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Differential responses of hillslope and channel elements to rainfall events in a semi-arid area

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Abstract

The degree of hydrological connectivity of hillslope elements in a semi-arid climate was studied at the season and event timescales. Field data were obtained in Rambla Honda, a Medalus project field site situated in SE Spain, on micaschist bedrock and with 300 mm annual rainfall. The season timescale was assessed using correlation analysis between soil moisture and topographic indices. The event timescale was studied by a quasi-continuous monitoring of rainfall, soil moisture, runoff and piezometric levels. Results show that widespread transfers of water along the hillslope are unusual because potential conditions for producing overland flow or throughflow are spatially discontinuous and extremely short-lived. During extreme events, runoff coefficients may be locally high (ca. 40% on slope lengths of 10 m), but decrease dramatically at the hillslope scale (< 10% on slope lengths of 50 m). Two mechanisms of overland flow generation have been identified: infiltration excess, and local subsurface saturation from upper layers. The former occurs during the initial stages of the event while the latter, which is quantitatively more important, takes place later and requires a certain time structure of rainfall intensities that allow saturation of the topsoil and the subsequent production of runoff. Hillslopes and alluvial fans function as runoff sources and sinks respectively. Permanent aquifers are lacking in Rambla Honda. Variable proportions of hillslope areas may contribute to flash floods in the main channel, but their contribution to the formation of saturated layers within the sediment fill is very limited.

Keywords: rainfall; semi-arid; season timescale; event timescale

1. Introduction

In humid temperate climates, where rainfall exceeds evapotranspiration during much of the year, a range of processes ensures that entire hillslopes remain hydrologically connected. Infiltration excess and saturation overland flow, saturated and unsaturated subsurface flow, return flow and groundwater flow, all help to convey water downhill (Whipkey and Kirkby, 1979). This hydrologic connectivity is

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made evident through the spatial distribution of soil water along the hillslopes. As these flows are largely driven by gravity, topography is an important constraint in the location of surface saturation zones and, in general, the spatial distribution of soil water. The likelihood of soils becoming saturated increases at the base of slopes and in depressions or swales, where both surface and subsurface flow converge (Kirkby and Chorley, 1967; Moore and Burch, 1986).

In contrast, hillslopes in semi-arid climates show poor hydrologic connectivity. Spatial patterns of soil water are less predictable, soil water content does not always increase towards the base of the slope and pockets of moist soil may remain isolated in uphill positions. In such climatic conditions, evapotranspiration equals or exceeds rainfall during large parts of the year, leaving very little, if any, water for drainage downhill. Rainfall events are few, short-lived and unreliable. Therefore, saturated subsurface layers are rarely formed and water transfer occurs mainly through overland flow or unsaturated subsurface flow. The importance of the latter, confirmed to occur under semi-arid conditions (McCord and Stephens, 1987), is probably much smaller than that of the former. Firstly, this is because gravity-driven unsaturated subsurface flow requires water contents to exceed field capacity, which occurs rarely, and secondly, because unsaturated flow velocities are about three orders of magnitude lower than those of overland flow (Kirkby and Chorley, 1967).

These features of semi-arid hillslopes imply that their hydrological behaviour is largely unpredictable. Application of physically or topography-based hydrological models does not seem appropriate because the steady state conditions of subsurface flow on which they are generally based rarely occur (Beven and Kirkby, 1979; O'Loughlin, 1986; Barling et al., 1994).

The objective of this paper is to provide field information on how and when hydrologic connectivity is built up in semi-arid hillslopes. Two complementary approaches have been followed. On the one hand, the extent to which soil moisture content correlates with topographic attributes, that quantify the local potential for drainage or flow accumulation, are examined at the seasonal time scale. On the other hand, soil moisture dynamics and its relation to overland flow at the plot and first order catchment level have been analysed at a quasi-continuous time scale, during a selected rainfall event.

2. Field site and methods

2.1. Geographical setting

Fieldwork was conducted at the Rambla Honda field site, which is operated within the framework of the *Medalus* project (Brandt and Thornes, 1996). Research at the site focuses on soil-plant interaction in semi-arid environments (Puigdefabregas et al., 1996). The field site is located on the southern slopes of the Filabres Range, in the eastern part of the Betic Cordillera (UTM 30S-WG-5509). The climate is semi-arid, with a mean annual temperature of 16°C and a mean annual rainfall of 300 mm which falls mainly in the winter season. A hillslope sector of 18 ha with a median slope angle of 22° was selected, stretching from the ephemeral river bed, at 630 m altitude to the water divide at 800 m. The area is characterised by a catena of soils and vegetation types. In the upper hillslope Typic Torriorthent soils and *Stipa tenacissima* tussocks occur on micaschist bedrock, while Typic Torrifluvent soils with *Anthyllis cytisoides* shrubs and *Retama sphaerocarpa* bushes are dominant, respectively, in the upper and lower parts of the alluvial fan sectors. In the upper hillslopes, *S. tenacissima* used to be harvested for cellulose, while the footslope sedimentary fill was cultivated with rainfed graincrops. Both types of land use were abandoned about 35 years ago.

2.2. Field measurements and methods

2.2.1. Runoff and soil moisture

In each of the three sectors of the catena, three measurement areas (MA) were established as part of the Medalus experimental field layout (Fig. 1). Each MA was equipped with a pair of runoff plots (2 m × 10 m), where the total volume of overland flow is determined after each rainfall event. A strict soil moisture sampling protocol is being conducted in the area. After each rainfall event, soil samples are taken for gravimetric moisture estimation. In each MA, a set of eight samples is taken, four from the surface

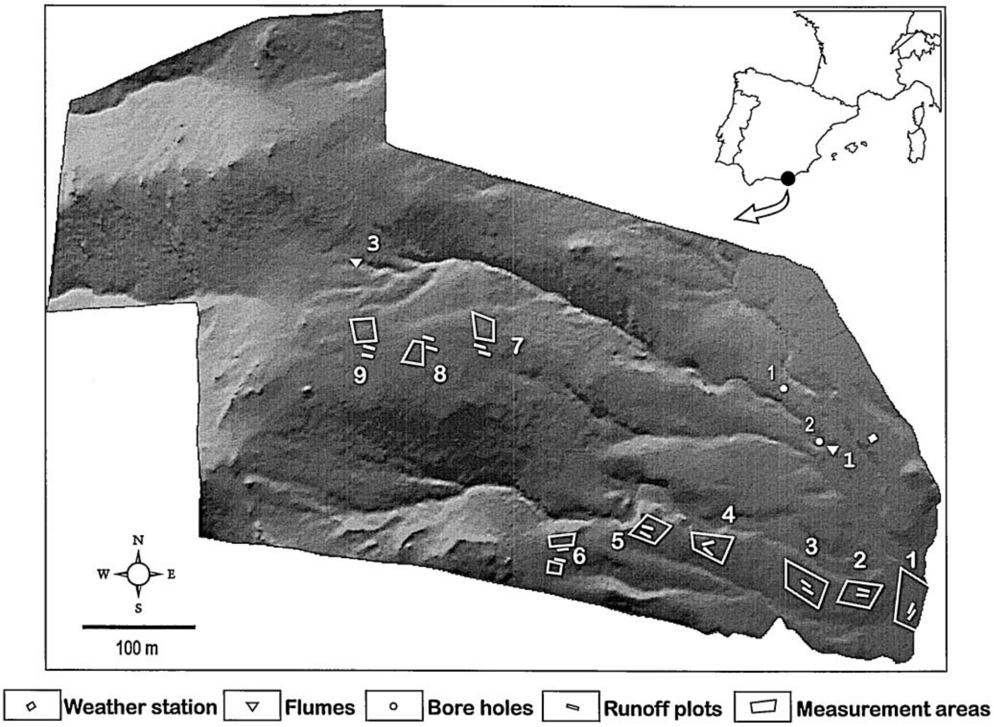

Fig. 1. Experimental layout at the Rambla Honda field site.

layer (0–5 cm), and four from the subsurface layer (5–20 cm). Within each layer samples are taken at random, two in intershrub areas and two below shrubs. Soil moisture data used in this paper cover the period October 1991 to December 1994, and are weighted averages for bush or tussock cover in each soil layer and each MA. Samples are taken at increasing time intervals, 1, 3, 6, 12 and 24 days after each rainfall event, and each 24 days afterwards, if there is no further rainfall.

In addition to this manual soil moisture sampling program, an automatic monitoring system was installed. The work described here is based only on a part of this system, consisting of two units. Each unit includes 5 SBIB soil moisture sensors (Vidal, 1994, Vidal et al., 1996), a runoff plot (2 m $\times$ 10 m) equipped with a 400 cm^3 tipping bucket recorder, and a rainfall recorder. The soil moisture sensors are located in bare ground patches, two at 2.5 cm, two at 12.5 cm, and one at 50 cm depth. One of these units is located in the distal fan sector, in the *Retama* plant community (MA 2) and the other is located in the upper hillslope sector, with *Stipa* cover (MA 8). In the latter unit no soil moisture sensor could be installed at 50 cm depth because of the very shallow soils that prevail in this part of the slope. The outputs of all the sensors are read in parallel with rainfall and are logged every 20 s. Soil moisture measurements are averaged in half-hour intervals.

In a first-order channel draining a hillslope sector adjacent to the measurement areas described above, two gauging H-type flumes were installed in April 1994 (Fig. 1). Water stage is recorded every 20 s by capacitive sensors installed at the flumes. Some topographic characteristics of the three catchment sectors are shown in Fig. 2(a–c). The upper flume (F3) drains a *Stipa*-covered area of 0.29 ha, with soil depths ranging from 30 cm to 50 cm. The lower flume (F1) has a catchment of 4.65 ha. At this point the channel is cutting the alluvial fan and runs over a sediment fill 9 m thick. This layout allows hydrological and erosional responses of the upper rocky hillslope to be compared with those of the lower sedimentary sector.

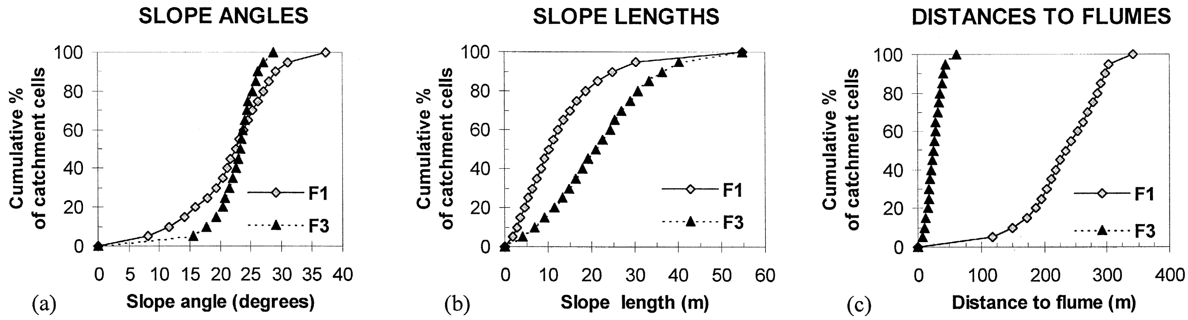

Fig. 2. Cumulative distributions of topographic attributes in the studied catchments.

Finally, a set of four piezometers, each reaching bedrock, was installed in the sediment fill along a transect from the hillslope (9-m depth) to the middle of the main channel (30-m depth) (Fig. 1). Water levels of these piezometers are surveyed manually after rainfall events and if water is found, observations are repeated daily until its disappearance.

2.2.2. Rainfall attributes

Two intensity raingauges were installed in the hillslope, one at the main weather station near MA 2, and another in the upper hillslope near MA 8. In addition, each MA was equipped with a totalising raingauge which provided readings of total rainfall volume per event. The smallest time interval at which rainfall intensity can be measured is constrained by the shortest recordable time between two tips of the tipping bucket, which in our case was 20 s.

2.2.3. Soil attributes

Particle-size distribution and organic C content were determined by the pipette and Walkey and Black methods, respectively. Total pore volume and field capacity were estimated from bulk density and Richards membrane. Bulk density was determined by the excavation method, saturated hydraulic conductivity by the inverse auger hole method, and infiltration rate by rainfall simulation experiments (using a sprinkler-type simulator) on circular plots of 0.5 m diameter at a constant rainfall intensity of 50 mm h^{-1} for 30 min. This should be considered as an exceptional value, because the highest intensity recorded in 30 min during three years, is 32 mm and occurred only once.

2.2.4. Topographic indices

A set of topographic indices estimating the influence of terrain form and topographic position on the flow of runoff and throughflow has been calculated for each MA (Table 1). The digital elevation model (DEM) at 4 m resolution was computed using the flood-fill algorithm r.surf.contour (USA-CERL, 1991), on 0.5-m contours from a 1:500 topographic map, which was in turn based on 1:3500 air photographs. The altitudinal precision of the DEM is 0.1 m, and the vertical RMS error is 0.6 m.

The calculated indices were the local slope angle (SLO), specific catchment area draining to each cell (ARE), wetness index ATB = ln (ARE/tan SLO), and length slope factor $\mathrm{LSF} = (\mathrm{ARE}/22.13)^n\ (\sin \mathrm{SLO}/0.0896)^m$, where n and m are constants, 0.4 and 1.3 respectively.

The ARE may be considered as a surrogate of the potential runoff volume reaching the target quadrat

Table 1
Values of topographic indices in the measurement areas studied along the Rambla Honda hillslope

MA no.	SLO (deg)	ARE (m^2/m)	ATB	LSF
1	4.87	1489.46	9.49	6.30
2	5.21	121.10	7.20	2.78
3	6.40	109.35	6.87	3.53
4	13.40	97.40	5.97	8.58
5	12.43	106.09	6.10	8.15
6	16.85	89.46	5.67	11.18
7	22.80	527.10	7.13	33.36
8	20.64	416.61	7.00	26.87
9	22.20	366.10	6.80	27.95

SLO: slope angle; ARE: specific catchment area; ATB: wetness index; LSF: length slope factor. MA1 to MA5, alluvial fan; MA6 to MA9, rocky upper hillslope.

(Speight, 1974). The ATB was originally designed to predict the spatial distribution and size of saturation zones (Beven and Kirkby, 1979). It is used as a local estimate of the capacity to acummulate runoff, in terms of ARE, and to store it, in terms of SLO. LSF was derived from the unit stream power theory by Moore and Burch (1986). It is a local estimate of the potential volume and flow velocity of runoff, and can be used as a surrogate of the sediment transport capacity of flowing water.

3. Results

3.1. Hillslope distribution of soil moisture

In a hypothetical landscape with uniform soils, the spatial distribution of soil moisture provides information on the importance of runoff and runon across hillslopes, and about the significance of lateral water transfers. Hence, the degree of association between soil moisture content and topographic indices describing spatial patterns of water flow is expected to convey information about the hydrologic connectivity of hillslope elements. Here, we are concerned with the interpretation of such associations rather than with predicting soil moisture distribution through topographic attributes.

In real landscapes, the spatial distribution of soil moisture not only depends on the lateral transfer of water, but also on local soil hydrological properties (Govers, 1991). These local effects must be removed to assess the topographic control of soil moisture. Therefore, as a preliminary step, the association between spatial patterns of soil hydrological properties and topographic indices should be examined in first place.

3.1.1. Patterns of soil properties and topographic attributes along the hillslope

Two landforms make up the Rambla Honda catena: the rocky upper hillslope, and the sedimentary fill at the footslope, which is an alluvial fan system that is being dissected by gullies. Values of

Table 2
Soil properties at the measurement areas along the Rambla Honda catena

MA no.	Depth (cm)	Crust cover (%)	RF > 2 cover (%)	O.M. (%)	Grain size (%)			TPV (v/v)	FC (v/v)
					> 2 mm	Silt	Clay		
1	0–5	15	15	1.6	13	21	4	0.34	0.16
	5–20			1.2	32	13	3	0.25	0.07
2	0–5	0	49	1.4	23	15	3	0.30	0.12
	5–20			0.7	39	12	3	0.32	0.08
3	0–5	0	61	1.4	41	13	3	0.29	0.12
	5–20			0.9	36	13	2	0.33	0.08
4	0–5	5	76	1.8	40	18	5	0.25	0.09
	5–20			0.8	36	23	4	0.29	0.09
5	0–5	2	60	2.6	41	16	4	0.23	0.08
	5–20			1.4	34	17	5	0.28	0.09
6	0–5	5	74	1.8	60	22	4	0.30	0.12
	5–20			1.3	41	24	4	0.35	0.09
7	0–5	13	75	5.2	56	25	7	0.36	0.16
	5–20			1.9	58	26	8	0.34	0.13
8	0–5	12	56	4.8	47	24	8	0.30	0.13
	5–20			2.4	67	30	10	0.32	0.12
9	0–5	4	73	3.8	55	22	3	0.34	0.15
	5–20			1.7	29	38	7	0.36	0.13

Weighted averages for plant cover of bulk soil values (including rock fragments). O.M.: organic matter; TPV: total pore volume; FC: field capacity; RF > 2: rock fragments > 2 mm at the soil surface; silt and clay: percentage over the fraction < 2 mm. MA1 to MA5, alluvial fan; MA6 to MA9, rocky upper hillslope.

topographic attributes and of relevant soil hydrological properties change together along the hillslope (Tables 1 and 2). SLO and LSF decrease downslope, while ARE and ATB generally increase from the divide downwards, but show minimum values in the apex of the alluvial fans, before increasing again down to the footslope. Lateral variability across the hillslope is also important, although less significant than the downward changes. It is particularly found in near channel areas of the midslope sector, where common bedrock exposures produce flash runoff responses to rainfall.

Being washed out by sequences of rainfall events, soils on the alluvial fans contain less clay and silt, less organic matter, and less coarse rock fragments, and have greater hydraulic conductivity and infiltration capacity than soils further uphill (Table 3). There is a downward enrichment of silt and clay and an impoverishment of gravels in the surface layer of the alluvial fan system. There also is a trend to develop a 'washed' surface layer (10–50 mm) of very fine gravel on top of an illuvial layer (< 10 mm) consisting of silt and very fine sand, quite compacted and only crossed by vertical and subvertical cracks (Nicolau et al., 1996).

Upper slope soils show greater cover of rock fragments and surface crusts, which are soft and brittle. Rock fragments larger than 120 mm are often embedded, while the smaller ones lie free on the surface. Bulk density and saturated hydraulic conductivity tend to be greater in the surface layers than in the subsurface ones. These differences are more apparent in the soils of the upper hillslope than in those of the alluvial fans (Table 3).

Table 4
Matrix of Pearson correlation coefficients between topographic attributes (see Table 1) and porosity values at the 0–5 cm and 5–20 cm soil layers in nine measurement areas of the Rambla Honda hillslope

$N=9$	SLO	log(ARE)	ATB	LSF
VTP (0–5)	0.328	0.735*	0.552	0.586
VTP (5–20)	0.594	−0.265	−0.495	0.508
FC (0–5)	0.222	0.822*	0.685*	0.518
FC (5–20)	0.922	0.302	−0.187	0.962*

VTP: total pore volume; FC: field capacity.
* $p < 0.05$.

Total pore volume and water content at field capacity can be used to summarize a range of physical and structural soil attributes of hydrological relevance. The correlation matrix of topographic indices and porosity values (Table 4) shows that ARE and ATB are associated with field capacity in the uppermost surface layer (0–5 cm), while SLO and LSF correlate with field capacity in the subsurface layer (5–20 cm).

In an attempt to remove the effect of soil structure from the correlation between soil moisture and topographic indices, a partial correlation approach was followed, using the SYSTAT package (SYSTAT for Windows, 1992). Partial correlation coefficients between SLO or LSF and seasonal soil moisture content were calculated while holding the field capacities in the subsurface layer (5–20 cm) constant. The same operation was performed with ARE and ATB, while holding the field capacities in the uppermost soil layer (0–5 cm) constant. Prior to these calcula-

Table 3
Physical soil properties (intershrub areas) at the upper hillslope sector (MA 8) and the footslope alluvial fan (MA2)

	Soil layer (cm)	Upper hillslope MA 8	Lower hillslope MA 2
Slope (deg)		20	5
Soil depth (m)		< 0.5	> 5
Total porosity	0–5	0.53	0.50
(vol/vol) fine earth	5–20	0.50	0.37
Total extractable water	0–5	0.38	0.33
(v/v at -33.3 kPa) fine earth	5–20	0.36	0.25
K_{sat} (mm/day)	0–5	1.01	1.73
	5–20	0.57	1.37
Infiltration rate (mm/h)		8	41

K_{sat}: saturated hydraulic conductivity.

tions, the specific catchment area (ARE) data were log-transformed to obtain a normal distribution.

3.1.2. Spatial distribution of seasonal soil moisture content

Seasonal mean values of soil moisture do not increase steadily downhill (Fig. 3). During winter and autumn, soil moisture content in the upper 0–5 cm layer is greatest in the upper and lower hillslope sections while it shows the smallest values at midslope positions. In the underlying layer (5–20 cm), this trend becomes more irregular. During spring and summer, soil moisture steadily decreases from the upperslope towards the footslope in both layers. These patterns are rather consistent despite the large interannual variability of rainfall.

As expected from the seasonal distribution of rainfall (Table 5), the highest soil moisture occurs in winter, followed by autumn and spring, while the lowest coincides with summer. Soil moisture in winter (6–20%) and in autumn (4–15%), are far below saturation (23–36%) but, as shown in Table 2, lie within the range of moisture contents that are required to reach field capacity (8–16%). The winter,

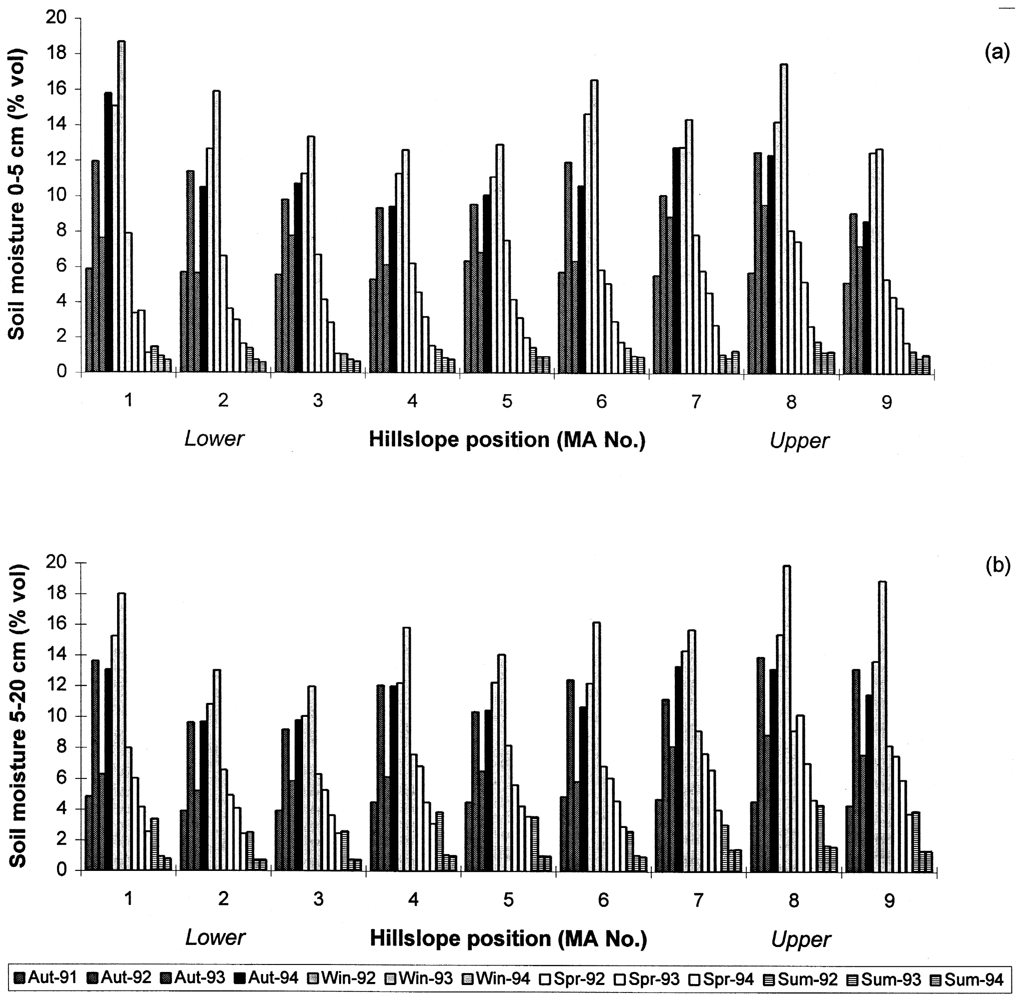

Fig. 3. Mean seasonal soil moisture distribution along the Rambla Honda catena in the study period. (a) 0–5 cm; (b) 5–20 cm. MA 1 to MA 5: footslope sediment fill; MA 6 to MA 9: rocky upper slope. The solid bar shows the soil moisture in autumn 1994, when the reported case study was carried out.

Table 5
Partial correlation coefficients between mean soil moisture and topographic variables, holding constant field capacity, in the Rambla Honda hillslope

Season	Rainfall (mm)	0 cm–5 cm soil layer				5 cm–20 cm soil layer			
		SLO.fcd	LARE.fcs	ATB.fcs	LSF.fcd	SLO.fcd	LARE.fcs	ATB.fcs	LSF.fcd
Autumn-91	56	0.29	0.4	0.45	0.42	0.71*	0.43	−0.08	0.75*
Autumn-92	70	0.16	0.09	0.22	0.57	0.27	0.54	0	0.4
Autumn-93	45	−0.12	0.38	−0.06	0.63	0.08	0.38	−0.33	0.65
Autumn-94	139	−0.12	0.61	0.71*	0.88**	0.14	0.71*	−0.11	0.8**
Winter-92	162	0.19	0.18	0.12	0.63	0.12	0.79*	0.15	0.76*
Winter-93	121	0.04	0.27	0.42	0.67	0.19	0.53	−0.09	0.38
Winter-94	53	−0.06	0.62	0.5	0.75*	0.19	0.64	−0.08	0.71*
Spring-92	87	0.49	0.03	−0.5	0.44	0.24	0.33	−0.32	0.45
Spring-93	55	−0.03	0.41	−0.19	0.72*	0.24	0.15	−0.53	0.74*
Spring-94	23	0.45	0.07	−0.49	0.55	0.43	0.3	−0.42	0.41
Summer-92	17	0.27	0.48	0.24	0.19	0.08	0.68	0.06	0
Summer-93	55	0.5	0.49	−0.04	0.49	0.44	0.28	−0.45	0.61
Summer-94	23	0.66	0.18	−0.55	0.76*	0.45	0.2	−0.52	0.59

Study period: Oct. 91–Dec. 94; SLO: Slope angle; LARE: ln(specific area); ATB: wetness index; LSF: length slope factor; fcs: field capacity at the 0 cm–5 cm upper soil layer; fcd: field capacity at the 5 cm–20 cm soil layer.
* $p < 0.05$.
** $p < 0.01$.

and to a lesser extent the autumn, are therefore the only seasons in which soil moisture is likely to exceed field capacity. Saturated conditions, if they occur at all, are likely to be of extremely short duration.

Partial correlation coefficients between seasonal soil moisture and topographic indices (holding field capacity constant) are shown in Table 5. The most significant associations are found with LSF and concentrate in the humid seasons of the year, winter and autumn, but even then, they were recorded only in four out of the seven observations included in the reference period. The highest correlation was found in autumn 1994, which was particularly rainy (139 mm), but no straightforward relation exists between the significance of the correlation coefficient and rainfall amount.

The correlation analysis of soil moisture and terrain attributes suggests that water transfer among hillslope elements, although rare, does occur. However, understanding its operation raises some relevant questions about runoff generation and connection between hillslopes and channels that cannot be answered solely by the topographic approach. To this end, a more detailed analysis of the relations between rainfall, soil moisture and runoff, was carried out. The study focuses on autumn 1994, because this season showed the highest correlation between the spatial distribution of soil moisture and LSF.

3.2. A case study of hillslope response: The rainstorms of autumn 1994

At the end of September 1994, following the dry summer months, a rainy period occurred from 29 Sept. 1994 to 4 Nov. 1994. Fig. 4 shows the main characteristics of these autumn rains, together with the resulting response of soil moisture contents along the hillslope, the timing of the runoff pulses at the flumes, and the temporal changes of the piezometric level.

The total rainfall collected during the whole period was about 150 mm; 140 mm fell in the fan area (MA 2) and 160 mm in the upper hillslope sector (MA 8). This rainy spell consisted of three main events, RE1, RE2 and RE3. RE1 started on 29 Sept. 1994 and ended on 10 Oct. 1994. The total rainfall amount of 50 mm was distributed in a series of four smaller storms, with a maximum intensity of 38 mm h^{-1} during 1.8 min. RE2 began on 15 October at 2100 h and continued until 16 October at 2000 h. The total amount of RE2 was 66 mm, which fell in

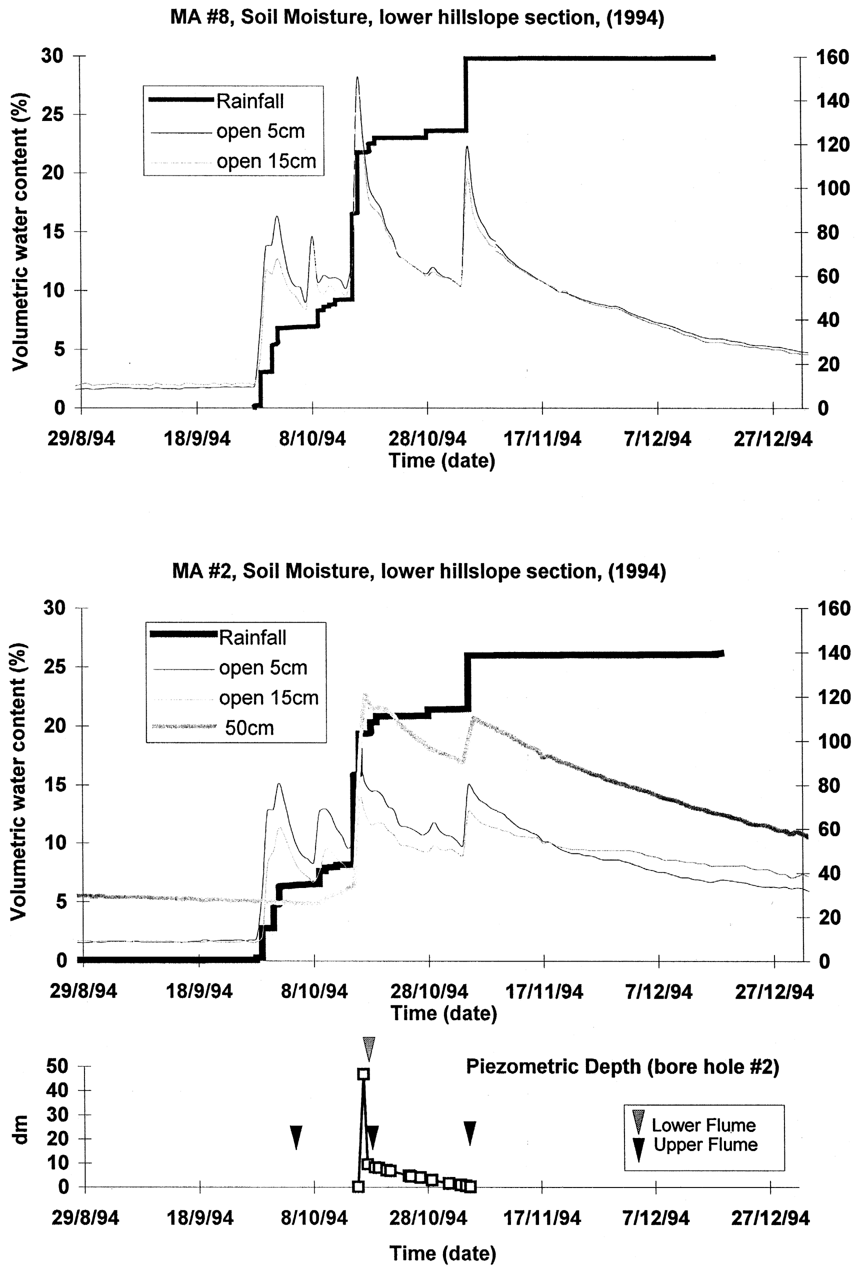

Fig. 4. Cumulative time evolution of rainfall and soil moisture, in bare ground (open) areas, at 5 cm and 15 cm depth, during the rain period of autumn 1994, at the hillslope sector (MA 8) and the lower fan sector (MA 2) of Rambla Honda. The phreatic level records are next to the lower flume and times when discharge was recorded at the flumes are indicated.

two subevents separated by a dry period of 12 h. The early subevent (RE2a) produced a total amount of 42 mm at a mean intensity of 12 mm h^{-1}, while the later subevent (RE2b) was characterised by a total amount of 24 mm and a mean intensity of 7 mm h^{-1}. The maximum intensity recorded during the whole event RE2 was 58 mm h^{-1} during 1 min. Finally, on the 4th of November, a third event occurred (RE3) which was a flash storm of 30 mm and a maximum intensity of 28 mm h^{-1} during 1 min.

Just before RE1, the soil was very dry with a moisture content of 1–2% (volumetric). In both MA, surface (−5 cm) and subsurface (−15 cm) soil layers showed two peaks of soil water content. The moisture content in the subsurface layer generally remained below that of the surface, except in the upper hillslope (MA 8) where both layers reached the same moisture content (15%) at the second rainfall peak. Deep soil layers (−50 cm) in the fan area

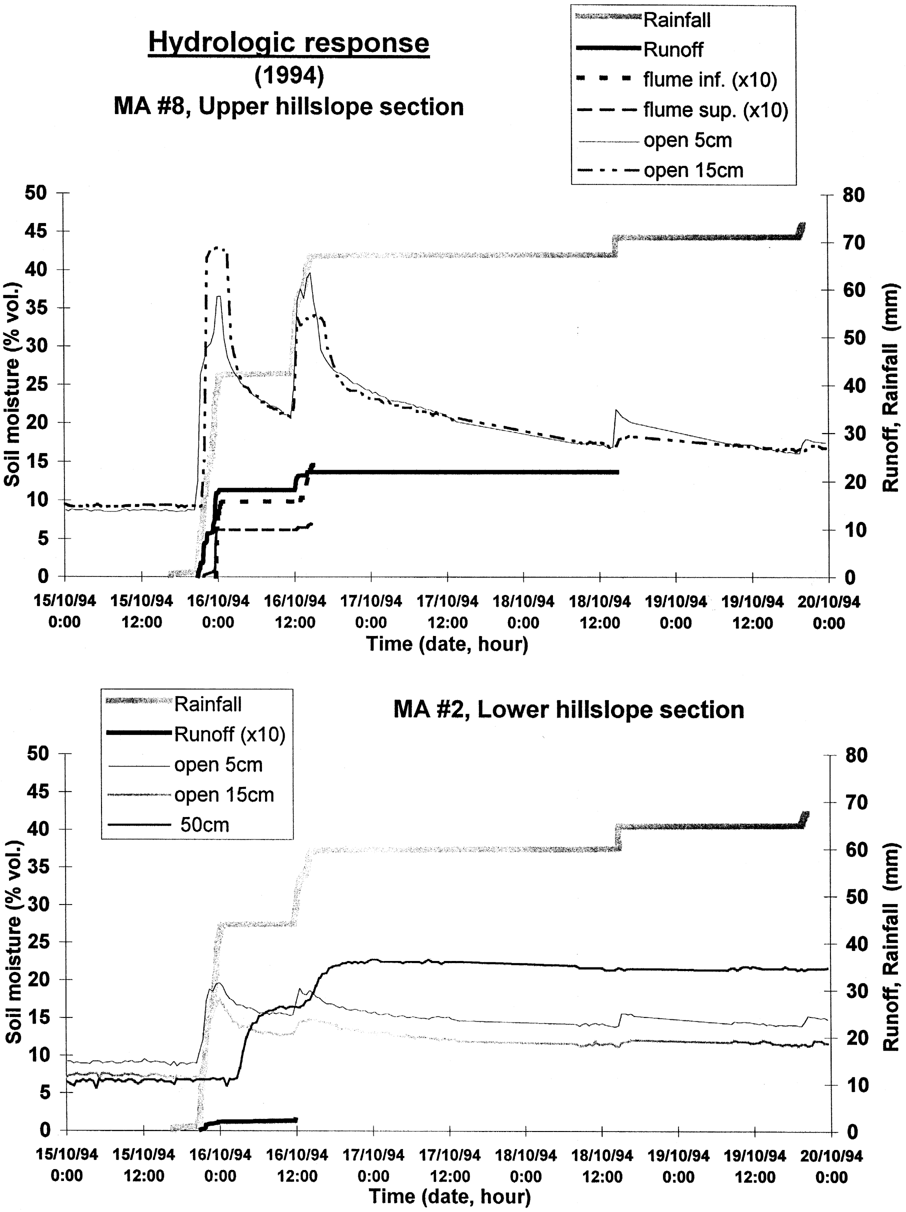

Fig. 5. The same as Fig. 4, but focusing on the period 15–20 October 1994 and adding information about overland flow in runoff plots (2 m × 10 m) and discharge at the flumes.

(MA 2) showed only a small moisture increase during the fourth and last subevent. During the third subevent, coinciding with the highest moisture peak in the surface soil layers (slightly over 15%), a small and flashy runoff pulse of 0.1 mm was recorded in the upper flume (F3) but not at the lower one (F1).

The second event (RE2) produced a very sharp increase in soil moisture content in the upper hillslope section (MA 8), where both surface and subsurface layers attained similar values. In the fan sector (MA 2) this peak was less pronounced, and subsurface values remained smaller, but soil moisture content of the deep soil layer rose dramatically, peaking well above the values measured in the surface soil layers. During this event not only the upper and lower flumes (F3 and F1) recorded discharge, 1.2 mm and 2.0 mm respectively, but the second piezometer (D2) also recorded a sudden rise of the ground water level (up to 4.5 m) which quickly declined again and disappeared completely 20 days later. This piezometer is located next to F1, in the first-order channel draining part of the studied hillslope area (Fig. 1). In spite of the two flash floods that were recorded in the main channel of the Rambla Honda during this rainy period, there was no evidence of water in any of the other piezometers.

The third event (RE3) also produced a quick rise of the soil moisture content, but the peak was less pronounced than during RE2. In both hillslope sections, soil moisture was greater in the surface than in the subsurface layers. In the fan area (MA 2) the response in the deep soil layer was also pronounced and moisture contents remained above those of the near surface layers. During this event only the upper flume (F3) recorded a very small discharge pulse (0.001 mm).

For the RE2 event, the temporal resolution of our graph was increased (Figs. 5 and 6) in order to follow the response of the soil moisture content in the upper hillslope (MA 8) and the fan sector (MA 2). In the upper hillslope section, right at the start of rainfall (RE2a), the moisture content of the surface soil layer rose very quickly to about 30%. The response of the subsurface layer was delayed by 1 h, but once started, soil moisture content also increased very rapidly and, at 45%, even exceeded surface layer values. If we take the total porosity of the subsurface layer (ca. 50% in the fine earth, see Table 3) into account, this part of the soil can be considered as being saturated. This situation remained for about 2 h after rainfall had stopped. The soil started to dry out and 10 h later, at the start of RE2b, the

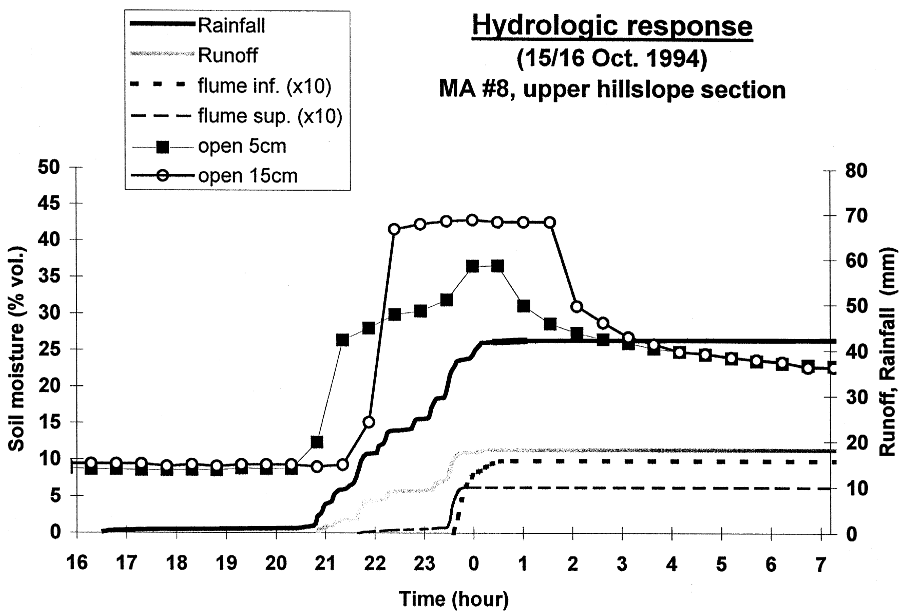

Fig. 6. The same as Fig. 4, but focusing on the period 15 Oct. (1600 h)–16 Oct. (0700 h), 1994.

moisture content of both soil layers had decreased to 22%. The second subevent caused a sharp rise of soil moisture content, exceeding 40% in the surface soil layer, but did not lead to saturation of the subsurface soil. Overland flow was generated in the runoff plot as soon as it started to rain, and the hydrograph developed in parallel to both rainfall and the moisture content of the uppermost soil layer. Most of the channel discharge at the flumes was only recorded after the last jump in rainfall intensity in RE2a (Fig. 6). By that time the subsurface layer became saturated, and contributed to a flash discharge pulse that lasted less than 30 min. Runoff coefficients for RE2a were 43% at the runoff plot, 2.4% at the upper flume (F3) and 3.8% at the lower flume (F1), but these values changed to 40%, 5%, and 8% respectively, in the rainfall pulse that occurred in the second half of RE2a, when the subsurface layer was already saturated. Larger runoff coefficients in the lower flume are explained by the inputs from exposed bedrock near the channel, in the lower hillslope sector, between F3 and F1.

The response in the fan sector (MA 2) was very different. Soil moisture content of the upper soil layers increased as rainfall started, and the values of the top layer remained above those of the subsurface layer throughout the event. The delay in the response of the deep soil layer was about 5 h during the first rainy spell, but only 2 h during the second. In the latter, soil moisture content reached values of 22%, which is well above the peak values in the upper soil layer (15–18%), and though below saturation, it is well above field capacity if we consider the porosity of the fine earth fraction (Table 3). Overland flow at the runoff plot started just after the initiation of rainfall (RE2a) parallel to the rapid increase of the moisture content in the upper soil layers, but its response was small (3 mm) and short lived (2 h). The runoff coefficient at RE2a was about 7% of the rainfall. The second rainy spell (RE2b) did not produce any overland flow.

3.3. Discussion

Correlation analysis shows that in Rambla Honda, the spatial distribution of soil moisture is controlled more by local factors than by topographic attributes that determine the transfer of water among different hillslope sections. Evidence of topographic control has been found, but only in some cases, during the more humid seasons of the year. During the rest of the time, local factors such as pore volume, rock fragment cover, silt and clay contents are more important in explaining the spatial patterns of soil moisture. In the spring and summer seasons, for example, soil moisture is higher in the upper slope section where soils are richer in clay and stones (Fig. 3 and Table 2).

The sequence of events during the complex storm in Figs. 5 and 6 enabled us to identify two mechanisms of overland flow generation occurring at different phases of an extreme rainfall event. According to the first mechanism, overland flow may start just after rainfall initiation once the infiltration capacity and the temporary saturation of the uppermost soil layer, that is above -5 cm, are exceeded. This phase is short-lived because it disappears as soon as deeper moisture penetration creates higher hydraulic conductivity rates. Runoff coefficients for the studied first-order catchment (2–4%) are not negligible. The generated overland flow shows, however, a heterogeneous spatial distribution, because it depends on very local soil conditions.

During storms of long duration and large total amounts, overland flow is likely to be generated by a second mechanism. Under such rainfall conditions, a very responsive situation may build up when the subsurface layer (-15 cm) becomes saturated. In such circumstances, moderate rainfall amounts can produce large scale runoff that may reach the channels, producing runoff coefficients of 5% to 8% for upper and lower flumes, respectively. This mechanism is probably the most important way in which hydrologic connectivity of hillslope elements is established. The ephemeral saturation of the subsurface soil layer may support some throughflow which is likely to involve only short distances because moisture contents fall below field capacity in less than 24 h. Only if rainfall events are frequent and the evapotranspiration is low, as it happens in winter, can this process attain some importance at the hillslope scale.

The second mechanism of overland flow generation probably requires lower rainfall amounts and thus operates more frequently where soils are shallow or have a less permeable layer at shallow depth.

Both conditions are met in the upper hillslope sections of the Rambla Honda field site. On the contrary, this overland flow generation mechanism requires larger rainfall amounts and is more rare where soils or regoliths are deep and saturated hydraulic conductivity remains high throughout the profile. These are the conditions that prevail in the alluvial fan sector. There, saturation of the deep layers of the sediment fill only occurs as a result of very large rainfall amounts. When this occurs, however, the responsive condition will be long-lived because the moisture content of the deep layers will remain high for considerable time. Differential behaviour of the upper hillslope and fan sectors under the second mechanism of overland flow generation may explain why, in general, the former acts as a runoff source and the latter as a runoff sink in the landscape system, as has been reported years ago for the northern Negev (Yair, 1983, Yair and Lavee, 1985). The only exception may occur in big and extended rainfall events, when alluvial fans become runoff sources (Nicolau et al., 1996) under long-lasting responsive conditions resulting from saturation of the subsurface layers.

Simple calculations based on the available field data show that the total runoff volume collected at the upper flume can be accounted for by the overland flow generated through the second mechanism in areas close to the channel, in response to rainfall between 23:30 h and 00:00 h (Fig. 6). The rainfall during this phase was about 20 mm and produced 8 mm of runoff in the runoff plot (2 m $\times$ 10 m) and 0.9 mm of runoff in the upper catchment (2912 m^2), corresponding to a total volume of 2.62 m^3. Fig. 2b shows that 15% (437 m^2) of the catchment area of the upper flume is situated at less than 10 m from the stream courses. If the response of the runoff plots represents the runoff yield from this part of the catchment, the total runoff would be 4.37 m^3, which is well above the volume collected by the flume.

These results suggest that though widespread overland flow may be generated under these specific conditions, its role in transferring water across hillslopes is probably limited, because the distances involved are short, ca. 10 m, and certainly less than the maximal slope lengths in the upper catchment (40–50 m, Fig. 2b). This concurs with overland flow distances estimated in the area from the diminution rate of annual runoff coefficients with slope length (Puigdefabregas and Sanchez, 1996).

The interpretation of piezometric levels recorded at D2 during the event RE2 is more uncertain. Its rapid response suggests that the main amount of water was provided by the hillslope, because it is the only piezometer that reacted and also the only one located in a channel draining a hillslope area.

Two important implications can be derived from the piezometric and soil moisture data recorded during this event in the alluvial fan. The first is that large events may increase moisture contents of deep layers above field capacity. The resulting gravity flow is likely to be more long-lasting than in the upper layers. It is controlled more by the distribution of fine-grained lenses in the sediment profile than by the surface topography. Therefore, this type of flow can produce ephemeral saturated wedges and is responsible for the vertical drainage into the sediment fill, which makes water available to deep rooted plants such as *Retama* (Haase et al., 1996). The second point is that overland flow from the hillslopes may contribute, during extreme events, to flash floods in the main ephemeral channel, but their contribution to the recharge of aquifers within the latter is very limited. This is, because the saturated wedges that occasionally develop near the outlet of gullies draining hillslope areas tend to dissipate within the sediment fill of the main channel.

4. Conclusions

In Rambla Honda, like other semi-arid landscapes developed on micaschists, hillslopes consist of two main types of landforms; rocky and colluvial-covered upper slopes, and alluvial fan systems at the footslopes. Both landforms tend to develop a thin layer of ‘washed’ gravel at the surface. In the rocky upperslopes, soils are thin and subsurface layers are fine-grained. In the alluvial fans, regoliths are much deeper and built by alternating and discontinuous lenses of gravel and fine sand or silt. These differences are reflected in the hydrological behaviour of both landforms.

Two mechanisms of overland flow generation have been distinguished. One is caused by infiltration being exceeded at the uppermost soil layer, while the other is produced by saturation of a subsurface layer. The first mechanism depends on the rainfall intensity at the beginning of an event and on the hydraulic properties of the soil surface. It occurs more frequently than the second, but is very short-lived and rarely reaches the channel. The second requires heavier rainfalls, and occurs after a shallow saturated layer has been built up due to a lack of soil depth, or to the presence of a less permeable layer. Once these conditions have been met, however, they lead to a situation in which small amounts of additional rainfall may produce widespread overland flow. Runoff coefficients resulting from either of the two mechanisms may locally be high, ca. 40% on slope lengths of 10 m, but were found to be low ($< 5\%$) at the hillslope scale for slope lengths of 40–50 m in areas without exposed bedrock.

This second overland flow generation mechanism is the most important for the transfer of water at the hillslope scale and the production of channel flow. The responsive conditions that lead to it are more frequent but less persistent in upper hillslope sections with shallow regolith, and are more rare and long-lasting in alluvial fans at the base of the slopes. In this way, although rocky hillslopes have small scattered runoff sinks, as a whole they often play the role of runoff sources while alluvial fans in the footslope sector act as runoff sinks.

Hydrological connectivity of hillslope elements is very poor. Firstly, structural differences between the two abovementioned landforms force a strong hydrological discontinuity. Secondly, the highly responsive condition, in which significant runoff may be produced, is mostly short-lived and its occurrence is probably in spatially-distributed patches. For that reason, lateral transfer of water along hillslopes is ephemeral, it covers short distances, and it occurs mainly as fast runoff in winter and autumn. In the lower sector of Rambla Honda, hillslopes may contribute to flash floods in the ephemeral channels but, given the limited runoff and the large amount of sediments stored in the main channel, their contribution to the recharge of aquifers in the valley bottom is very limited.

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