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Influences of micro-relief patterns and plant cover on runoff related processes in badlands from Tabernas (SE Spain)

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Abstract

Soil surface morphology, soil thickness and their evolution strongly affect infiltration processes. Badland surfaces are characterised by a substantially low plant cover and a reduced soil development controlled by high erosion rates. In the badlands of Tabernas (Almería, SE Spain), the soil surface morphology exhibits a marked spatial variability, caused by different processes under moisture and temperature alternations in different slope aspects. Previous studies on the area have revealed the different hydrologic behaviour of North- and South-facing surfaces. In this paper, we go into more detail trying to establish the influences of both micro-relief patterns and plant cover on the hydrological behaviour of sixteen representative soil surfaces from the badlands of Tabernas. Rain simulations at a constant intensity of 55 mm/h have been carried out on 16 circular plots of 0.24 m^2, during 30 min, to evaluate runoff, infiltration, and sediment production parameters. Surface morphology has been evaluated by image analysis of photographs, before and after the simulations; the following parameters have been considered: plant cover and type, length and width of cracks, and stoniness. Surface roughness was determined with a laser profile meter. Runoff and erosion responses have been gathered in three and four groups, respectively, which are related to differences in slope gradient, soil depth and surface morphology. Runoff is positively correlated with slope gradient and negatively correlated with plant cover and total cover. Erosion is negatively correlated with lichen cover, with non-cryptogamic plant cover, with total cover and with surface area occupied by cracks. In some aspects, Tabernas badlands have an hydrological behaviour similar to other badlands described elsewhere (i.e., shallow moisture penetration, short

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times to runoff, different responses in runoff). However, they are particular in the following: (a) apparent morphological stability after rainfall events of high magnitude and intensity, along with high sediment production associated either from micro-rills that follow open cracks in the regolith, or from overland flow on bare, crusted, silty surfaces; (b) runoff enhancement by surface roughness through the channelling effect of the sealed depressions among pedestals and mounds of crustose lichens.

Keywords: Badland; Surface roughness; Runoff; Erosion; Plant cover

1. Introduction

Badland surfaces are characterised by a low or an absent plant cover and very little soil or regolith development controlled by high erosion rates. Under these conditions, geomorphic processes are highly dependent on rock properties and climatic characteristics (Bryan et al., 1978). When both rock and climate are homogeneous within a small area, processes become dependent on small differences in surface morphology (Bryan et al., 1978) and relative position within a catchment (Berndtsson and Larson, 1987), and specifically on either N or S orientations (Yair et al., 1980; Yair and Lavee, 1985) or simply time dependent (Schumm, 1964; Campbell, 1982; Calvo-Cases et al., 1990). As a consequence, significant differences in hydrological properties have been measured over distances of a few centimetres, indicating the extreme variability of surface conditions in badland areas (Bryan et al., 1978; Hodges and Bryan, 1982; Yair et al., 1980).

Römkens et al. (1990) summarise that different soil surface morphologies mostly arise during and after rain events as a consequence of different facts namely: (a) aggregate collapse due to rain drop impacts, (b) shear stresses induced by runoff, and (c) physico-chemical factors from the soil and its solution. In fact, on badland areas, these three factors can act in very different ways depending on the gross morphology (i.e., slope position) or on the weather alternation. The result is a wide set of different micro-relief patterns which are characteristic of each part of the slopes and valleys (Yair et al., 1980).

Tabernas badlands, in Almería province, is the most extensive badland area in southeastern Spain. Despite a generalised homogeneity when considered globally, a high variability appears when surface cover is analysed at the hectometre to decametre scale, variability which certainly affects the hydrological response.

Previous studies in the area have already revealed different hydrologic behaviour of surfaces from North- and South-facing slopes as well as some specific processes related with the influence of lichens in the hydrological and erosional response of badlands (Alexander and Calvo, 1990; Calvo-Cases et al., 1991a,b).

In this paper, we go into more detail trying to establish the influence of both major micro-relief patterns and soil thickness on runoff related processes occurring at hillslope scale within a few hectares catchment in Tabernas badlands.

Sixteen representative surface morphologies have been selected and the following surface properties, as variables under study, have been measured: surface area occupied by cracks, rock fragments, lichens, and plants; also the surface roughness under dry conditions (before rainfall). The relationships of that set of variables with infiltration and erosion, both parameters obtained by means of rain simulation, have been investigated. The results are interpreted considering soil and/or regolith thickness, and the erosional pattern shown by the overall badland area as well as those of other badland sites.

2. Materials and methods

2.1. Site characteristics

Tabernas badlands have developed on highly bioturbated and unclear stratified marls from the Chozas formation of Tortonian age, within the Sorbas–Tabernas basin (Figs. 1 and 2). The stratigraphic series giving rise to badlands are about 150 m thick and this favours the considerable extent of this landform (Kleverlaan, 1989). Badlands development is related to episodic tectonic uplift which has been active during the Quaternary, producing several stages in their development (Alexander et al., 1994) in a context of sequential dry climates (Rohdenburg and Sabelberg, 1973).

The climate of the area is thermo-mediterranean semiarid, with a mean annual precipitation of 218 mm (for a 25-yr recording period in the nearby Tabernas station) and a Pearson coefficient of monthly variation ranging from 76 to 215.

Annual precipitation ranges from 115 mm to 431 mm (Pearson coefficient of inter-annual variation = 37.4). The number of rainy days varies from 25 to 55 (with an average of 37 and a coefficient of variation of 23); only 6% of the rainfall events yield more than 20 mm and only 0.7% exceeded 50 mm/day. The maximum recorded rain intensity at the on-site meteorological station during the study period (1992–1993) was 85.2 mm/h during 5.7 min.

The mean annual temperature is 17.9°C in Tabernas, with an average minimum of 4.1°C in the coldest month and an average maximum of 34.7°C in the hottest month. Daily amplitudes average 13.7°C in summer in Tabernas. During the study period, on-site average daily amplitudes have ranged from 11.6°C in summer to 9.6°C in winter.

In general, valleys are dissected following either a N–S or an E–W direction. North and East slopes, in one hand, and South and West slopes, on the other, differ

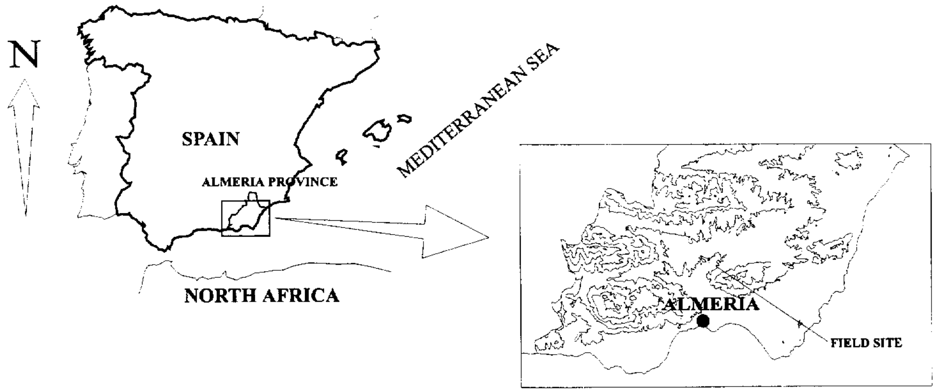

Fig. 1. Location of the Tabernas Desert.

Fig. 2. General view of the badland area.

considerably in gradient and plant cover due to differences in solar radiation, and thus in soil moisture, as described elsewhere (Churchill, 1982; Yair et al., 1980).

North- and East-facing slopes have gradients averaging 28° ± 8°, with a high cover of annuals, perennials and lichens. Rills are rare on these hillslopes. Mass movements are not frequent but when they occur, they can affect large soil volumes.

South- and West-facing slopes are much steeper (averaging 47° ± 9°), straighter in profile, and, in general, are uncovered or scarcely covered by annuals and/or lichens. Rills are quite frequent and develop almost from the top to the bottom of hillslopes. Very shallow mass movements have been frequently observed on such hillslopes following rainfall events larger than 50 mm.

At the foot of any hillslope, a pediment can form, more frequently and larger on North- and East-facing slopes; their gradient averages 10°. Rills and mass movements are absent from these morphological units. Some pipes developing at the contact between the hard mudrock and the upper-layered sediment can be observed.

2.2. *Mudrocks, regoliths, soils, and corresponding studied surfaces*

The parent material is a hard and compacted mudrock, petrographically identified as calcareous and composed dominantly by silt-size (> 60%) siliceous and calcareous particles. The coarse sand fraction is almost absent, the fine sand fraction ranges from 20 to 35%, and clay ranges from 5% to 10%. Bulk mineralogical composition is quartz, muscovite, paragonite, calcite (up to 30%), gypsum (up to 30% in some strata), and minor amounts of smectite (< 5% of the clay fraction). The only visible porosity is formed by very scarce fissures. Some joints of either stratigraphic or tectonic origin are filled with veins a few centimetres thick of crystalline calcite (esparite), which when exposed by erosion, break down in gravel-size fragments that partially cover pediments and channels.

The weathering of mudrock is presumably caused by the combined effects of wetting–drying and gypsum solubilisation–recrystallisation (Winkler and Singer, 1972), once the unloading of the consolidated sediment has originated the development of an extensive network of cracks (Taylor and Smith, 1986) which widen upwards, until the rock shatters into irregular pieces of a few centimetres in size. After extended wetting under saturation (as observed in ponds after rain showers) or seemingly after several wetting–drying cycles, these pieces of mudrock further disintegrate into smaller grains to finally give fine silt. In outcropping regoliths, these fine particles are usually found in cracks, among gravel size pieces of mudrock, and can be easily eroded and transported. When this fine material is deposited downslope, it can form either thin surface layers over steep slopes or thick pediments, which can reach almost two meters. Developed soils can be found only on pediments, and specially on dissected, old pediment surfaces, where reduced erosion has allowed further pedogenesis.

North- and East-facing slopes include three distinct morphological units: *pediments* at the footslope, *side slopes* in the central part and *crests* at the summit. Pediments are usually covered with annuals, perennials and cryptogamic crusts (studied cases TB03 and TB34). In both side slopes and crests, the vegetation is mostly formed by lichens, which may cover completely or partially the whole surface, giving rise to degraded areas in which thick and dense cryptogamic and physical crusts develop; lichenic masses usually have an average diameter about 30 mm, and are separated by smaller crusted depressions. In general, characteristic surfaces on North- and East-facing slopes are covered by: (a) a combination of annuals and perennials (TB09 and TB10), (b) a combination of annuals and lichens (TB11) (Fig. 3), (c) mostly lichens, and (d) a combination of degraded lichens and physical crusts (TB12 and TB13).

In general, South- and West-facing slopes, are steeper than the North- and East-facing ones, and are sometimes covered by a thin layer of fines along with a variety of surface features, giving the following main types of surfaces: (a) a combination of discontinuous lichens and physical crusts; lichenic masses are usually about 30 mm in diameter, and are separated by crusted depressions of also about 30 mm; (b) a combination of degraded lichens and physical crusts, with a similar pattern than above (TB04); (c) a

Fig. 3. Suface covered by lichens in a North-facing slope. (Diameter of the ring = 55 cm).

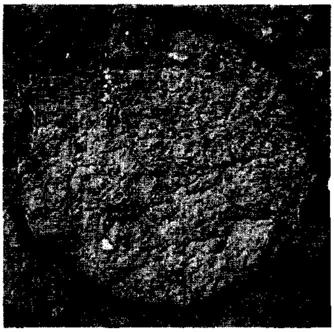

Fig. 4. Suface covered by silts in a South-facing slope. (Diameter of the ring = 55 cm).

combination of isolated hard rock fragments (from a few millimetres to a few centimetres), usually on the top of pedestals which are separated by crusted depressions (TB05); (d) bare regolith, commonly formed by a juxtaposition of mudrock fragments of gravel size (TB08) (Fig. 4); and (e) a continuous or cracked physical crust over a layer of fines (TB06 and TB07), usually thinner than 10 cm.

Pediments and side slopes, at any aspect, are formed by superposed very fine layers and/or lenses of different textural composition, always finer than very fine sandy loams. Only in pediments, thicker deposits (> 10 cm) of fines can be found. Sediment thickness, layering and the presence of vesicular pores formed during the crusting process due to the compacting effect of rainfall (Valentin and Bresson, 1992) is probably important to understand the hydrological behaviour of these geomorphologic surfaces.

Divides are either completely bare, with a continuous or cracked physical crust over a layer of fines, several centimetres thick (TB13 and TB15), or have a combination of cryptogamic crusts and annuals (TB01 and TB02) above a 10–15-cm thick layer of fines, most of which being formed in situ by weathering of the underlying mudrock.

Drainage channels have two distinct parts: (a) channel bottoms, in which the hard mudstone outcrops, as it has been scoured by runoff; when the slope gradient is small, some sediment load can be observed; and (b) channel sides, showing always the bare regolith, more or less shattered (TB08).

In Tables 1 and 2, the principal characteristics of the different studied surfaces are given. No characteristics are provided for the scoured channel bottoms; the imperviousness of the mudrock suggests runoff rates near 100%.

Despite the fact that in general badland surfaces vary enormously throughout the year (Yair et al., 1980; Campbell, 1982), the identified surface patterns in Tabernas badlands have varied relatively little within the 2-yr study period, in which only three rainfall events lasting 24 h or more, exceeded 50 mm, causing some minor sharpening of rills. The seasonal or after-rain-event changes mostly have affected the thickness of the surface layer of fines over the mudrock. Because of its implication for the hydrological and erosional model at the whole catchment level, it is important to mention that the

Table 1
Plant species and lichens in rain-simulation plots

Plots	Perennials and annuals	Lichens
TB34	*Stipa capensis, Linum strictum*	*Diploschistes diacapsus, Squamarina lentigera*
TB01	*Sideritis pusilla*	*Squamarina lentigera, Diploschistes diacapsis, Fulgensia fulgida, Buellia zohariy*
TB02	*Euzomodendron bourgaeamum*	*Squamarina lentigera, Diploschistes diacapsis, Fulgensia fulgida, Buellia zohariy*
TB03	*Helianthemum, Stipa cap.*	*Squamarina lentigera, Diploschistes diacapsis, Fulgensia fulgida, Buellia zohariy*
TB04	*Moricandia foetida*	*Squamarina lentigera, Toninia coeruleonigricans*
TB05	*Moricandia foetida*	No lichens
TB06	*Moricandia foetida*	No lichens
TB07	*Moricandia foetida*	No lichens
TB08	No plants	No lichens
TB09	*Artemisia barrelieri, Helianthemum almeriense, Anthyllis terniflora, Stipa capensis*	*Squamarina lentigera*
TB10	*Artemisia barrelieri, Helianthemum almeriense, Anthyllis terniflora, Stipa capensis, Linum strictum*	*Squamarina lentigera*
TB11	*Siderites pusilla, Euzomedendron bourgaeamum*	*Lepraria crassissima, Diploschistes diacapsis, Fulgensia fulgida, Teloschistes lacunosus*
TB12	*Moricandia foetida*	*Diploschistes diacapsis, Fulgensia fulgida, Squamarina lentigera*
TB13	*Moricandia foetida*	No lichens
TB14	No plants	No lichens
TB15	No plants	No lichens

aerial distribution of the different surface patterns has barely changed over the study period.

2.3. Soil surface morphological determinations

Before and after rainfall simulations, a colour photograph was taken of every plot (Figs. 3 and 4). Surface morphology has been characterised in every scanned photograph by digital image analysis using the 'MicroScale TC' system (by Digithurst, England), in which the blue band provided the best discrimination for the semiautomatic identification and measurement of the following features: plant and lichen cover and type, length and width of cracks and stoniness.

For the characterisation of micro-topography in every surface type, undisturbed samples (20 × 10 cm, 5 cm thick) were taken to the laboratory for surface roughness determination with a non-contact profile-meter. Detailed profiling was determined by means of a laser scanning method (the technique consists in the measurement of elevations) over twenty transects, following an orthogonal grid (ten transects in the direction of maximum slope gradient and ten in a normal direction). With the data

Table 2
Surface parameters from plots in wihich rainfall simulations were performed. Total cover refers to the sum of lichen + plant + stone cover

Plot	Aspect (°)	Slope (°)	Lichen cover (%)	Plant cover (%)	Stone cover (%)	Total cover (%)	Crack area (%)	Crusted surface (%)	Tortuosity index	Roughness index (cm)		Soil[a] thickness
										R_{30}	R_5	
TB34	120	14	10	5	10	25	0.2	74.8	0.31	1.84	0.57	70
TB01	260	5	12.5	1	5	18.5	1	80.5	0.28	2.33	0.59	15
TB02	290	10	11.5	10.5	1	23	0.5	76.5	n.a.	n.a.	n.a.	15
TB03	10	8	5	23	2	30	0.5	69.5	0.12	0.87	0.31	170
TB04	270	24	4	12	3	19	0.5	80.5	0.68	2.88	1.07	10
TB05	190	28	0	4	8	12	0.5	87.5	0.36	3.11	0.69	5
TB06	206	35	0	1.5	1	2.5	1.5	96	n.a.	n.a.	n.a.	7
TB07	160	38	0	0.5	3	3.5	2.5	94	0.1	1.31	0.22	10
TB08	230	40	0	0	1	1	4	95	0.81	2.68	1.23	< 5
TB09	10	15	5	85	1	91	0	9	n.a.	n.a.	n.a.	100
TB10	14	22	5	90	1	96	0	4	n.a.	n.a.	n.a.	80
TB11	346	32	15	27.5	1	43.5	0.5	56	0.28	2.36	0.58	35
TB12	350	40	0.5	2	1	3.5	2	94.5	n.a.	n.a.	n.a.	20
TB13	32	33	0	3.5	0.5	4	0.5	95.5	0.24	2.08	0.38	20
TB14	26	9	0	0	0	0	3.5	96.5	n.a.	n.a.	n.a.	7–10
TB15	32	12	0	0	0	0	3	97	0.05	0.4	0.21	7–10

[a] Soil or regolith.
n.a. = not available.

generated from every transect (coordinates x and y), several indexes were calculated: (a) the *tortuosity* index (Boiffin, 1984), as the rate between the contour length of the transect (measured as the sum of the minimum distances between two consecutive points) and the length of the chord transect; (b) a *roughness* index, in which the variance of the differences among elevations are calculated taking into account a running mean (Grant et al., 1990); in this study, two roughness indices were calculated based upon two running means: 5 mm and 30 mm. The roughness index using the first running mean, named R_5, was chosen to express short wavelength roughness, while the roughness index using the second running mean, named R_{30}, depicts a large wavelength roughness and was based on field observations: the depressions surrounding lichenic mounds average 30 mm in width, as well as those around pedestals; also pedestals and lichenic mounds average 30 mm in diameter; and (c) average semi-variograms of the elevation data from the different transects.

No micro-topographical measurements have been done after the rainfall simulations because surfaces have shown to be very little affected by 1-h rainfall at 55 mm/h.

2.4. Rainfall simulations

Rainfall simulations experiments were carried out over the 16 chosen surfaces using a sprinkler type rainfall simulator (Calvo et al., 1988; Cerdà Bolinches, 1993) to know their hydrological behaviour under extreme events.

Two consecutive runs of simulated rainfall were applied over circular plots 0.24 m^2 of surface at a constant intensity of 55 mm/h for 30 min; the first run on dry soil, the second one, on the previously rainfall simulated soil.

Time to ponding, time to crack closing and time to runoff were recorded from all runs. Runoff was measured at one minute intervals. Sediment concentration in runoff waters, comprising the first and the second 5-min interval and also between the 20th and the 25th minute, was determined in the laboratory. After the first 30 min and after 1-h rainfall, the infiltration front was also measured.

Runoff hydrographs have been fitted to the Horton (1933) infiltration model adapted to the characteristics of the simulated rainfall experiments according to Cerdà Bolinches (1993). The meaning of the parameters are as follows: P_o is the amount of rainfall necessary to initiate runoff, F_c is the constant infiltration rate in mm/h, and a is the parameter describing how steeply the curve reaches the basic infiltration.

2.5. Statistical treatments

Pearson correlation analysis (r), when possible, and Spearman rank correlation analysis (r_s) were carried out using the data from the 16 studied plots. In some cases, analysis of variance using a general linear model or the Kruskall–Wallis test, as a nonparametric ANOVA, was applied to determine the relationships between morphological parameters and hydrological variables.

3. Results

3.1. Surface morphology of plots

Slope aspect and gradient, percentage of surface cover occupied by lichens, annual and perennial plants, rock fragments, and cracks, as well as micro-topographical parameters (tortuosity, roughness indexes and semivariograms) of all the studied plots are found summarised in Table 2.

Not only lichens, pedestals and rock fragments are responsible for surface roughness. These may be considered as 'permanent' or 'quasi-permanent' structures. Stems, leaves and plant residues, as 'mobile' elements, also contribute to surface roughness and have a sure influence in the effects of rainfall (i.e., reduction of splash), but a smaller effect on runoff. Consequently, it was decided not to remove those 'mobile' elements before the micro-topographical measurements. However, we later found out that those elements bring a considerable noise in roughness values, hindering the interpretations in relationship with hydrological parameters (infiltration and runoff). The enormous variability found between micro-topographical data in a same surface might also be explained by this fact.

Here are the most significant relationships among some of the surface parameters.

(i) The area occupied by cracks is inversely related to total cover (sum of lichens, plants and rock fragments), $r_s = -0.91$, $s = 0.08$, indicating that bare crusted surfaces are those that mostly tend to crack.

(ii) Both tortuosity (t) and roughness (R_5 and R_{30}) extreme values come from completely bare marls over South and West exposures ($t_{TB08} = 0.81$, $R_{30_{TB08}} = 2.68$, corresponding to very rugose surfaces) and from crusted divides ($t_{\mathrm{TB15}} = 0.05$, $R_{30_{\mathrm{TB15}}} = 0.4$, corresponding to even, smooth surfaces). Surfaces covered with lichens present intermediate values.

(iii) No simple relations were found between surface roughness parameters and either surface cover or area occupied by cracks.

3.2. Water and sediment budgets

Except the results of the infiltration fronts, the two rainfall simulation runs have been considerably similar. Consequently, only the results of the first run, over dry soil, are presented (Table 3).

Time to runoff is less than 4 min in bare or crusted surfaces (either physical or cryptogamic) and from 5 to 21 min under vegetated surfaces.

Maximum infiltration fronts after 30 min of rainfall only reach 5 cm, being 2.5 cm the average; after 1 h of rainfall, the maximum is 5 cm and the average, 7 cm.

Most runoff hydrographs presented in Fig. 5 show a considerable fluctuation during rainfall simulations instead of the general equilibrium that is usually reached on a majority of situations. Despite the very small sprinkled area and the continuous applied rainfall, this behaviour might be caused by a combination of soil features: (a) surface roughness, (b) surface horizons layering, and (c) existence of siphon-type pores connecting different layers, as observed in thin sections (Solé-Benet et al., 1994, unpublished data).

Table 3
Hydrological and erosion parameters obtained from rainfall simulations

Plots	Time (in min) to			Runoff rate (mm/h)	Runoff coeff. total	Runoff coeff. final	Horton parameters			Erosion (g/m^2)	Infiltration front (cm)after	
	Ponding	Crack closing	Runoff				a	P_o (mm)	F_c (mm/h)		30 min	60 min
TB34	1.4	0	2	32.18	0.54	0.62	n.a.	n.a.	n.a.	28.32	n.a.	n.a.
TB01	6.3	16.4	9	6.31	0.12	0.23	0.29	8.19	44.71	5.58	n.a.	12
TB02	4	4.5	5.3	10.84	0.21	0.23	0.69	5.04	41.17	9.82	2–4	11
TB03	5.1	2	5.15	4.44	0.08	0.24	n.a.	n.a.	n.a.	4.65	2–5	5
TB04	2	7.2	2.3	39.42	0.76	0.92	0.53	2.29	9.76	49.41	1	4–6
TB05	2.1	3	3	37.76	0.73	0.96	0.27	2.81	7.13	122.27	1.5–2	6–8
TB06	2.3	6.4	2.2	22.76	0.44	0.5	1.58	2.12	29.71	36.13	3	6–8
TB07	2.2	3	2.45	25.59	0.5	0.71	0.52	2.44	25.29	567.51	2.5	6–7
TB08	2.3	3.5	3.05	35.77	0.72	1.04	0.77	2.82	13.78	439.21	2	5
TB09	9	0	9.2	4.38	0.09	0.21	0.21	7.21	47.7	5.6	3.5	10
TB10	15.3	0	21	0.87	0.02	0.1	n.a.	n.a.	n.a.	0.74	3	4–10
TB11	3.15	3.3	3.3	37.47	0.75	0.88	1.3	3.14	12.03	18.68	2–3	6–7
TB12	30	10.3	3.45	18.81	0.36	0.54	0.25	3.01	30.76	90.24	3	4–10
TB13	2.4	8	4.3	25.5	0.49	0.84	0.16	3.83	17.47	95.95	2	4–6
TB14	1.5	2.3	2.3	36.03	0.7	0.83	1.93	2.3	15.31	267.36	2.5	5–6
TB15	2.1	4.2	3.1	33.4	0.63	0.75	0.52	2.78	18.74	255.64	n.a.	3–4

n.a. = not available.

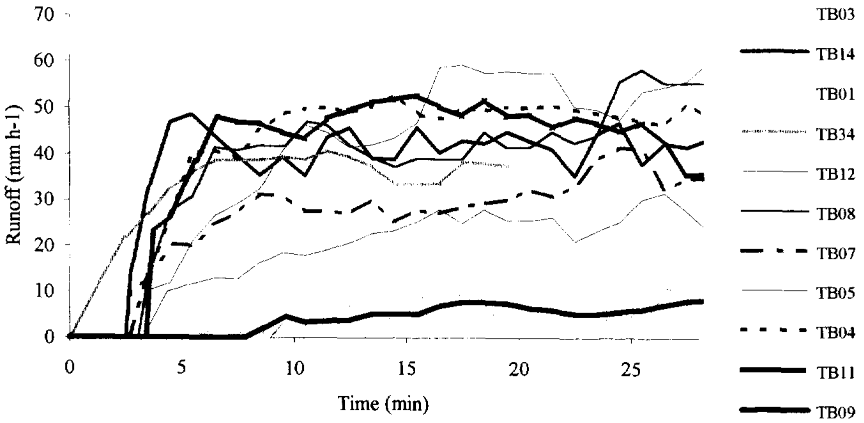

Fig. 5. Some runoff curves from rainfall simulations.

Three groups of curves can be observed as follows.

The first group of plots correspond to deep regolith areas near divides (TB01 and TB02) or on pediments (TB03, TB09 and TB010). In these sites runoff remains quite low (around 10 mm/h) during the whole rainfall simulation and the high infiltrability can be explained by the combination of three factors: deeper regolith or soil, low slope gradient and plots fully covered by non-cryptogamic plants or partially covered by lichens and annuals.

In the second (TB04, TB05, TB08, TB11, TB14, TB15 and TB34), runoff increases quite sharply and reaches high values (between 40 and 50 mm/h). All these plots, except TB34, have shallow regoliths or soils, with, in general, high gradient slopes, with the exception of TB14 and TB15. Most of these surfaces are either covered by stones and/or lichens or the regolith appears completely bare and crusted.

Finally, in some plots (TB06, TB07, TB12 and TB13), runoff increases not so sharply as in the previous category and reaches intermediate values (around 30 mm/h). They correspond to steep surfaces, covered with a few centimetres thick, layered silts, with a thin crusted surface which appeared quite cracked before the rain simulation. The effect of cracks enhancing infiltration may be counteracted by the crusted silts which enhance runoff.

Although the plot size is not much appropriate for soil erosion studies on these very erodible materials, a good relative erodibility scale can be obtained. Four well-differentiated groups can be inferred from the data set: (i) the 'high erosion' group (from 255 g/m^2 to 567 g/m^2), formed by TB07, TB08, TB14 and TB15, characterised by the presence of unconsolidated silts, as prepared sediment, either within the discontinuities among mudrock fragments constituting the highly rugose bare regoliths (TB08) or as smooth silty surface layers as in South- and West-facing slopes covered by silts (TB07) or in bare divides (TB14 and TB15); (ii) the 'low erosion' group (less than 10 g/m^2), formed by TB01, TB02, TB03, TB09 and TB10, all characterised by a low gradient. TB03, TB09 and TB10 have a considerable plant cover; TB01 and TB02 are covered by a combination of annuals and liquens; and (iii) two 'intermediate erosion' groups: the 'medium–high' one (from 90 g/m^2 to 122 g/m^2) formed by TB05, TB12 and TB13; and the 'medium–low' one (from 18 g/m^2 to 49 g/m^2) formed by TB04, TB11 and TB34.

Relationships between runoff and erosion are confusing, only the low erosion group fully coincides with the low runoff one. Actually, considering the overall data, erosion is only badly to moderately related with runoff: the Spearman rank correlations between erosion and runoff coefficients are 0.65 ($s = 0.07$) and 0.73 ($s = 0.03$) for the initial minutes and the last 25% of runoff, respectively.

3.3. Relationships between morphological and hydrological parameters

Surfaces have shown to be very little affected by the two runs of 30 min rainfall, 1 h in total, at 55 mm/h; it is suggested, consequently, that the hydrological characteristics of most surfaces vary quite little with most rainfall events. Therefore, it is thought that relationships between soil surface parameters and surface hydrological behaviour can be applied to a wide range of rainfall conditions.

Runoff is positively correlated to slope gradient ($r_s = 0.50$, $s = 0.04$). The fact that the correlation coefficient is not high may be attributed to the effects of surface roughness.

Lichens, plants, total cover (rock fragments + lichens + plants) and area occupied by cracks are related to rainfall responses as follows.

(i) Lichen cover is positively correlated to Horton P_0 ($r = 0.58$, $s = 0.04$) indicating that lichen cover favours initial infiltration, delaying the time to runoff, and is negatively correlated to erosion ($r_s = -0.8$, $s = 0.025$), indicating the protective effect of lichen cover to sediment delivery.

(ii) Non-cryptogamic plant cover has no significative linear correlation with erosion ($r_s = -0.77$, $s = 0.12$). However, an asymptotic relationship is found between these two parameters: erosion $= A \times 1/$plant cover $+ B(r^2 = 0.7$, $s = 0.001)$ in which $A =$ 226.26 and $B = -10.62$

(iii) Total cover is linearly correlated to runoff and asymptotically to erosion parameters ($r = 0.77$, $s = 0.000$ with time to runoff, $r = -0.60$, $s = 0.01$ with runoff coefficient, $r = 0.61$, $s = 0.03$ with P_0 and $r = -0.49$, $s = 0.05$ with erosion): erosion $= A \times 1/$total cover, where $A = 485$ Fig. 6).

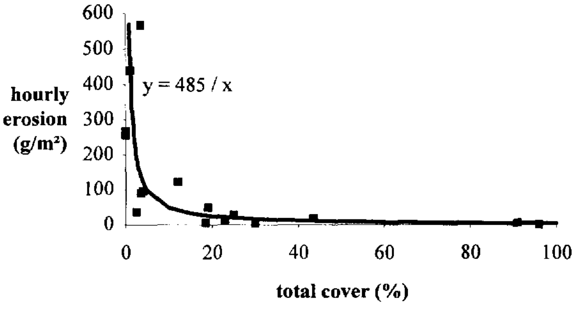

Fig. 6. Hourly erosion vs. total cover.

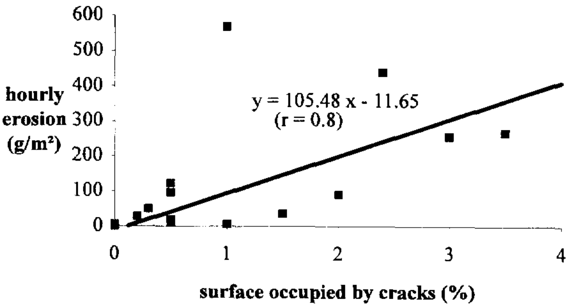

Fig. 7. Hourly erosion vs. surface occupied by cracks.

Surface area occupied by cracks is linearly related to the square root of sediment production ($r = 0.85$, $s = 0.0001$ for sediment yield; $r = 0.80$, $s = 0.0002$ for erosion) but not related to runoff.erosion $= A \times$ cracks $+ B$, in which $A = 105.4845$ and $B = -11.65$ (Fig. 7).

On the contrary, rock fragment cover, most often quite sparse, is not related to any hydrological parameter.

Surface area occupied by crusts are significantly related to hydrological parameters: to time to runoff ($r_s = -0.5$, $s = 0.0002$), runoff rate ($r_s = 0.41$, $s = 0.017$), runoff coefficient of last 25% runoff ($r_s = 0.46$, $s = 0.014$) and P_o ($r_s = -0.57$, $s = 0.03$).

Micro-topographical data (tortuosity and roughness indices) also control at some extend the rainfall response, as determined by ANOVA.

The tortuosity index, R_5 and R_{30}, both longitudinally and transversally, show an inverse relationship with the Horton F_c parameter: when the above parameters are low, F_c is high (the probabilities of error are 0.03, 0.02 and 0.04, respectively, for tortuosity, R_{30} and R_5).

All this indicates that a high surface roughness enhances runoff and so reduces final infiltration.

As no direct relationships were found between roughness indices and erosion parameters, the roughness indices have been arranged in three main categories in order to perform an analysis of variance: not significant ($P = 0.08$), erosion is enhanced when R_5 values are either low (square root of erosion = 12.86) or high (square root of erosion = 13.99), but is quite reduced (square root of erosion = 5.41) when R_5 values are intermediate.

4. Discussion and conclusions

As previously stated by other authors (Yair et al., 1980; Campbell, 1982; Calvo-Cases et al., 1991a,b), the results confirm again the complexity of the response of badland surfaces to rainfall.

The main interest of the present study has been to document the hydrological behaviour of representative surface types in the Badlands from Tabernas, under intense rain events. In some instances these surfaces are similar to those described in the litterature, but in others, they are unique.

Similarities refer to: (a) moisture penetration, always quite shallow (Bryan et al., 1978); (b) different responses in infiltration rates and sediment yield for a same type of rainfall event (Campbell, 1989); (c) behaviour in runoff and sediment production in bare regoliths as in 'popcorn' type surfaces, (Campbell, 1989; Imeson and Verstraten, 1988); and (d) short times to runoff (less than 4 min, 4-mm rainfall, in bare or crusted surfaces) (Campbell, 1989);

Uniqueness refers to: (a) the apparent morphological stability of all surfaces along with high erosion rates in some of them; after two rainfall runs of 30 min, the surfaces have been very little affected, with no apparent morphological changes as micro-slumps, micro-rills, etc.; however, considerable sediment delivery by overland flow has been measured over bare surfaces with physical crusts and over bare regolith; (b) the main source of sediments: on the bare regolith, prepared sediment mostly come from the open cracks and not from the surface; this explains why after 1 h of rainfall, morphology did not change while sediment yield was relatively high (up to 500 g/m^2); and (c) runoff enhancement by surface roughness, the contrary of what is usually documented: in our case, surface roughness is due to micro-relieves formed by crustose lichens and pedestals, surrounded by crusted, smooth surface, micro-depressions functioning as micro-channels that convey runoff water; within this category, bare regoliths behave similarly, with water flowing through a network of cracks among mudrock fragments; Imeson and Verstraten (1988) have described a similar hydrological behaviour in badlands from Granada (SE Spain) in which surface morphology differ from Tabernas and with macropores from a completely different origin (swelling–shrinking in theirs, while dissolution–crystallisation and detachment in ours).

However, not all the above-mentioned surface types enhancing runoff, contribute similarly to erosion: pedestals and rugose bare regolith contribute notably, whereas lichens contribute only moderately, which is an expected finding. Surfaces occupied by pedestals and rugose bare regoliths constitute one of the groups of high roughness giving high amounts of erosion, as shown in the ANOVA results. Low roughness surfaces, like those in the bare divides, which also contribute with high runoff, can also produce large amounts of erosion because of the surface layer of unconsolidated silts, which will be easily detached and consequently eroded.

Three types of response to rainfall have been found on infiltration and runoff in the badlands of Tabernas. (i) High infiltration–low runoff corresponds to relatively deep soils or regoliths, with a considerable mixed plant cover of either perennials and annuals or annuals and lichens. (ii) Low infiltration–high runoff corresponds to a range of soils and soil-surface conditions that have in common the following parameters: shallow soils or regoliths, surface covered either by stones and/or lichens. (iii) Intermediate infiltration or runoff, along with low values of parameter A, correspond exclusively to bare surfaces, from both North and South slopes, with a surface layer of fines; the low value of A means a progressive saturation of the surface layer, a pattern that is also satisfied for the high infiltration family.

From the four types of erosional responses, only the low erosion one coincides with the high infiltration group. From the other groups, only some cases (soil surfaces) belong to similar erosion and runoff groups. This indicates that in most cases erosion seems to be more dependent on sediment availability than on runoff parameters.

Sediment availability at this instance can only be attributed to weathering and/or previous sedimentation.

Some morphological parameters do not seem to respond to simulated rainfall: the expected relationships with slope gradient and antecedent soil moisture could not be fully proved. As already mentioned by Calvo-Cases et al. (1991a,b), the slope gradient effect on runoff and erosion is partially masked by the different surface morphologies.

If it has been possible to advance in our knowledge about some processes from Tabernas badlands, it is evident that much work is still to be done: first, to cover much ample rainfall conditions bearing to a deeper soil saturation in order, for instance, to model mass movements; second, it is not known if higher rainfall intensities than the one applied could eventually affect micro-topography as a consequence of splash (which role in the overall sediment production is not clear yet, though the splash process is inferred by the existence of pedestals); and finally, third, there is the problem to upscale the present results to a whole hillslope, to a micro-catchment and to the whole catchment.

However, without considering the unknown upscaling factor to full hillslopes and catchments, we might speculate about the main sediment sources for the Tabernas badlands: according to our study, most sediments come both from channel sides and from almost bare South- and West-oriented steep hillslopes. North- and East-oriented hillslopes, with lower gradients and much more plant and cryptogamic cover, contribute little to sediment yield.

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