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Hydrological and erosion response of a badlands system in semiarid SE Spain

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Abstract

A long term monitoring program is being conducted to study runoff and erosion processes in a semiarid badlands environment (Tabernas Desert, SE Spain). The first six years of data from an instrumented experimental area with nested microcatchments are presented. The overall area is composed of a complex mosaic of soil surfaces with contrast hydrological and erosion behaviour. At microcatchment scale, runoff and erosion are controlled by the types of soil surfaces: small bare microcatchments had the highest runoff coefficients and the highest erosion rates, while those completely covered by vegetation had the lowest. Rainfall intensity significantly affected water and sediment budgets. The effect of antecedent soil moisture could only be observed when soil was near saturation and a few millimetres of additional rainfall were sufficient to produce Horton-type runoff, but it was very difficult to separate this from the effect of surface crusts formed in the first minutes of rainfall. Most of the rainfall events were below the threshold for producing runoff although they were important for sediment preparation through weathering. Small magnitude, low-intensity rainfall events along with protective plant cover over half of the total surface, are the main factors explaining low overall erosion rates at microcatchment scale.

Keywords: Runoff; Erosion; Badlands; Rainfall intensity; Antecedent soil moisture; Semiarid

1. Introduction

Badlands are attractive to geomorphologists and surface hydrologists because their predominantly barren surfaces facilitate observation of a variety of erosion processes as well as surface and subsurface runoff. A large body of references reported by Bryan and Yair (1982), Campbell (1989), Howard (1994), Bryan (2000), amongst others, prove this. Moreover, the off-side effects of what occurs in the badlands could have an important environmental impact (Mathys et al., 1989; Torri and Bryan, 1997).

The Tabernas Desert Badlands in SE Spain, some of the most extensive badlands in Europe, may be considered a paradigmatic landscape in which, together with other badlands elsewhere, such as those of the Negev in Israel (Yair et al., 1980), Alberta in Canada (Campbell, 1989; Bryan et al., 1978), Basilicata and Tuscany in Italy (Alexander, 1982 and Torri et al., 1994, respectively), the Rif mountains in Morrocco (Imeson et al., 1982) and Western Colorado in USA (Schumm, 1964), the studies carried out have produced a wealth of geomorphological and hydrological data.

The Tabernas badlands were first studied by Harvey (1982) and since then, the work of other authors has provided considerable information, reviewed here, about this landscape (Harvey, 1987; Alexander and

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Calvo, 1990; Harvey and Calvo, 1991; Calvo et al., 1991a,b; Alexander et al., 1994; Lázaro and Puigdefábregas, 1994; Calvo and Harvey, 1996; Solé-Benet et al., 1997; Cantón, 1999; Nogueras et al., 2000; Lázaro et al., 2000; Cantón et al., 2001). A large part of the work published on Tabernas has concentrated on defining badlands development and process interaction based mostly on observation, though hydrological and erosion data have been obtained from rainfall simulation.

From the above-mentioned rainfall simulations, it would appear that the hydrological behaviour of the Tabernas badlands is similar to others (shallow moisture penetration, short time to runoff, variable runoff responses), although the importance of specific peculiarities which might apply elsewhere has also been shown: (a) runoff enhancement by surface roughness through the channelling effect of sealed depressions among pedestals and mounds of crustose lichens; (b) high-magnitude, high-intensity rainfall events which can produce a large amount of sediment from micro-rills following open cracks in the regolith, but apparently, without affecting overall morphology (Solé-Benet et al., 1997).

The variability in hydrological behaviour of the Tabernas soil surface has also been revealed by inter-storm weathering conditions, recently studied by some of the authors (Cantón, 1999; Cantón et al., 2001). Antecedent climatic conditions are recognised as important in erosion models (Carson and Kirkby, 1973; Regüés et al., 1995; Bryan, 1996). In Cantón et al. (2001), it was shown from an initially fresh mudstone that the amount of sediment exported per six-month periods was proportional to the number of rainfall events over 3 mm during those periods. The process originating this relationship was the repeated wetting–drying experienced by the fresh mudstone, which significantly increased its porosity and consequent weathering.

However, no data for long periods were available for runoff and erosion processes or hillslope and microcatchment rates in the Tabernas Desert framework. Data on present climatic conditions, as well as long monitoring studies are of great importance in two contexts: (a) possible climatic changes and (b) as most studies about this area are based on paleohydrological and geomorphological evidence, an approach based on the simultaneous monitoring of runoff, erosion, and weather would provide a more refined assessment of processes and rates, which might be used in similar environments elsewhere.

Although the mechanisms and generation of runoff and soil erosion have been widely studied in semi-arid areas in general, most field measurements and modelling efforts have hitherto concentrated on runoff and water erosion operating at the plot scale, despite their limitations for hydrologic predictions are well known. Some studies show how topographic features at a larger scale, e.g. catchment, do have significant influence on runoff generation and soil erosion (Yair and Lavee, 1985; Moore et al., 1988; Moore and Grayson, 1991; Connolly et al., 1997; Grayson and Moore, 2000) and some models are incorporating areal differentiation and routing of flows down through basins and channels. However, there is still a considerable lack of empirical work on the spatial distribution of runoff and its transfer downstream or at catchment scale, to improve and to validate these models. Moreover, there is a lack of long-term records, particularly for the Mediterranean where runoff and erosion processes are dominated by extreme events that are rare to occur during most research projects. Consequently, long-term monitoring and experimentation on runoff and soil erosion processes operating at a range of scales are required (Poesen and Hooke, 1997). Therefore, in order to determine the factors controlling runoff generation and sediment production at different spatial and time scales in gully landscapes a long term monitoring program under natural rainfall was conducted in the Tabernas Desert.

2. Site description

2.1. Geology

The Tabernas badlands are located in the province of Almería (SE Spain) in the Sorbas–Tabernas basin. This basin is partially surrounded by the Betic cordillera system and is located leeward of the Filabres, Nevada and Gádor ranges, all of which are over 2000 m above sea level. The stratigraphic series, the Tortonian-age Chozas formation that gave rise to the Tabernas badlands, is about 150 m thick and includes mudstone and some calcareous sandstone (Kleverlaan, 1989). Episodic tectonic uplift and sequential dry climates during the Quaternary led to development of a multi-age badlands landscape (Alexander et al., 1994).

The mudstone has been identified as calcareous and gypsiferous (Solé-Benet et al., 1997; Cantón et al., 2001) predominantly composed of 80% silt grains with the following mineralogical composition: muscovite 35%, paragonite 10%, minerals with a main peak at 1.4 nm (mainly chlorite and a small amount of smectite) 3%, quartz 9%, calcite 20–35%, dolomite 2–5% and gypsum 5–20%. According to these authors, mudstone weathering is caused by the combined effects of wetting–drying and gypsum solubilization–crystallisation, once the unloading of the consolidated sediment has initiated the development of an extensive network of cracks which widen upwards, until the rock shatters into irregular pieces of a few centimetres. After extended wetting under saturation or after several wetting–drying cycles, these pieces further disintegrate into smaller grains, finally producing a fine silt.

2.2. Climate

The climate is semiarid thermomediterranean (Lázaro and Rey, 1990) with an average annual temperature of 17.8°C and an average annual rainfall of 235 mm, as recorded over a period of 30 years (period 1967–1997) (Lázaro et al., 2001) in Tabernas, which is among the driest areas in Europe (Capel-Molina, 1986). Rainfall events are produced by rain-bearing fronts, associated with the Atlantic Ocean, coming from the west, principally in the cold season. The pronounced regional semiarid climate in the SE Iberian Peninsula is determined by its geographical location, in the rainfall shadow of the main Betic ranges and the proximity of northern Africa (Geiger, 1973). In the autumn, rainfall is associated with incoming fronts from the Mediterranean Sea, which sometimes results in storms and torrential rains. Precipitation over the Almería region is influenced both by the December North-Atlantic Oscillation and by the October Southern Oscillation (Rodriguez-Puebla et al., 1998). Most rainfall events are low magnitude (only 6% over 20 mm) and low intensity (only 0.7% exceed 50 mm d^{-1}) (Solé-Benet et al., 1997).

As stated by other authors, e.g. Carson and Kirkby (1972), climate plays a key role in the formation of a weathered mantle and on the transport-limited condition for overall erosion in arid and semi-arid environments.

2.3. Landscape

The landscape is dominated by dissected NW–SE valleys with a marked asymmetry between NE and SW slopes. Northeast slopes have gradients of up to 30° with vegetation. Near the top of these hillsides, soils are incipient (Eutric Leptosols) and covered with dense crusts of lichens and disperse annual and perennial plants. At the foot, pediments are topped by a denser annual and perennial plant cover and soils are more developed (Calcaric Regosols as found by Cantón, 1999). South-west slopes, on the other hand, are steeper (slope gradients up to 77°, average 40°), uncovered or scarcely covered by lichens or annual plants and with nearly no soil development (Lithic Leptosols).

Solé-Benet et al. (1997) have identified 15 types of soil surface that can be reduced to four based on the relative percentage of their surface, their differential hydrological behaviour, topographic characteristics and soil type. These four main surfaces are:

(a) *MAR*: bare marl regolith sometimes covered by a cracked physical crust over a silty layer (no thicker than 10 cm) or by a degraded lichen crust. *MAR* surfaces occur predominantly on southwest slopes with gradients from 20° to more than 70° (average 40°).
(b) *LIQ*: characterised by the presence of an almost continuous lichen crust along with a sparse cover of annual and perennial plants. This type is found mainly near the top of northeast slopes having gradients between 10 and 40° (average 27°).
(c) *STI*: vegetated surface soil dominated by a scattered cover of high perennial herbs and other perennial plants on the oldest steep slopes at the area's headwaters. This surface is associated with steep slope gradients between 30 and 40° (average 34°).
(d) *PER*: dwarf shrubs and annual plants forming

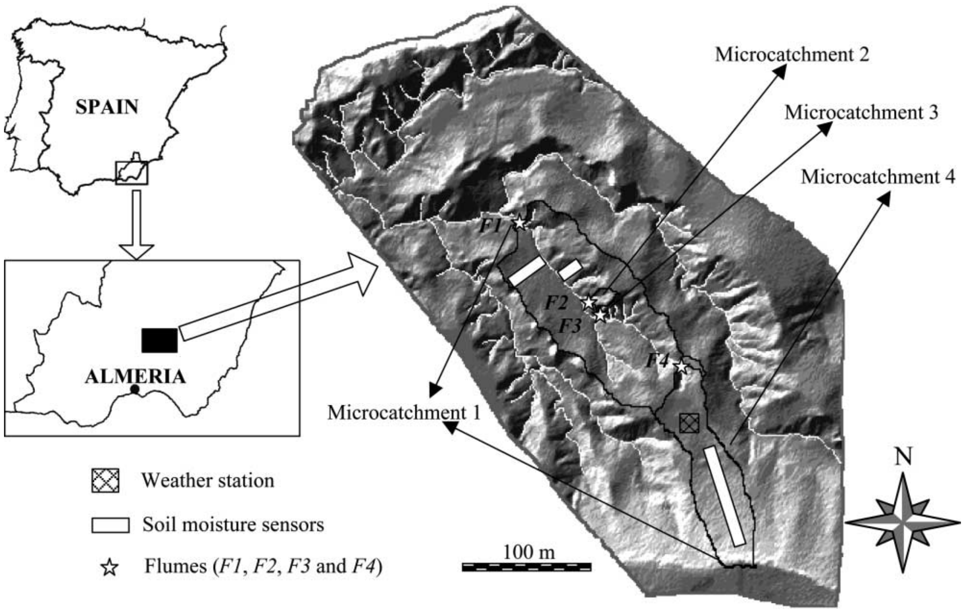

Fig. 1. The Cautivo field site (map compiled from a Digital Elevation Model at 1 m resolution), including the nested instrumented microcatchments, corresponding H-flumes (*F*1, *F*2, *F*3 and *F*4), location of soil moisture probes and weather station.

rather dense patches. This soil surface is usually found on pediments at the foot of north-east slopes with gradients of less than 30° (average 19°).

2.4. Microcatchments

The experimental work was conducted at the Cautivo field site, an area of about 13 ha, at an altitude of between 247.5 and 382.5 m (Fig. 1). A representative microcatchment, called 1, and three smaller nested microcatchments, called 2, 3 and 4, were selected (Table 1). Microcatchment 3 is a first-order gully and is completely devoid of plant cover. Microcatchment 2 is a second-order gully, with half of its surface made up of bare marl regolith outcrops, and over one third covered by thin, crusted silty deposits; the rest of its surface is occupied by patches of annual plants and lichen (Table 1). Microcatchment 4 at the top occupies nearly one third of Microcatchment 1 and is made up mainly of vegetated surfaces (97%). Microcatchment 1 is third order and comprises all of the above types of surfaces: 52% vegetated surfaces with medium to high infiltration capacity, 25.5% bare surfaces and 22.3% lichen crusts, both with a low infiltration capacity.

Table 1
Characteristics of the four microcatchments: surface area in m^2 and the area occupied by each type of surface in percentage. In *MAR*, two surface types can be distinguished: bare marl outcrops plus bare regolith and regolith covered by very thin crusted silt deposits.

Micro-catchment	Area	Relative percentage of area occupied by every surface type			
		MAR	*LIQ*	*STI*	*PER*
1	18796	Bare: 20.1, Covered by silty deposits: 5.4	22.3	17.7	34.5
2	255	Bare: 49.8, Covered by silty deposits: 29.3	4.5	0	16.4
3	62	Bare marl: 100	0	0	0
4	5775	Bare: 1.2, Covered by silty deposits: 1.9	13.4	57.3	26.2

3. Methods

A period of six hydrological years, from 1 October to 30 September, 1991–1992 to 1996–1997, was studied. The hydrological year taken for this study starts on 1 October, because it is assumed, according

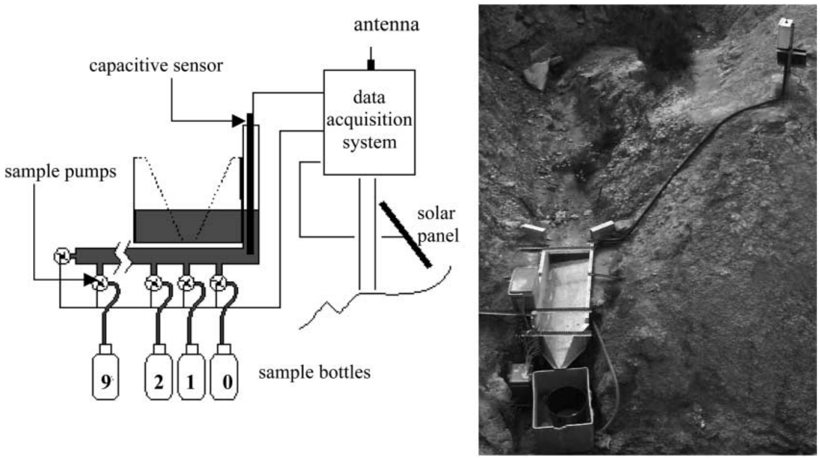

Fig. 2. H-flume gauging station in which a capacitive sensor records the height of water and an automatic pumping system samples runoff (with solutes and suspended sediment for further analysis). The data acquisition and transmission systems are also shown.

to the criteria applied by other authors (Piñol et al., 1991; Domingo et al., 1994), that soil moisture content is at the annual minimum at that time, after the summer drought.

3.1. Runoff and erosion rates

Soil surface responses were obtained from small runoff plots (0.24 m^2) monitored from May 1994 to June 1997. Total runoff and erosion were sampled after each rainfall event.

The microcatchment-scale response was obtained from four H-flume gauges (Brakensiek et al., 1979) installed at the outlet of each microcatchment and called $F1$, $F2$, $F3$ and $F4$, respectively (Fig. 1). The H-flumes are somewhat over-dimensioned for the estimated maximum flow rates with regard to the corresponding contributing areas. H-flume heights are: $F1 = 60$ cm, $F2$ and $F3 = 23$ cm and $F4 = 30$ cm. These were installed along with approach boxes depressed below the natural surface of the channel. Each gauging station is equipped both with a capacitive sensor which continuously records the depth of the water in the H-flume and a system of automatic pumps to sample water along with any suspended and dissolved sediments (Fig. 2). The measurement interval is 20 s. A microprocessor controls sampling times according to the height of the water in the H-flume. Because of a filter installed in the pump inlets to avoid obstruction by rock fragments, sampled sediments have a diameter of less than 1 mm. Particles over 1 mm diameter are obtained from sediment collectors, 300 L tanks, at the flume outlet.

The data acquisition system is a new low-speed digital network field facility consisting of several remote Motorola MC68Hco5/11 microprocessor stations and a central unit connected to a PC (Vidal et al., 1996b). All data generated by the weather station and the 4 H-flume gauging stations are centralised and transmitted in real time to the Institute headquarters in Almería (25 km from the field site).

Sediment concentration was determined in the laboratory from dry weight after filtration (Millipore 0.54 μm pore diameter), and weight averaged according to the runoff flow measured during the corresponding time intervals (Domingo et al., 1994).

Problems may arise when measuring runoff and discharge sediment samples with automatic gauging stations operating on badlands lithologies that can produce hyper-concentrated flows, as reported by other authors working in similar environments (Honsaker et al., 1984; Chodzko et al., 1991; Bryan and Campbell, 1986; Lecompte et al., 1996; Oostwoud Wijdenes and Ergenzinger, 1998). The main problem here was clogging of the capacitance sensor by excessive silting in both the approach box and the H-flume. Consequently, an incorrect signal produced an erroneous recession limb on the hydrograph after the real runoff event had ended. This could usually be

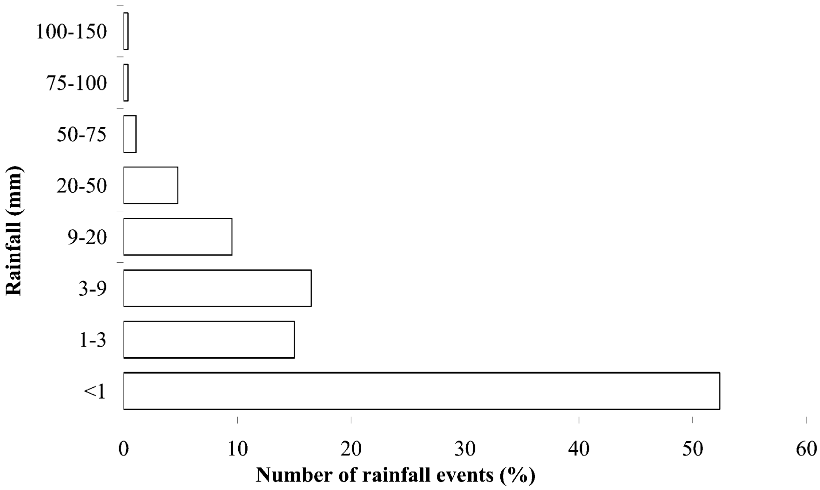

Fig. 3. Frequency distribution of rainfall events recorded throughout the six-hydrological-year study period.

solved with regression equations between time and runoff from the last rainfall peak to the start of the recession limb. When the H-flumes were installed in 1991, this affected *F*1, *F*2 and *F*3 and as an acceptable solution (Brakensiek et al., 1979) false floors were inserted in both approach boxes and H-flumes. However, the solution was not successful in *F*2 and *F*3, where silting still occurs during exceptional events. On some occasions, mud has also clogged the pumps impeding suction of samples. Another problem was loss of data due to failures in the data acquisition and transmission systems.

3.2. Rainfall volume and intensity

Rainfall volume was recorded by three gauges, two installed near the top and one at the bottom of Microcatchment 1. Intensity was measured by an automatic tipping-bucket gauge (0.24 mm resolution) connected to the general data acquisition and transmission system. The shortest time interval for which rainfall intensity was measured was 20 s.

3.3. Soil water content

To monitor soil water content (θ), a new low-cost dielectric-constant sensor based on the Self-Balanced Impedance Bridge (SBIB) technique developed at the EEZA (Patent No. 9401681; Vidal, 1994; Vidal et al., 1996a) was used. This device can measure both real and imaginary parts of soil dielectric permitivity separately, with two different analogue outputs, one for volumetric water content and the other for the bulk electrical conductivity, not used in this work. Sensor output also includes soil temperature for general-purpose measurements, and water dielectric-constant compensation. It has good tolerance to high-salinity soils. Several replicates of the same prototype have been in operation in semiarid soils in Almería for four years with good results (Domingo et al., 2001; Puigdefábregas et al., 1996, 1998, 1999; Vidal et al., 1996a).

Twenty-three SBIBsensors were installed in the four main types of soil surfaces at a depth of 0.03 m from July 1996 to December 1997. θ was also measured in *PER* soil surfaces at 0.15 m. For *PER* and *STI* surfaces, the probes were installed in open areas. Campbell CR10X data loggers were set to record soil moisture data every 15 min. Average soil moisture for the entire Microcatchment 1 was estimated from θ measured for each type of surface. Between May 1991 and August 1992, θ was measured by the gravimetric method and converted to volumetric values using the bulk density of each soil surface type.

4. Results

4.1. Rainfall characteristics

Annual average rainfall between 1991–1992 and

Table 2
Total runoff (mm yr^{-1}) and erosion (g m^{-2}) measured in micro-plots of the main soil surfaces, during three hydrological years. Figures in brackets in *MAR* surface correspond to rates when *MAR* surface is covered by silty deposits

Hydrological year	Rainfall (mm)	*PER*		*STI*		LIQ		MAR	
		Runoff (mm yr^{-1})	Erosion (g m^{-2})	Runoff (mm yr^{-1})	Erosion (g m^{-2})	Runoff (mm yr^{-1})	Erosion (g m^{-2})	Runoff (mm yr^{-1})	Erosion (g m^{-2})
1994/1995	151.00	7.66	2.57	10.75	8.64	28.19	16.99	23.79 (11.83)	164.81 (155.85)
1995/1996	197.50	17.75	3.57	23.48	15.35	23.19	31.46	39.81 (32.78)	627.76 (328.13)
1996/1997	230.50	8.48	2.00	20.06	1.51	35.01	15.85	37.44 (28.86)	131.50 (69.65)

1996–1997 was 250.7 mm with high inter-annual variability (CV = 39%). The rainiest year was 1991–1992 with 416.7 mm and the least rainy was 1994–1995 with 151 mm. The distribution of rainfall event magnitude is shown in Fig. 3: 52% of the events were 1 mm or less, 67 % were 3 mm or less, 84% 9 mm or less and only 2% exceeded 50 mm. The number of rainy days per year during the study period ranged between 32, in 1991–1992, and 69, in 1996–1997, indicating a quite high inter-annual variability in rain intensity.

Threshold rainfall required to produce runoff ranged between 3.5 and 14.2 mm, with a statistical mode of 9 mm. Although events under 9 mm are more frequent (84%), it was those over 9 mm (16%) during the period studied that provided the majority of rainfall depth, except during hydrological year 1995–1996. A large proportion of the annual volume (between 60% and 90%) was produced by large magnitude events. In general, only one or two significant events a year were over 20 mm. The heaviest rainfall intensity in five minutes (I_5) was 55.9 mm h^{-1} in 1991–1992, which was also the rainiest year and the one with the most intense events. Most events were low intensity: 70% had a maximum intensity, I_5, of less than 10 mm h^{-1}.

4.2. Micro-plot-scale runoff and erosion

Micro-plots with different soil surfaces monitored for three years showed contrasting hydrological and erosion responses (Table 2). Vegetated soil surfaces like *PER* yielded the lowest runoff and erosion. Both *MAR* and *LIQ* produced the highest runoff. *MAR*, bare marl regolith, also showed the highest total erosion, while *LIQ*, dominated by a nearly continuous lichen crust, yielded much less sediment. When the marl regolith in *MAR*, is covered by a silty layer 1–10 cm thick with a cracked physical crust or a degraded lichen crust, runoff and erosion are also high.

4.3. Factors controlling runoff at microcatchment scale

4.3.1. Type of surface

The differences in runoff response behaviour to the same rainfall event in the four microcatchments monitored were influenced by both scale and the proportions of soil surface types making up the microcatchments. Fig. 4 illustrates such differences during the rainfall event of 31 October 1993 when Microcatchments 2 and 3, composed mainly of *MAR* (Table 1), had the highest runoff coefficients.

Runoff coefficients for the recorded events during the entire period ranged from 10.7 to 73.2% in Microcatchment 3, which was completely devoid of vegetation, and in Microcatchment 2 (composed mainly of non-vegetated surfaces i.e. MAR bare or covered by silty deposits) from 4.4 to 61.2%. The soil surface composition of these two microcatchments explains such high runoff coefficients.

Microcatchment 4 is made up of vegetated *STI* and *PER* surfaces, characterised by high infiltration and weak erosion (Calvo et al., 1991a,b; Solé-Benet et al., 1997). Runoff coefficients were between 0.03 and 4.1%.

In Microcatchment 1 runoff rates ranged between 0.04 and 90.7 L s^{-1} and runoff coefficients between 0.01 and 15.2% (Table 3), due to its mosaic of soil

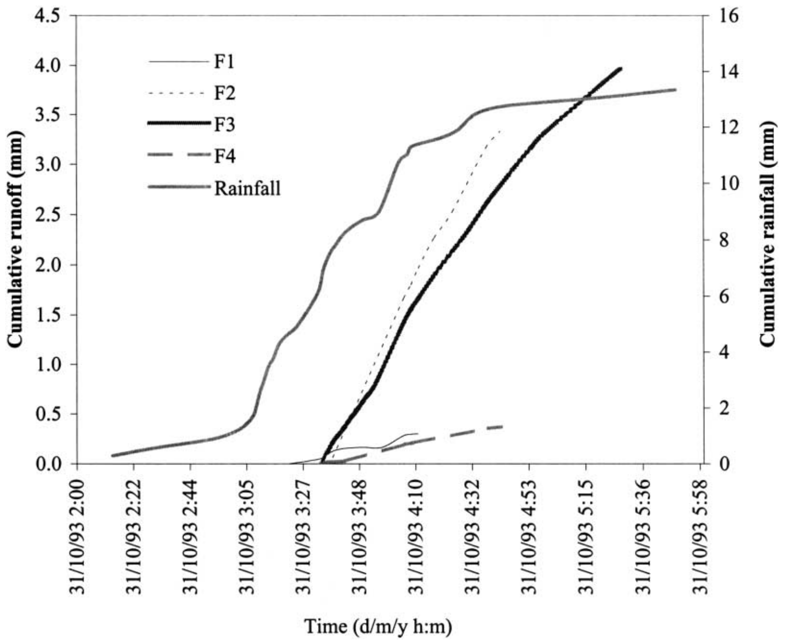

Fig. 4. Accumulated runoff and accumulated rainfall for Microcatchments 1, 2, 3 and 4 during the event recorded on 31 October 1993.

surfaces, in which non-vegetated surfaces and/or lichen crusts, both with high runoff coefficients, coexist with vegetated surfaces, with low runoff coefficients.

4.3.2. Rainfall intensity

Runoff was also controlled by rainfall intensity: a comparison of the hyetograph and stream-flow hydrograph for every runoff event shows a close relationship to rainfall intensity, as observed in the runoff event of 15 October 1994, at Microcatchment 1 (Fig. 5). In all the events in $F1$, there was a time lag between rainfall intensity and runoff flow which varied from 2 min and 50 s to 13 min and 45 s. Rainfall intensity peaks promoted runoff peaks proportional to the magnitude of the intensity (Fig. 6).

4.3.3. Total rainfall

Runoff increased with magnitude of rainfall, but at a different rate in each of the four microcatchments (Fig. 7). The largest increase was found for Microcatchment 3, followed by Microcatchments 2 and 1, with 4 being the lowest, following a gradient from bare soil surfaces to relatively dense plant cover.

4.3.4. Antecedent soil moisture

No relationship was found between runoff coefficient and antecedent soil moisture for the measured events (Fig. 8). However, the effect of θ on the hydrological response is better understood when the evolution of θ and runoff is analysed on a detailed time scale. Fig. 9 illustrates the behaviour of θ for different soil surfaces during the rainfall event of 31 May 1997. The soil moisture patterns of all runoff events from July 1996 to December 1997 were similar.

The total rainfall measured during this rainstorm was 15.9 mm, with a maximum intensity of $I_5 = 30$ mm h^{-1}. As observed in Fig. 9, before rainfall started, θ was less than 0.1 m^3 m^{-3}. Twelve minutes from the start, after 2 mm of rainfall, a small increase in θ was observed in open areas of *PER* at a depth of 0.03 m due to the high infiltration capacity of this soil surface. In the other soil surfaces the increase in θ was only detected at that depth when the rainfall exceeded 5 mm. At a depth of 0.15 m, θ remained constant. When the cumulative rainfall attained 7.3 mm, runoff began to be recorded, first by $F1$ and then by $F3$ and the increase in θ at 0.03 m doubled, while only a slight increase was

Table 3
Hydrological and erosion characteristics of Microcatchment 1: rainfall; maximum rainfall intensity of the event (I_5, in five minute intervals); total runoff; runoff coefficient; total erosion per event (Er < 1 mm) as suspended sediments <1 mm and solutes; total erosion of sediments per event >1 mm (Er>1 mm); total erosion (sediments larger than and smaller than 1 mm) (Total Er). n.a.: data not available

Events	Rainfall (mm)	I_5 max (mm h^{-1})	Runoff coefficient (%)	Er.(<1mm) (g m^{-2})	Er.(>1 mm) (g m^{-2})	Total Er. (g m^{-2})
28/01/92[a]	141.25	15.93	7.31	47.71	24.27	>71.98
19/02/92	52.27	55.90	6.90	n.a.	47.64	n.a.
31/03/92	14.24	16.85	0.17	0.00	0.00	0.00
03/05/92	31.92	8.33	1.48	40.54	1.60	42.14
07/05/92	10.90	n.a.	0.01	0.00	0.00	0.00
13/06/92	40.61	13.39	1.33	5.40	n.a.	n.a.
21/06/92	30.84	19.86	4.51	79.42	31.19	110.61
18/10/92	9.29	20.36	0.05	0.07	0.00	0.07
07/11/92	87.56	29.44	15.19	341.44	33.54	374.98
01/02/93	18.86	13.44	0.95	5.62	50.85	56.47
02/02/93	70.26	11.76	5.10	n.a.	20.34	n.a.
05/05/93	33.72	n.a.	n.a.	n.a.	n.a.	n.a.
31/10/93	13.94	17.37	2.16	13.76	2.39	16.16
06/01/94	11.02	9.04	0.21	0.22	0.00	0.22
16/02/94	65.57	10.05	3.55	70.16	4.73	74.90
28/02/94	18.85	14.80	0.85	1.77	7.91	9.68
15/10/94	21.87	51.31	9.57	0.08	85.00	85.08
04/11/94	22.63	23.75	5.10	53.74	3.79	57.53
28/02/95	24.95	13.37	1.09	6.10	11.12	17.23
01/03/95	16.55	20.37	n.a.	n.a.	n.a.	n.a.
17/01/96	11.90	16.76	0.11	0.21	0.06	0.28
23/01/96	15.67	12.79	2.66	5.39	11.26	16.65
01/02/96	20.60	14.12	5.01	8.01	11.88	19.89
09/04/96	9.01	35.02	4.07	43.23	21.04	64.27
06/05/96[a]	8.21	49.29	9.11	21.13	24.63	>45.76
11/09/96	32.13	17.09	n.a.	n.a.	37.10	n.a.
14/10/96	19.48	11.62	1.81	n.a.	2.19	n.a.
05/12/96	22.23	11.47	n.a.	n.a.	8.82	n.a.
29/12/96	8.99	14.62	0.63	1.30	0.95	2.26
02/01/97	21.47	9.65	n.a.	n.a.	2.21	n.a.
22/01/97	17.74	7.34	n.a.	n.a.	0.04	n.a.
31/05/97	18.50	30.03	11.50	88.74	6.91	95.66

[a] Event not fully recorded.

recorded at 0.15 m depth. At this point, runoff had not yet been recorded by *F*4 because Microcatchment 4 was made up of soil surfaces with high infiltration capacities and because of the spatial distribution of patches of different infiltration capacities with respect to the flume position. The *PER* surface with the highest infiltration capacity is located downstream of an *STI* surface with a lower infiltration capacity and will therefore infiltrate any possible runoff that could be generated in *STI*.

After the first runoff peak, runoff dropped to zero in Microcatchments 1 and 3. θ continued to rise quickly, except at *MAR*, until the first θ peak was reached (Fig. 9). After the first pause in the rainfall event, the soil started very slowly to dry out (no more than 0.02 m^3 m^{-3} in 3 h and 30 min) due both to slow evapotranspiration during the night and water redistribution within the soil profile.

Three-and-a-half hours later, the second phase of the event began and just 2 mm of rainfall were enough to produce runoff from Microcatchments 1 and 3 and Microcatchment 4 recorded runoff for the first time. In the second part, volume and intensity of rainfall was lower than in the first part, but θ at the soil surface was

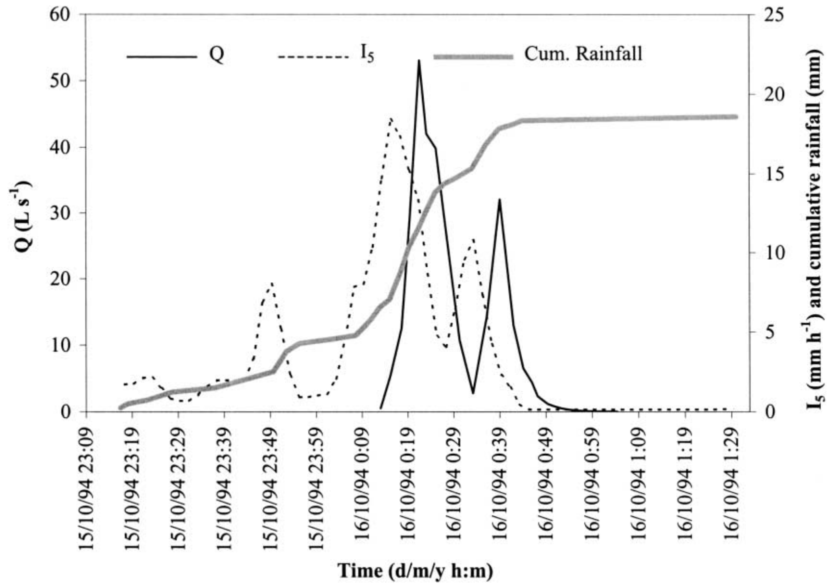

Fig. 5. Hydrograph, accumulated rainfall and rainfall intensity in 5 min (I_5) for the event recorded on 15 October 1994 in Microcatchment 1.

very high, close to saturation, and the surface crusts of bare surfaces were still sealed. A decrease in the infiltration rate because of both this sealing and the new soil moisture conditions, which also affect water infiltration (Bowyer-Bower, 1993), explain why a few millimetres of rainfall were enough to produce runoff again in all four microcatchments. Only 3.5 mm of rainfall were able to produce a new θ peak.

4.4. Microcatchment erosion

In zones where plant cover was scarce, such as in Microcatchments 2 and 3, sediment discharge can be very high. Sometimes during an event, highly charged (up to 0.4 kg L^{-1}) to hyper-concentrated (up to 0.8 kg L^{-1}) flows were recorded. The highest total sediment discharge per event was 2.89 kg m^{-2} in Microcatchment 3, and 0.31 kg m^{-2} in Microcatchment 2.

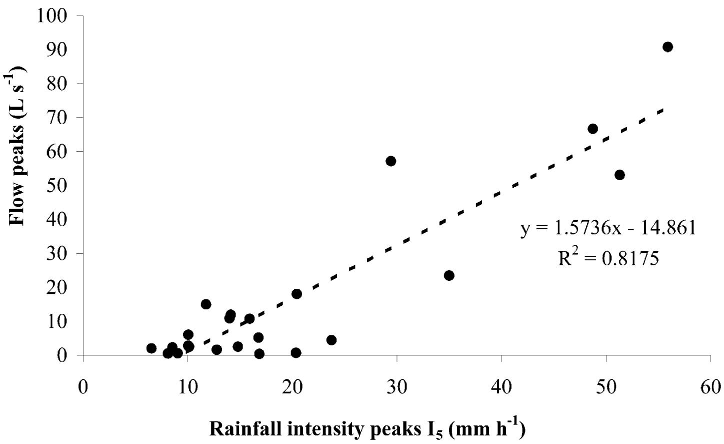

Fig. 6. Relationship between maximum runoff flow peaks per event and their corresponding rainfall intensity peaks (I_5) in Microcatchment 1.

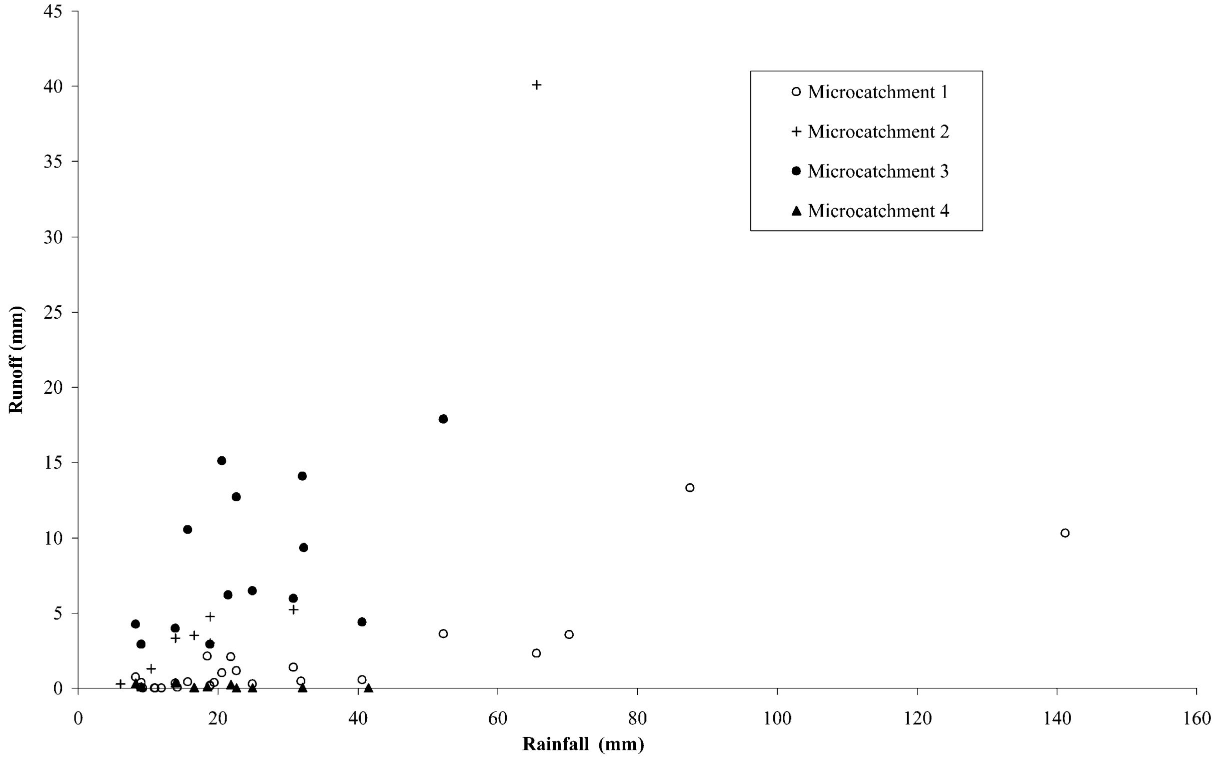

Fig. 7. Relationships between rainfall and total runoff for each microcatchment.

However, these maximums might be higher because many events could not be fully recorded when the approach boxes, H-flumes and outlet collector tanks became filled with debris.

When debris flow or other types of mass movement were sampled a few days after the event, mudstone fragments were found to constitute more than 50% of the collected sediment, with fragments of up to 10 cm in diameter. However, if the sediment is left (on the flume or on the channel) for longer periods, sequential wetting–drying progressively comminutes the large fragments, and only particles smaller than 2 mm are recorded, which further disintegrate into the mudstone primary particles and the resulting silts can be

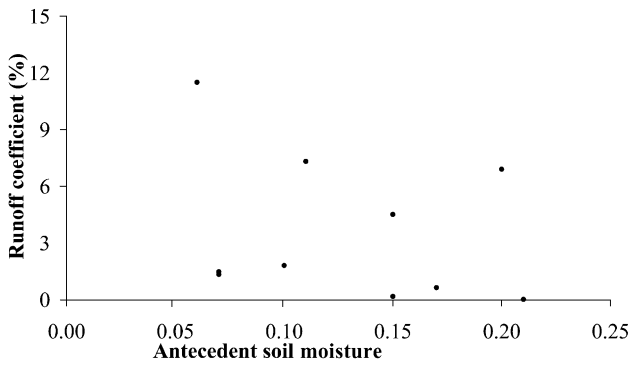

Fig. 8. Relationship between antecedent soil moisture and runoff for the available events in Microcatchment 1.

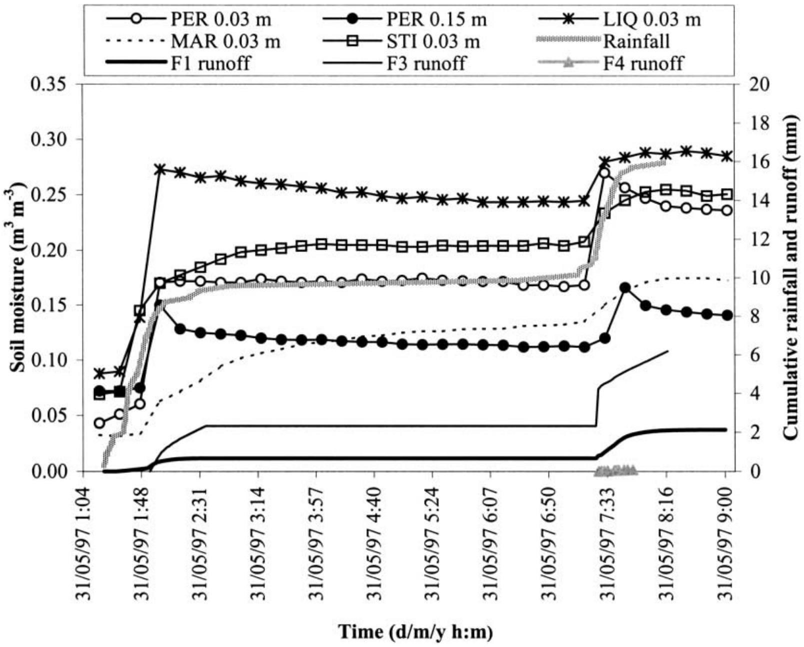

Fig. 9. Time evolution of accumulated rainfall, runoff and soil moisture (θ_v) in bare ground (open) areas at 0.03 m depth for *MAR*, *LIQ*, *STI* and *PER* soil surfaces. Soil moisture evolution is also shown in *PER* at 0.15 m depth.

exported easily by much lower energy flows. This occurs when detached masses are smaller than a few kilograms, but when the mass movement is considerable, i.e. several hundreds or thousands of kilograms, as observed once during the period of study, the total export of the detached mass is only effective after runoff events occurring at later dates. First or second order channels with high slope gradients are usually scoured, but those of higher order, with low slope gradients, are generally filled with several centimetres to decimetres of sediment.

Uncovered surfaces, such as *MAR*, are those which essentially contribute to the overall sediment yield. In zones mostly covered by annual and perennial plants, such as in Microcatchment 4, erosion rates were low, with a high of 60 g m $-$ ^{2} in a single event. In such areas, most sediment comes from scarce bare rills and gullies.

Table 3 shows the sediment discharge per event in Microcatchment 1, where erosion rates have attained 370 g m^{-2}. In 70% of all events, suspended solids were the main type of sediment, along with 5% of solutes. However in some events, like those from 1 February 1993 and 15 October 1994, the majority of the exported sediments were particles larger than 1 mm. In the first, the maximum rainfall intensity in five minutes (I_5) was 13.4 mm h^{-1} and in the second 51.3 mm h^{-1}. In these events, bed load was higher than suspended sediments. This fact is explained by the antecedent conditions of sediments in the main channel before the event. For the event of 1 February 1993, field notes described a high amount of coarse sediments in the main channel, prepared by a previous runoff event (7 November 1992; see Table 3). Moreover, between the period between 7 November 1992 and 1 February 1993, only one event of 5.9 mm occurred indicating a limited weathering of the coarse sediments because of the short number of wetting-dry cycles. Under these conditions, a low-intensity event was able to transport sediment from the channels, as demonstrated by the event of 1 February 1993, with an intensity of 13.4 mm h^{-1}. During the event of 15 October 1994, not only was this condition met, but rainfall intensity was very high during all the events (the maximum I_5 was 51.3 mm h^{-1} the second highest for the period).

Sediment concentration also varied with runoff flow, hence flow peaks coincide with the highest

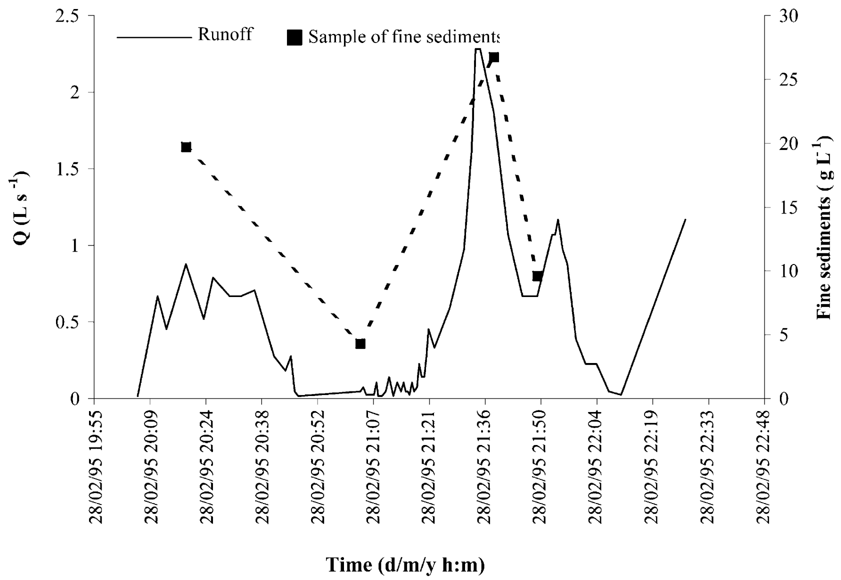

Fig. 10. Hydrograph and sedimentograph (only fine sediments of less than 1 mm) for the event of 28 February 1995 in Microcatchment 1.

sediment discharge peaks. Fig. 10 shows the hydrograph and the sedimentograph (only fine sediment of less than 1 mm) for the event of 28 February 1995 in Microcatchment 1.

The highest annual erosion rates correspond to the wettest years, 1991–1992 and 1992–1993 (Fig. 11).

Differences are observed when comparing the distribution of all erosion rates recorded per event in the four microcatchments (Fig. 12): Microcatchment 3, mostly formed by *MAR*, was the most susceptible to erosion and the median value for total erosion was 430 g m^{-2}, followed by Microcatchments 2 and 1 (190 g m^{-2} and 40 g m^{-2}, respectively); Microcatchment 4 was the least erodible with a median of 7 g m^{-2}.

To examine the spatial distribution of erosion, a comparison of erosion rates in the different microcatchments was done and two events are provided as examples. During the event of 31 October 1993 (see Table 3) it may be observed that total erosion rates for Microcatchment 1 were 16.2 g m^{-2} and for Microcatchments 2, 3 and 4 were 34.1, 43.0 and 7.9 g m^{-2}, respectively. Assuming that the bare surfaces in Microcatchment 1, which make up 25.5% of the total, respond in a manner similar to Microcatchment 3, the bare hillslopes would yield 206 kg. As Microcatchment 1 produced a total of 303.7 kg, the remaining sediments would then come from other surfaces (*LIQ*, *STI*, *PER*), which is quite in agreement with the total yield for Microcatchment 4 which was 45.6 kg. It can be inferred that all the eroded material for this event was exported out of Microcatchment 1. However this overall erosion pattern does not occur during all events: on 28 February 1995, when the erosion rate in Microcatchment 3 was 435.6 g m^{-2} and 2088 kg of sediments were estimated to be produced by bare soil surfaces, *F*1 nevertheless recorded only 324 kg, which leads us to presume that a large quantity of sediment was left in the channels. Non-exported sediment was thus available for a following event.

It is also important to point out that most sediment-generating surfaces (like *MAR*) are spatially distributed in such a way that they are almost always connected to channels, allowing the transfer of sediments from hillslopes to channels.

5. Discussion and conclusions

5.1. Runoff

Results from micro-plots during three years of monitoring under natural rainfall agree with previous

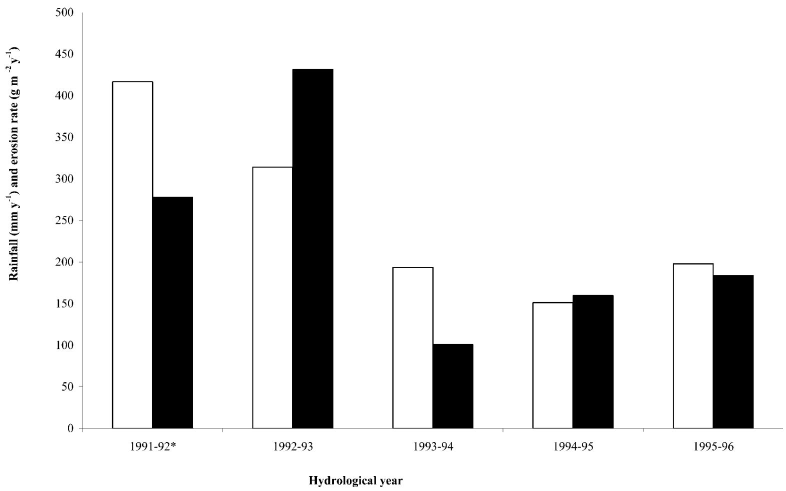

Fig. 11. Distribution of annual erosion rates (■) and rainfall volume (□) per hydrological year for Microcatchment 1. (*): annual erosion rate is underestimated for the hydrological year 1991–1992 due to the loss of data of suspended sediments in two events (13 November 1991 and 19 February 1992).

results from rainfall simulations in the same badlands area (Calvo et al., 1991a,b; Solé-Benet et al., 1997): the type of soil surface, defined in terms of plant cover and plant type, rock pavement, crust and seal development and cracks, constitutes the first control for runoff discharge. Regardless of the amount of rainfall or its intensity, some soil surfaces have a very high infiltration capacity, which produces almost no runoff, while others, crusted, produce fast runoff.

At microcatchment scale, results proved that rainfall characteristics affected runoff generation: peaks in rainfall intensity were followed by increase in runoff rates in Microcatchment 1 (Fig. 6). Although there is a clear relationship between rainfall intensity and runoff rates, some points diverge from the trend, as described in other arid areas: rainfall events in such areas are frequently composed of several short duration spurs of a few millimetres (Yair, 1990), and can produce quick but discontinuous runoff (Yair and Lavee, 1985). Another factor is the formation of crusts, which depends on rainfall characteristics, influencing the heterogeneity of runoff and erosion processes. As in most semiarid zones, the main mechanism of runoff generation in the Tabernas area is Horton overland flow (Dunne and Leopold, 1978; Yair and Lavee, 1985; Abrahams et al., 1989, 1991; Peugeot et al., 1997; Puigdefábregas et al., 1998;). The sharp, fast changes in runoff that follow variations in rainfall intensity prove this (Figs. 5 and 6).

The four microcatchments differ significantly in hydrological and erosion behaviour. These differences can be explained by two factors: (a) the occurrence of different soil surface types within the microcatchment and (b) the scale effect, i.e. decrease in runoff depth as scale increases. Overland flow is very spatially heterogeneous due to the variation in soil surface infiltration in these microcatchments. Other researchers have found similar results in other badlands (Bryan et al., 1978; Yair et al., 1980; Scoging, 1982; Hodges and Bryan, 1982; Campbell 1989, among others).

Lichen crusts (*LIQ* surface) which represent 22% of Microcatchment 1 have a substantial role. Results show that lichen crusts enhance runoff but at the same time, they reduce soil detachment. This increase in runoff could promote erosion downstream. However, field observations indicate that most of this surplus runoff is mostly infiltrated by *PER* surface, which is usually located downstream *LIQ*, thus reducing erosion risk. The same occurs with *STI* surfaces, also located upslope *PER*. In summary, the spatial distribution of the soil surfaces in microcatchments have an important role that should be evaluated in further work.

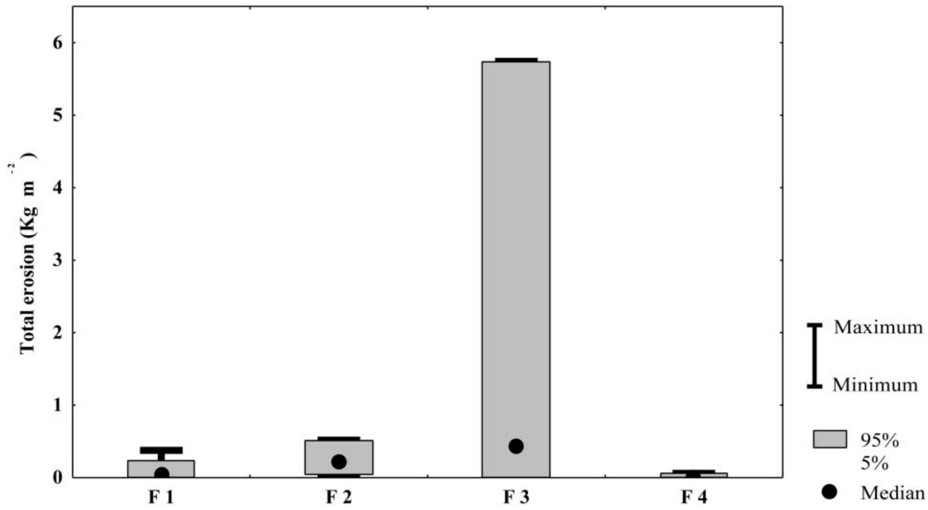

Fig. 12. Distribution of erosion rates per event for the four microcatchments during the six hydrological years.

5.2. Influence of antecedent soil moisture

By monitoring rainfall, runoff and soil moisture during a rainfall event, the mechanism of overland flow generation can be described. Overland flow starts just after rainfall intensity exceeds the infiltration capacity of the uppermost temporarily saturated soil layer. This occurs first in those soil surfaces, such as *MAR*, with infiltration rates below 10 mm h^{-1}, which also explains the reason why the increase in θ is slower at 0.03 m in such surfaces (*MAR*) than in the rest (Fig. 9).

The effect of soil moisture on runoff was only detected within multiple peaks rainfall events. A few millimetres of rainfall were enough to produce runoff once the soil surface has become almost saturated (Fig. 9). The role of θ in such cases is difficult to establish because: (a) antecedent soil moisture influences infiltration (Bowyer-Bower, 1993), sealing and hydrocompaction processes (Bryan, 2000) and (b) soil crusts (present after the first peak), formed by splash, decrease infiltration. Crusts are responsible for reducing the hydraulic conductivity of the surface layer, and consequently infiltration (Helalia, 1988; Morin et al., 1989; Römkens et al., 1990). Therefore, it is very difficult to determine the effect of θ distribution on infiltration when soil crusts are present.

5.3. Influence of antecedent weathering conditions

In the Tabernas Desert, few rainfall events (16%) exceed the threshold (9 mm) for runoff generation. However, the role of the remaining 84% is not negligible: sequential wetting–drying is essential to weathering of the main rock in the area, a gypsiferous mudstone, and provide easy-to-transport sediments (Cantón et al., 2001). As annual erosion rates in most years are slower than weathering, regolith accumulates. Cantón et al. (2001) have reported weathering rates ranging from 1.79 to 20.74 kg m^{-2} yr^{-1} at the same site. Hence, according to other authors (Campbell, 1989; Bull and Kirkby, 1997), the limitation of the erosion processes in this type of landscape is not the availability of weathered material, but the frequency and magnitude of the events able to transport this material. Cantón et al. (2001) showed that in a period of 45 months, the number of rainfall events of over 3 mm during 6-month intervals was proportional to the amount of weathered sediment during those periods. The sediment yield generated by both weathering (Cantón et al., 2001) and erosion between 1995 and 1997, as well as the total output at the end of the three-year period is presented in Table 4. The sediment produced by weathering per approximate 6-month sample is related to the number of rainfall events greater than 3 mm (Cantón et al., 2001). However, sediments produced by erosion in a *MAR*

Table 4
Weathering and erosion yields per approximately 6-month sampling interval, number of rainfall events higher than 3, 9 and 20 mm for each period. Erosion sediments correspond to the yielded in a micro-plot on *MAR* soil surface

Sampling dates	Sediment produced in weathering plots ($g\ m^{-2}$)	Sediment produced in erosion micro-plot ($g\ m^{-2}$)	Rainfall >3 mm	Rainfall >9 mm	Rainfall >20 mm
06/07/95	Start of the experiment				
17/01/95	2865	162.42	5	4	2
23/06/95	4574	73.83	5	2	1
19/01/96	12776	3.06	10	2	0
09/07/96	12748	516.12	11	5	2
15/01/97	7331	309.17	13	7	4
Total	40294	1064.60	44	20	9

micro-plot is related to the number of events over 9 mm. Specifically, during the third period recorded (sampling date: 19 January 1996, see Table 4), weathering was the most severe because of the large number of rainfall events over 3 mm, though there was the least erosion because only two events were over 9 mm and none greater than 20 mm.

5.4. Erosion

It was shown that those microcatchments composed of highly erodible soil surfaces, like *MAR* in Microcatchments 2 and 3, had the highest erosion rates. However, when the microcatchment is mainly formed by plant-covered surfaces, such as *STI* and *PER* in Microcatchment 4, erosion is reduced. Where the surface is made up of a combination of surface types, both plant-covered and bare, as in Microcatchment 1, overall erosion rates are relatively low.

Comparison of erosion rates from all microcatchments allows to notice different patterns of sediment export. In some events sediment delivery from Microcatchment 1 was lower than the estimated delivery from its nested microcatchments, indicating a temporary storage of sediments within the channels. Nevertheless, a different pattern can occur in other events when a much better scouring is produced in channels. This fact explains the variability of the relationship between runoff and erosion and why low energy events can produce higher than expected erosion rates.

Better understanding of the interaction between hydrological and erosive processes had to be complemented by in situ observations during rainfall events and with antecedent weathering conditions provided by the detailed meteorological record of the previous months or even years.

When the percentage of rainfall events that yield runoff are compared to the proportion of sediment moved for Microcatchment 1 (Fig. 13), the least frequent rainfall events are those over 40 mm, though those over 80 mm were the most efficient in exporting sediments. The most frequent runoff events correspond to rainfalls of between 10 and 20 mm (45%), but these only removed 19% of the sediments. During the period studied, only one event was able to remove 36% of all recorded sediments: the 87.6 mm rainfall of 7 November 1992, exported 375 $g\ m^{-2}$ of sediment. Another example of an extreme event occurred at the beginning of October, 1997, not included in this study, which consisted of several showers amounting to 130 mm (Lázaro et al., 2001), which produced erosion of over 80 mm, measured by erosion pins in rills. In this event, field observations revealed important changes in the landscape: deepening of the rill network, development of new rills even in the lower, flatter terraces and mass movements. However, extreme events (e.g. over 100 mm) are infrequent in this area (Esteban-Parra et al., 1998; Lázaro et al., 2001). The latter authors used the Gumbel asymptote (Faragó and Katz, 1990) to analyse return periods of extreme rainfall events over a 30-year rainfall series at the Tabernas weather station: they estimated that the return period for events of more than 50, 70 and 100 $mm\ d^{-1}$ are longer than 5, 11 and 30 years, respectively.

Consequently, events that may produce changes are

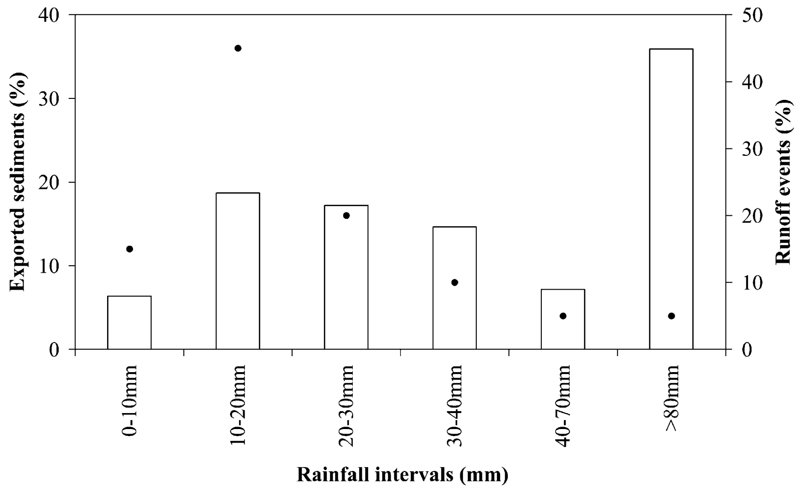

Fig. 13. Exported sediments (%) (columns) and runoff events (%) (●) for rainfall volume intervals for the whole studied period.

scarce and most erosion in the Tabernas badlands seems to advance in strokes: long periods, during which rainfall events do not produce significant changes, although the material is being prepared and partially transported, are cut by high magnitude events producing changes and exporting the material out of the system.

In sum, erosion processes in this landscape were limited by both vegetated soil surfaces with very low erosion rates constituting half the area studied, and the scarcity of rainfall events with enough energy for runoff generation and sediment transport. Although more than 2800 g m^{-2} were measured at elementary gully scale, erosion rates at microcatchment scale (about 2 ha) ranged between 100 (0.08 mm yr^{-1}) and 430 g m^{-2} (0.35 mm yr^{-1}). These rates are close to those found for other Mediterranean badlands like those in the Zin valley in Israel where erosion rates ranged between 0.48 mm yr^{-1} on small plots (1.5 m^2) and 0.17 mm yr^{-1} on 30 m^2 plots (Yair et al., 1980). Archaeological evidence from the Guadix badlands (province of Granada, SE Spain), where a gully landscape has survived 4000 years of denudation, confirms the stability of apparently highly active badlands (Wise et al., 1982).

Although badlands are assumed to be dynamic with high rates of erosion, this is not always the case, at least in semi-arid environments, and models must take this into account. From these results, it may be stated that badlands in semiarid environments erode slowly. However, it is not possible to generalise to other semi-arid Mediterranean locations, as shown in Alexander (1982), Clarke and Rendell (2000) and even less to sub-humid areas such as Torri and Bryan (1997). On the other hand in SE Spain, erosion rates in badlands areas are still much higher than surrounding areas with other lithologies, and as sources of both runoff and sediments may have important off-side effects, such as water pollution, clogging of channel beds by sediments reducing aquifer recharge, etc. especially downstream. The Rambla Honda field site, belonging to the same Sorbas–Tabernas basin, but on a mica schist substrate, has provided considerably lower runoff and erosion rates (Puigdefábregas et al., 1996, 1999), and minor off-side effects. Although these badlands erode at a slow pace, a change in the climatic conditions, such as a change in rainfall distribution and probably, an increase in rainfall intensity, could have important consequences for the erosion of this system due to a drastic reduction or even destruction of the perennial plant cover apart from the erosion induced by the greater intensity of the rainfall.

This study has also helped to establish the main sources of runoff and sediments. In this area, most of the runoff is generated on bare and lichen-covered soil surfaces, which are those with the highest runoff coefficients. And most of the sediments also come from bare soil surfaces. However, further work is necessary to model the specific contribution of every type of soil surface to the total runoff and erosion of an entire microcatchment and the effect of their spatial distribution.

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