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The influence of slope angle on sediment, water and seed losses on badland landscapes

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Abstract

By means of simulated rainfall the influence of the slope angle on the soil, water and seed erosion has been studied on badland surfaces. Slope angle has a clear positive effect controlling soil erodibility and erosion rates, but it does not have any influence on the volume of runoff after 40 minutes of rain at an intensity of 55 mm h^{-1}. In contrast, slope angle has a clear influence on runoff initiation, with cracks and crusts as the main factors controlling the time to ponding and time to runoff. Both ponding and runoff initiation start earlier on pediments than on slopes, where more cracks exist. Steady-state infiltration rates and seed losses have an inverse relationships with slope angle. Pediments have 40 times lower erosion rates and 6 times higher seed losses than slopes. The different behaviour of seed losses between pediment and slope is due to the strategy of the seeds against erosion processes.

Keywords: badlands; hydrology; erosion; seed losses; rainfall simulation

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1. Introduction

Badland areas are intensely dissected natural landscapes where vegetation is sparse or absent and which are useless for agriculture (Bryan and Yair, 1982a). The fluvial origin of badland morphology explains the very high drainage densities, V-shaped valleys and short, steep slopes. At the foot of the hillslopes a gently sloping planar pediment surface is often present.

The lithologic conditions are basic for understanding the geomorphological processes operating on badland surfaces (Bryan and Yair, 1982b). Normally, badland development is associated with unconsolidated or non-cemented materials. Marls, silty-clay formations and even sandy Quaternary sediments are susceptible to badland development. Badlands can develop in a variety of climatic conditions, but they are most common in semiarid regions (Clotet et al., 1987).

Badlands can be part of the natural landscape, representing an erosional response to limited vegetation cover on favourable lithologies, while other badlands may be partly or wholly human-created

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(Campbell, 1989). In southeast Spain, the construction and abandonment of agricultural terraces in the valley bottoms often results in the degradation of basal pediments (Rodríguez Aizpeolea, 1992) and as a consequence the whole slope may be subject to erosion. Variations in the rates of activity of the geomorphological processes in badlands are high (Campbell, 1989; Cerdà, 1993a) as in other semiarid environments (Scoging, 1982). Indeed, badlands include some of the most erosionally active areas on earth with both surface erosion (Campbell, 1970) and subsurface erosion or piping (Jones, 1981).

In the southeast of the Iberian Peninsula the development of badland areas has been well-documented (Harvey and Calvo, 1989; Calvo-Cases et al., 1991; Harvey and Calvo, 1991; Payà and Cerdà, 1992), as in other places around the Mediterranean (Vittorini, 1977; Yair et al., 1980, Alexander, 1982, Harvey, 1982; Imeson, 1983; Sdao et al., 1984; Berndtsson, 1988; Alexander and Calvo, 1990; Benito et al., 1991) and in other semiarid environments (Campbell, 1974; Churchill, 1981; Laronne, 1982).

Slope angle plays an important role in the dynamics of geomorphological processes, especially for bare soils. In theory, rainsplash, sheet and concentrated overland flow, and as a consequence soil losses, are accelerated on high angle slopes. Normally, the slope angle shows an inverse relationship with infiltration rates because of the location of the most degraded soils on the steepest slopes (Munn et al., 1973). Other researchers have demonstrated that this relationship is not so simple (Cerdà, 1995), or has a threshold at 12° (Abrahams et al., 1991) or the relationship does not exist at all (Lattanzi et al., 1974).

Another interesting topic to which this research relates is the dynamics of the seed bank in areas threatened by land degradation processes. Some aspects of the seed bank in badland areas have been studied elsewhere (García-Fayos and Recatalà, 1992; García-Fayos et al., 1995; Cerdà and García-Fayos, 1994/95), but here it will be related to water and soil losses. Seeds are very important within the ecosystem, because they have the possibility to transform the badland surface into a vegetated environment by means of the surface stabilization (Alexander et al., 1994). Issues such as the dynamics and rates of runoff and sediment losses on badland surfaces, the ability of rainwash to erode seeds, and how slope angle influences the soil, water and seed losses from badland surfaces are important to address. This paper aims to examine the above mentioned topics.

2. Material and methods

A typical badland area was selected in southeast Spain, near the village of Petrer in the province of Alicante (Figs. 1 and 2) (Calvo-Cases et al., 1991; Harvey and Calvo, 1991; Cerdà, 1993a). In total, sixteen experimental plots were selected, 13 of these on slopes and 3 on pediments. The sites for the rainfall simulation experiments and soil sampling were selected from the most representative surface-morphologies on the slopes, which have a large degree of spatial variability (Harvey and Calvo, 1991). The pediments are more homogeneous surfaces and more limited in spatial extent thus only three experiments were carried out.

The Petrer Badlands are developed on Cretaceous (Senonian) marls. The origin of badland slopes is related to the Pleistocene valley dissection and to recent land-use changes (Rodríguez Aizpeolea, 1992) (Fig. 3). On the badland slopes, the dominant processes are rilling, swelling and cracking and the development of shallow bridge piping. Shallow slips are a secondary process (Harvey and Calvo, 1989).

Climatic conditions at Petrer are characterised by a mean annual precipitation ranging from 296 to 339 mm (Geiger, 1970; Payà and Cerdà, 1992). The mean annual temperature is 16°C, the mean monthly maximum temperature is 25.7°C in August and the mean monthly minimum temperature is 11.4°C in January. The mean number of rainy days is 33 per annum.

The study is related to interrill processes, for this purpose a special plot of 0.24 m^2 has been designed. See Fig. 4a for a general view of the badland site, Fig. 4b for a slope plot and Fig. 4c for a pediment plot. Rainfall simulation experiments where performed by a small and portable rainfall simulator (Fig. 5) (Cerdà, 1993c).

Rainfall simulation experiments of 40 minutes duration at an intensity of 55 mm h^{-1} were carried out in Spring, 1993 and Spring, 1994 with distilled water. Several authors have studied the frequency

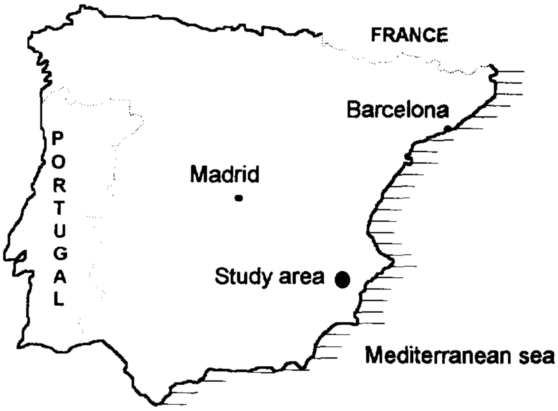


Fig. 1. Location of the study area.

and duration of natural rainfall events in this region and they have demonstrated that storms similar to the ones simulated have a return period of 4–5 years (Elías Castillo and Ruiz Beltrán, 1979; García Bartual, 1986).

Vegetation on all sampled surfaces was negligible, always lower than 2%. Slope angle was 2° on the pediments and ranged between 22° and 55° on the slopes. A mixture of 24 seeds from different species was placed in the middle of each plot, along a 30 cm line from the plot outlet (Fig. 6). After 40 minutes of simulated rainfall, the runoff and the sediment concentration were measured and seed losses were counted. 30 minutes has been demon-

Fig. 2. View of the study area.

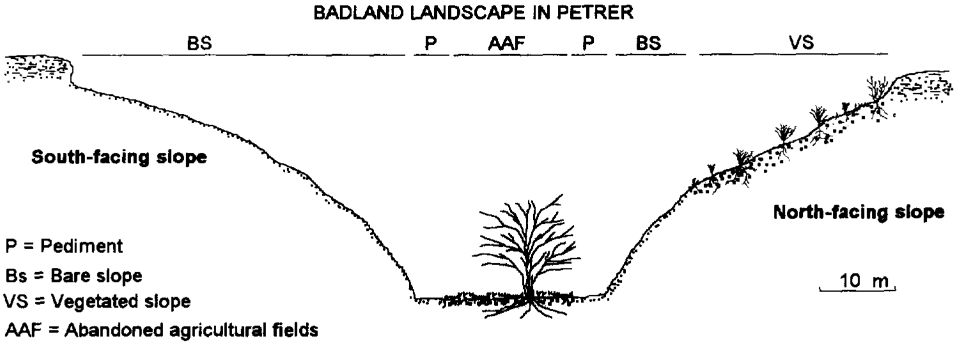
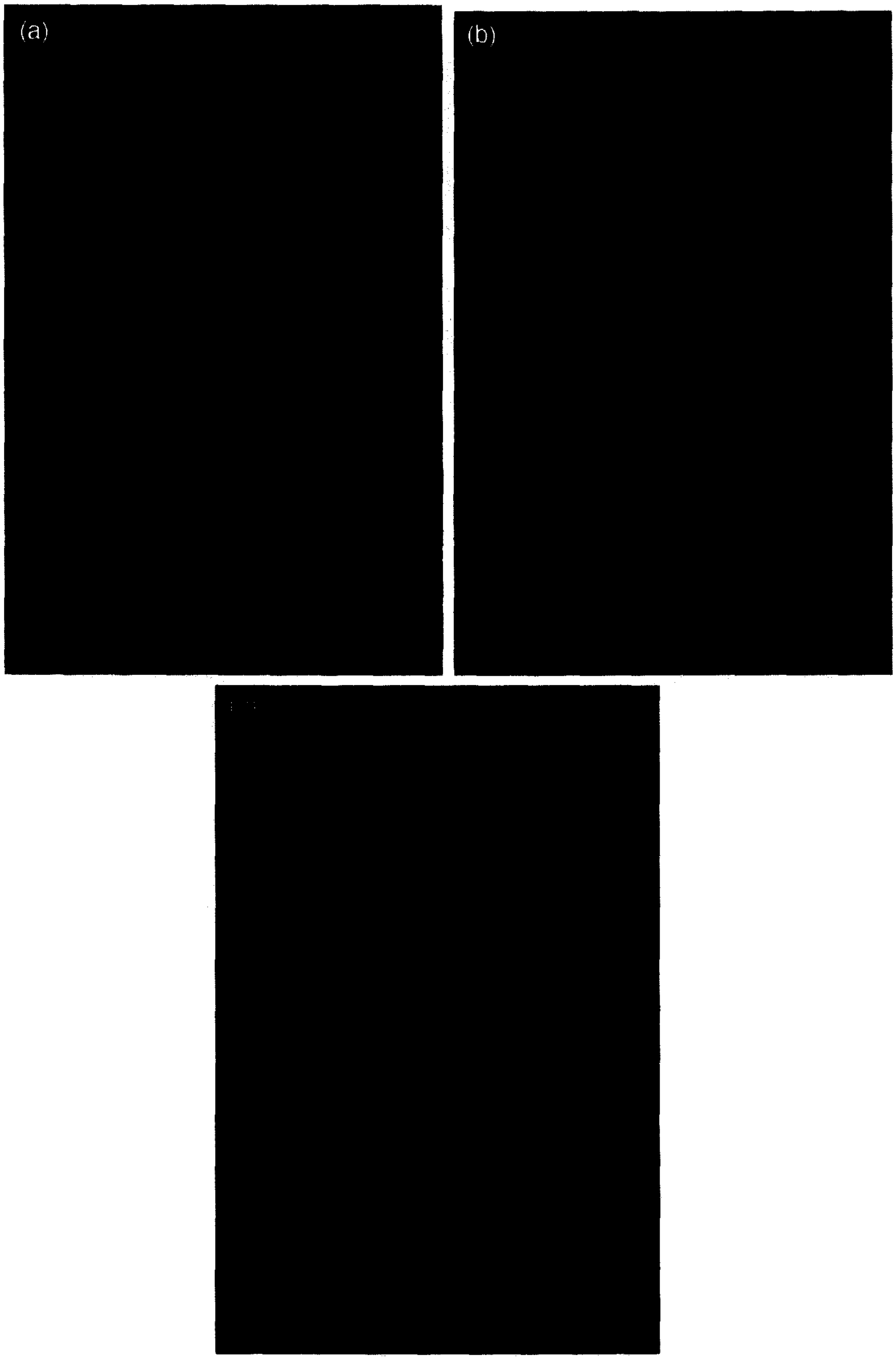


Fig. 3. Scheme of the distribution of pediment and bare slopes in a cross-section in the experimental watershed of Petrer.


(a)
(b)

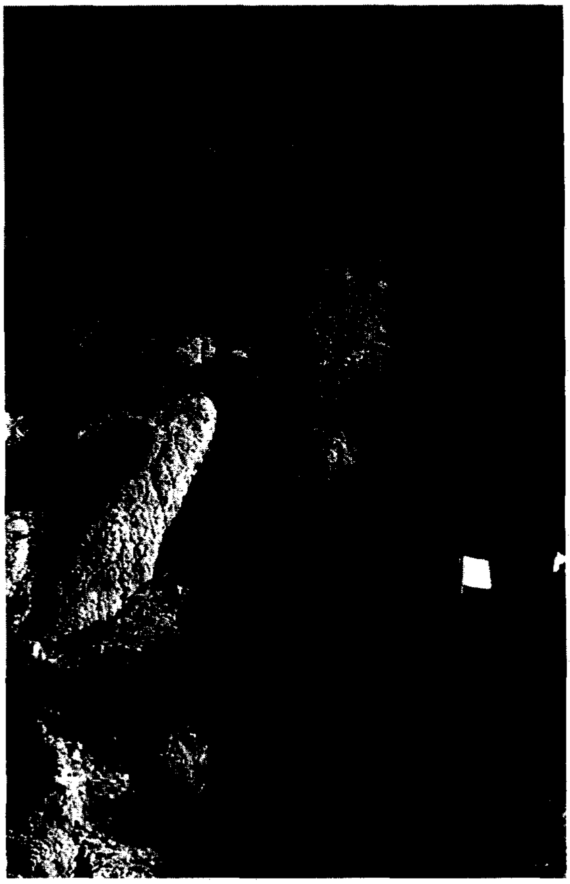


Fig. 5. View of the rainfall simulator.

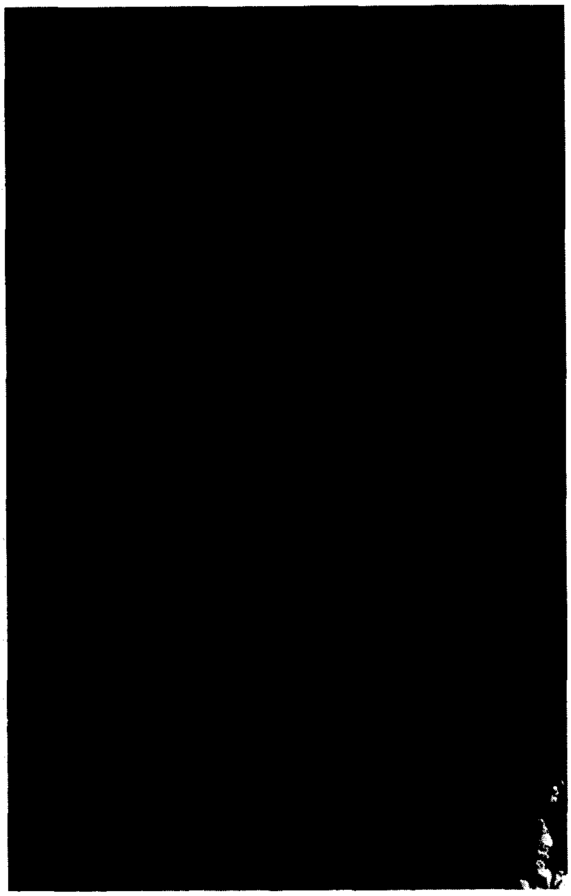


Fig. 6. Disposition of the seeds on a slope plot.

strated to be sufficient for obtaining the steady-state rates of erosion and runoff (Cerdà, 1993a).

Seeds of the following species were used in the experiments: *Cheirolophus intybaceus*, *Helichrysum stoechas* and *Phagnalon saxatile* (Compositae), *Cistus albidus* (Cistaceae), *Erica multiflora* (Ericaceae), *Lygeum spartum* (Gramineae), *Moricandia arvensis* (Cruciferae), *Pistacea lentiscus* (Anacarciaceae), *Salsola genisoides* (Chenopiaceae) and *Sedum sediforme* (Crassulaceae). These species were selected for their dominance in the adjacent areas. Seeds were selected from populations living in the study areas, air-dried in the laboratory and then dyed with blue aniline for identification.

The time to ponding (t_p) was taken from the start of rainfall to when 40% of the surface was ponded. The plot runoff contribution (t_r) starts when runoff was measured in the collector. The runoff was measured every 30 or 60 seconds and samples for sediment concentration were taken continuously.

The infiltration curve was drawn by subtracting the runoff rate from the rainfall intensity. Real infiltration values were fitted to the Horton infiltration equation (Horton, 1940):

$$f = f_c + (f_0 - f_c) e^{-\alpha_t}$$

$$F = f_{ct} - (f_0 - f_c)/(e^{-\alpha_{t-1}})$$

where f = instantaneous infiltration rate, F =

Fig. 4. (a) General view of the convex slope and the flat pediment of the badland; (b) view of a badland surface plot on the slope; (c) view of a badland surface plot on the pediment.

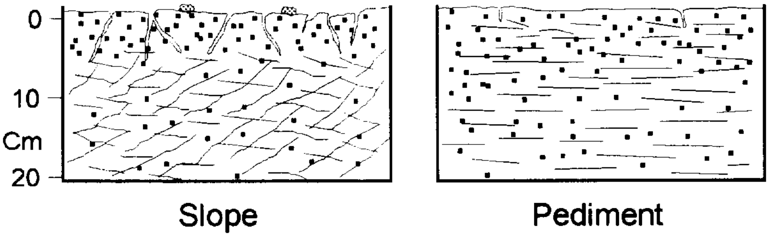


Fig. 7. Typical soil profiles of slope and pediment plots.

cumulative infiltration rate, f_c = steady-state infiltration rate, f_0 = initial infiltration rate ($t = 0$), α = empirical constant (infiltration curve form).

Soil samples were taken at the surface (0–2 cm depth). Experience has shown that the wetting front after similar rainfall simulation experiments does not reach more than 2–3 cm depth either on pediment or on slopes in the study area (Cerdà, 1993a). The soil water content was measured gravimetrically, and the sediment concentration in the runoff by evaporation in the laboratory. The organic matter content (Walkley-Black method), grain-size distribution (USDA classification), and calcium carbonate content (Bernard calcimetry) were also determined at each of the soil plots. The Bulk density was measured by the ring method.

3. Results

3.1. Soil characteristics

In the badland areas, soils are bare, crusted and cracked, especially on slopes (Fig. 4aFig. 4b). The pediment crusts have fewer cracks than the slopes (Fig. 4c). Other differences are the depth of the cracks, a few millimetres on the pediments and some centimetres on the slopes. The regolith of the slope soil is 3–5 cm deep and the cracks are connected to underlying rock fractures. On the pediment, the sedimentary layer is thicker than 20 cm and the crack network is less developed (Fig. 7).

The amount of organic matter is very low, both on the pediments (0.36%) and on the slopes (0.23%) (see Table 1). The bulk density is very high: 1.46 g cm^{-3} and 1.52 g cm^{-3} for pediment and slope surfaces respectively. Calcium carbonate content is extremely high: 65.24 and 67.60% respectively (Table 1).

The grain sizes of the badland materials show two distinct distributions (Fig. 8). The first is for the pediment soils, in which the sand content is more than 31%, the clay content 21% and the silt fraction is very large: 48%. The second is for the badland slopes themselves, which have a very low sand content (9%), high clay content (39%) and very high silt content (52%). The texture is loam/silty-loam for the pediment and silty-clay/silty clay-loam for

Table 1
Main soil characteristics. Organic matter, bulk density, calcium carbonate and slope angle

Plots	Organic matter (%)	Bulk density (g cm^{-3})	CaCO$_3$ (%)	Slope angle (°)
Pediment				
1	0.46	1.53	65.24	2
2	0.25	1.42	62.35	2
3	0.37	1.43	68.14	2
Average	0.36	1.46	65.24	2
Slope				
1	0.12	1.45	70.25	25
2	0.45	1.52	65.35	25
3	0.14	1.46	62.54	40
4	0.35	1.48	63.41	42
5	0.24	1.55	68.26	35
6	0.42	1.49	70.15	35
7	0.19	1.63	72.54	25
8	0.08	1.54	70.12	25
9	0.17	1.52	68.25	22
10	0.06	1.46	63.14	40
11	0.29	1.60	64.90	30
12	0.23	1.52	69.64	50
13	0.26	1.54	70.25	55
Average	0.23	1.52	67.6	34.54

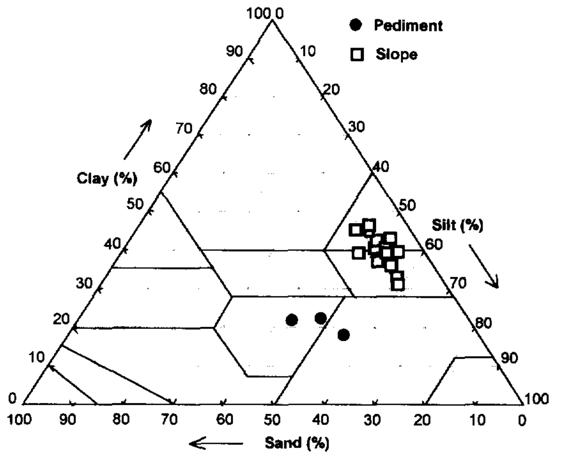


Fig. 8. Grain sizes of the 13 slopes soils and 3 pediment soils at the experimental watershed of Petrer.

the slopes (Fig. 8). The slopes are erosive surfaces that have a texture similar to the parent material. In contrast, the pediments are a sedimentation or transport surface, with a higher sand content and lower clay content.

3.2. Water losses

The badland surface suffers quick changes induced by rain. On the pediments, ponding and runoff appear very quickly (39″ and 1′55″ respectively). On the slopes, both surface changes are delayed until 1′59″ and 2′55″ respectively (Table 2). Both pediments and slopes can generate surface runoff quickly, although on the pediments it tends to be instantaneous. This is due to the differences in cracks. The cracks persist during the experiment on the slopes, which favours infiltration. Normally, the first surface runoff infiltrates at the beginning of the rain into the crack networks. Cracks are closed by the flow generated in the areas between cracks. The cracks became saturated (by water), closed (by swelling of clays) or plugged (by sediment). This results in sheet and concentrated overland flow into rills. Sometimes there are open cracks, which can become incipient pipe inlets, and more rarely a combination of pipes and rills.

Although the rainfall duration in the experiments was only 40 minutes the runoff rates were very high. The average runoff rates were normally higher than 40 mm h^{-1}, which is close to 75% of the rainfall. The steady-state infiltration rate is very low, close to zero in some cases. The resulting calculated forms of the runoff curves are very steep, reaching the final infiltration rate very soon (Fig. 9).

The wetting fronts were very shallow in these soils (Cerdà, 1995), which after rainfall would favour a quick evaporation. 24 hours after the rainfall event, the cracks will reappear, and 48 hours after the experiment, the soil surface will have values of soil moisture lower than 0.08 $g \cdot g^{-1}$.

3.3. Soil losses

Soil erosion rates were very high on the slope plots, ranging between 4514 and 1748 g m^2 h^{-1}. This is due to both the high runoff volumes and to high sediment concentrations (47–105 g l^{-1}) (Table 3). Although the plot surface was very small (0.24 m^2) the sediment yield reached values of 600 gr during one hour.

Table 2
Hydrological characteristics. Time to ponding (t_p), time to runoff (t_r), runoff coefficient (RC) and steady state infiltration rate (f_c)

Plots	t_p	t_r	RC	f_c (mm h^{-1})
Pediment				
1	0′31″	2′35″	0.69	14.28
2	0′40″	1′20″	0.84	4.30
3	0′45″	1′10″	0.58	22.50
Average	0′ 39″	1′ 55″	0.70	13.69
Slope				
1	1′00″	1′51″	0.64	3.91
2	2′56″	3′31″	0.76	4.08
3	1′35″	2′20″	0.90	2.43
4	1′30″	3′20″	0.65	−2.79
5	2′40″	3′27″	0.51	6.51
6	1′50″	2′05″	0.85	1.71
7	2′30″	4′00″	0.73	3.27
8	1′39″	2′30″	0.78	2.42
9	1′50″	2′40″	0.75	0.34
10	1′40″	2′35″	0.81	−0.18
11	1′40″	2′20″	0.78	5.56
12	2′10″	3′00″	0.80	1.31
13	2′45″	4′10″	0.76	1.53
Average	1′40″	2′40″	0.74	2.21

In contrast, the pediments generate runoff with lower sediment concentrations (2.29 g l^{-1}) and consequently lower erosion rates (100 g m^2 h^{-1}).

The sediment concentration increases with time on the slope surfaces, which when also combined with increases in runoff results in very high increases of erosion rates. On the pediments the sediment concentration decreases with time (Fig. 9).

3.4. Seed losses

During the 40 minutes of simulated rainfall the amount of seed loss was very low on the slopes. Only 4% of the seeds were eroded (Table 4). Most of the seeds were eroded during the first few seconds of the experiments, when the soil was still dry and splash erosion moved some of the seeds downslope.

In contrast, on the pediment surfaces the seeds were not eroded at the beginning by splash because the low slope angle. Ponding on the pediment, however, was much deeper than on the slopes (up to 1 cm was recorded) and this induced floating of the seeds, resulting later in their washing out. This process explains the higher loss of seeds in the pediment areas (23%). On the slopes, after a few (15–45) seconds, the soil surface was wet and the seeds were "glued" to the soil surface by the awns, hairs, pappus and other structures on the seed surfaces which the seeds have developed as important strategies against erosion processes (Van der Pijl, 1972).

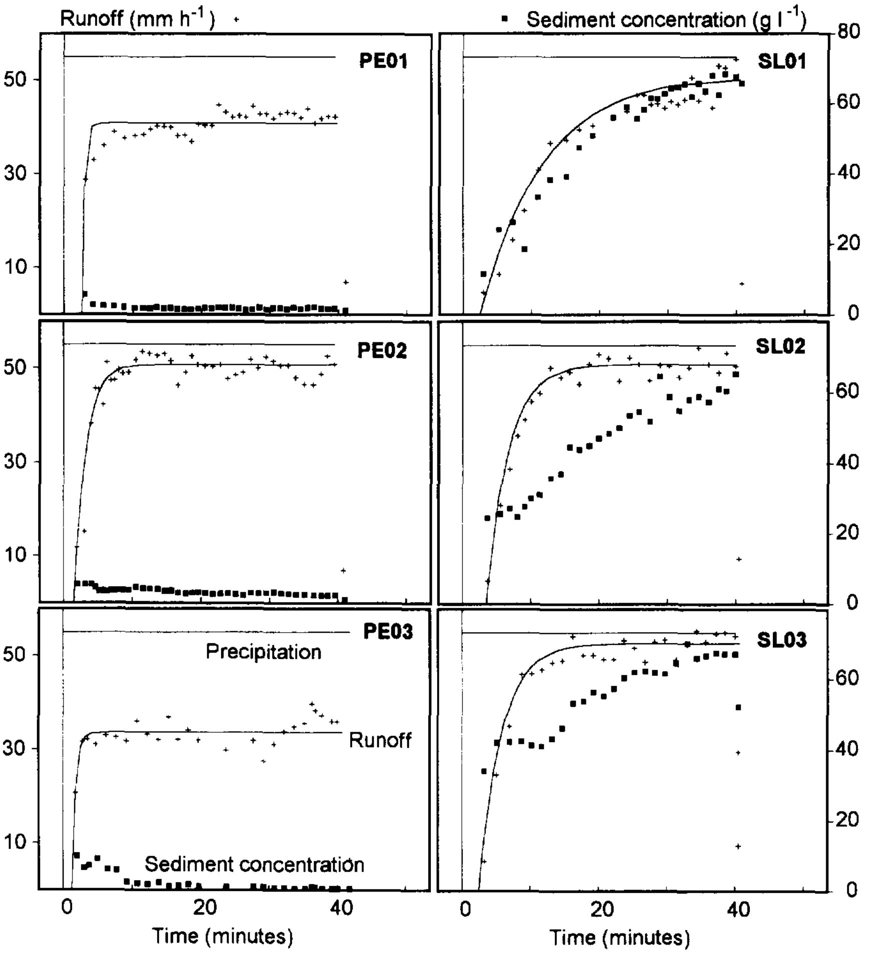


Fig. 9. Runoff hydrographs of the pediments (PE01, PE02 and PE03) and the slopes (SL01, SL02 and SL03) in Petrer.

Table 3
Soil losses. Sediment concentration and erosion rates

Plots	Sediment concentration (g l^{-1})	Erosion rates (g m^2 h^{-1})
Pediment		
1	1.64	59.17
2	2.93	130.02
3	2.12	61.93
Average	2.29	94.6
Slope		
1	54.16	1818.17
2	47.22	1925.75
3	69.51	3407.09
4	65.09	2255.82
5	64.50	1748.23
6	62.92	2876.33
7	50.79	1980.22
8	70.70	2974.35
9	65.64	2624.35
10	63.15	2761.76
11	64.53	2752.51
12	105.07	4514.13
13	102.52	4182.59
Average	60.61	2373.24

Table 4
Seed losses

Plots	Seed losses (%)
Pediment	
1	27.35
2	21.34
3	19.35
Average	22.68
Slope	
1	3.90
2	2.65
3	8.90
4	2.92
5	0.48
6	7.92
7	1.67
8	2.50
9	2.50
10	4.58
11	4.17
12	4.58
13	4.58
Average	3.95

Two species, *H. Stoechas* and *M. Arvensis* have the capability to secrete mucilage under moist conditions, allowing them to be actually glued onto the surface.

Very important are the temporal dynamics of the seed losses. Due to the process mentioned, the seed losses increase with time on the pediments because of the depth of ponding and runoff velocity. On the slopes, the seeds losses decrease with time due to the influence of the soil surface moisture and the strategies of the seed against erosion.

4. Discussion. The influence of slope angle

The influence of slope angle on the initiation of ponding and runoff is positive. The steeper the slope, the later the start of the ponding and runoff. This is true for both the badland slopes and the pediments (Figs. 10 and 11) and is likely to be due to the greater depths and higher numbers of cracks on the steeper slopes. This favours high infiltration rates at the beginning of the rain (Cerdà and García-Fayos, 1994/95). Moreover, the area of exposed surface increases with slope angle, and as a consequence infiltration can be high. Another explanation is that the high rate of erosion on steep slopes may induce the degradation of the surface crust and as a result may increase infiltration rates (Poesen, 1986).

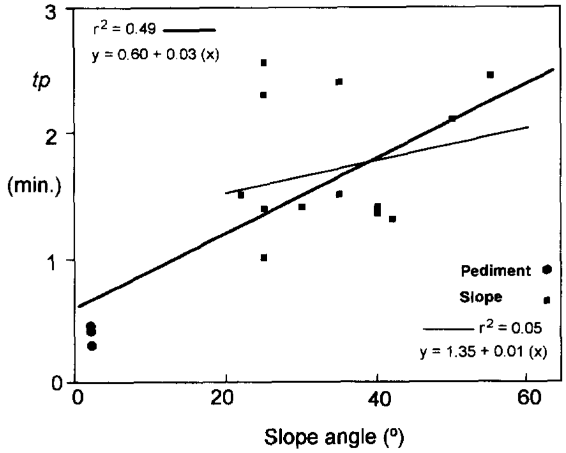


Fig. 10. Relationship between the slope angle (°) and the time to ponding (minutes) (t_p).

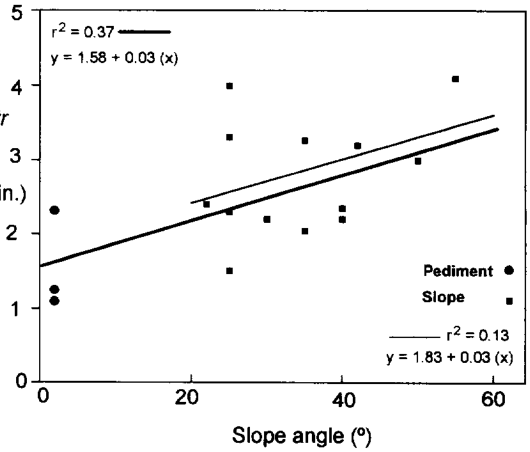


Fig. 11. Relationship between the slope angle (°) and the time to runoff (minutes) (t_r).

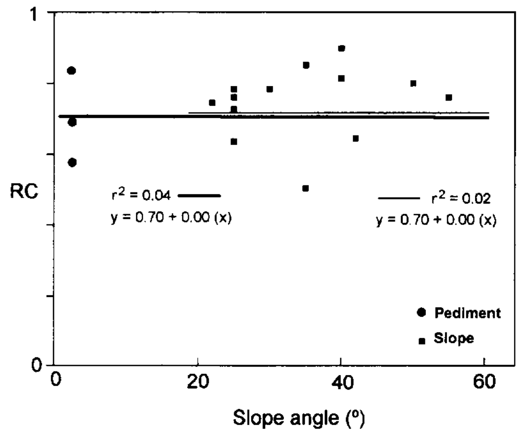


Fig. 13. Relationship between the slope angle (°) and the runoff coefficient (RC).

The steady-state infiltration rate (f_c) is higher on the pediments than on the slopes (Fig. 12). This is because the study was carried out on typical badland slopes on soils which have the lowest infiltration rates of any in the study area (Payà and Cerdà, 1992). Other soil morphologies on the slopes have very high infiltration rates due to the number of cracks and the swelling clays (Cerdà, 1995).

Although the steady-state infiltration rate is greater on pediments, the runoff coefficient is not affected by slope angle (Fig. 13). The explanation is related to the runoff hydrograph form, which is very steep and starts very quickly on the pediment. The runoff curve forms are delayed and smoother for the slopes, but the steady-state infiltration rate is lower than on the pediments. This implies that short duration thunderstorms would result in a quicker start of runoff on the pediments than on the slopes, but when the rain event is longer the overall runoff contribution of the slopes is higher. This is directly related to the soil texture, which is loamy in the slopes and sandy in the pediments.

Soil erodibility shows the positive influence of increasing slope angle. The pediments have lower sediment concentrations than the slopes, and on the slopes it is the steeper plots which generate overland flows with higher sediment concentrations (Fig. 14).

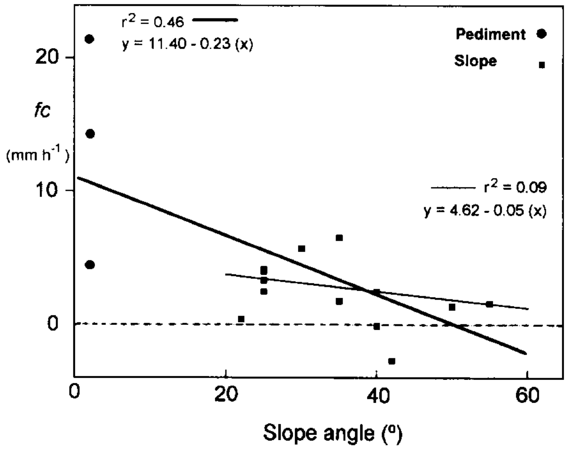


Fig. 12. Relationship between the slope angle (°) and the steady-state infiltration rate (mm h^{-1}) (f_c).

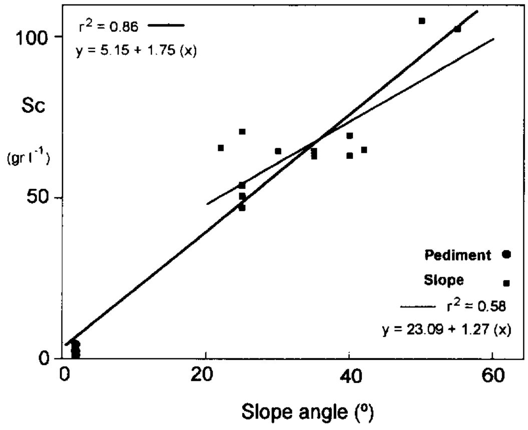


Fig. 14. Relationship between the slope angle (°) and the sediment concentration (g l^{-1}) (Sc).

Also, the erosion rates have a clear positive relationship with the slope angle (Fig. 15). The pediments are the most stable surfaces.

The most complicated dynamics have been found concerning the seed losses (Fig. 16). The pediments favour high seed losses and the slopes low seed losses. But within the slopes the influence of the slope angle appears to be positive, although the relationship is not statistically significant. If this is so, it may be due to the dynamics of the processes, which work mainly at the beginning of the rain storm, when splash on the dry surface erodes most of the seeds. Like sediment transport by splash, seed depletion increases with slope angle (Savat, 1981).

Other authors have found a positive relationship between slope angle and erosion and runoff rates from 0 to 12° and an inverse relationship on surfaces with slope angles higher than 12° (Abrahams and Parsons, 1991; Abrahams et al., 1991). This may be due to the influence of slope angle on soil texture, increasing the sand content with increasing slope angle (Luk et al., 1986; Abrahams et al., 1988). The badland system studied here has a different spatial distribution of processes, rates and soil types, than the landscapes mentioned above. In this area the relationship is negative. The soils on steeper slopes have lower steady-state infiltration rates and higher erosion rates. This is because we are dealing with an erosive system, in which the finer soil textures appear on the steeper slope from which the coarse sediments of the pediments are derived.

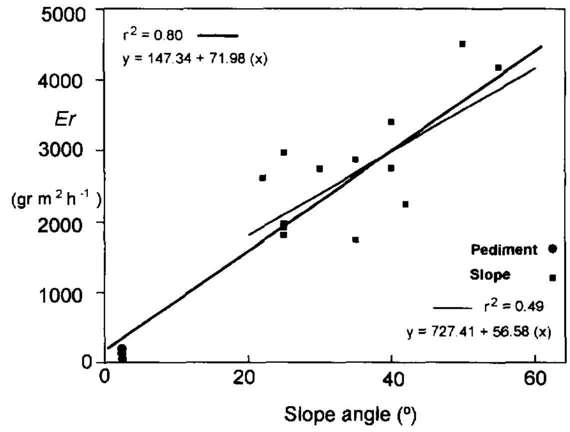


Fig. 15. Relationship between the slope angle (°) and the erosion rates (g m^2 h^{-1}) (Er).

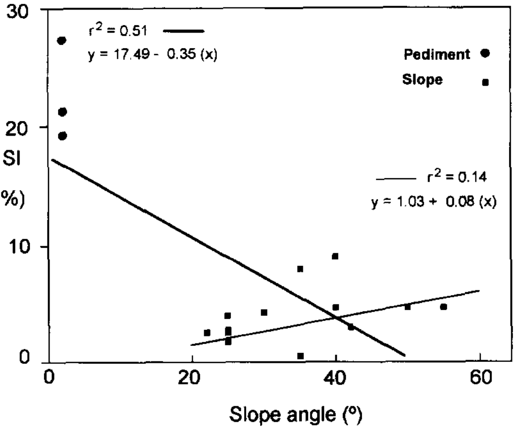


Fig. 16. Relationship between the slope angle (°) and the seed losses (%) (SI).

Moreover, laboratory experiments demonstrate that in non-vegetated and crusted soils higher slope angles imply higher erosion rates, and as a consequence the degradation of the crust and an increase in the infiltration rates (Poesen, 1984). In this study we have found the same results related to the erosion rates, but the increasing slope angle has not had any implication for runoff rates and a slightly negative effect on the steady-state infiltration rates.

The results demonstrate that the geomorphological dynamics of these badlands are dominated by overland flow as other authors have found in semi-arid environments (Scoging, 1982). The overland sheet flow measured here at a scale of half meter plots generates very high sediment concentrations and high erosion rates. The runoff volumes are also high: 75%, due to the low infiltration capacities and the fast initiation of runoff. But, the seed losses are very low due to the strategy of the seeds adopted against erosion processes by overland flow.

The rain duration and intensity could both have important effects on the hydrological processes. Other rain intensities and durations might result in different responses (Dunne et al., 1991).

Another geomorphological implication for badland dynamics in general is the behaviour of the badland slope as an erosive surface and the pediment as a transport surface (Hodges, 1982). Soil texture, slope, morphology, and hydrological and erosional response demonstrate the differences between slopes and pediments. This is likely to be due to the chemical control of the geomorphological processes in the badland areas (Imeson et al., 1982; Imeson and Verstraten, 1988; Gerits, 1991). In contrast with the pediment surfaces or with other soils types (Abrahams et al., 1988), the high erosion rates on the slopes are due to the increase in sediment concentration with time. This is because of the dispersion of clays which causes a higher stability of dry soil aggregates than in wet conditions (Cerdà, 1993b). Most of the sediments eroded on the badland slopes flow over the slope and over the pediment to reach the channels. Sedimentation on the pediment only concerns the bigger particles, the sands, which explains the higher sand content on the pediments.

The seed losses are very low on the slopes. This suggest that the absence of vegetation on the badland surfaces must be explained by the mortality of the seedlings or by non germination due to the moisture regime within the soil. In fact, overland flow does not remove the seeds entirely. The erosion of the seeds is more effective on the pediments, but still not enough to explain the low vegetation cover (Cerdà and García-Fayos, 1994/95).

5. Conclusions

The results show that the pediment surfaces produce ponding and runoff quicker than the slope surfaces, although in both cases the response to rain is very fast. Runoff volumes are very large due to the quick response, the steep runoff curves and the very low steady-state infiltration rates both on pediments and slopes. However, soil losses are lower on the pediments than on the slopes, where the sediment concentration is higher. With regard to the seed losses, they are negligible on the slopes, but high on the pediments. The absence of vegetation on these badland slopes is therefore not related to the erosion of seeds by the overland flow, and it must therefore related to the non-germination of seeds or the non-survival of seedlings. Slope angle has a positive effect on the soil erodibility and on erosion rates, but an inverse effect on the seed losses, and on the main hydrological parameters: time to ponding, time to runoff and steady-state infiltration rate.

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