the grassland hydrology at Walnut Gulch. It is only be producing mutually consistent explanations of the results using this range of different techniques that we will improve our understanding of the processes in these environments (see also Richards, 1990).

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