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Seasonal changes in the soil hydrological and erosive response depending on aspect, vegetation type and soil water repellency in different Mediterranean microenvironments

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Abstract. Mediterranean areas are characterized by a strong spatial variability that makes the soil hydrological response highly complex. Moreover, Mediterranean climate has marked seasons that provoke dramatic changes on soil properties determining the runoff rates, such as soil water content or soil water repellency (SWR). Thus, soil hydrological and erosive response in Mediterranean areas can be highly time- as well as space-dependant. This study shows SWR, aspect and vegetation as factors of the soil hydrological and erosive response. Erosion plots were set up in the north- and the south-facing hillslope and rainfall, runoff, sediments and SWR were monitored. Soil water repellency showed a seasonal behaviour and it was presented in three out of four microenvironments after the summer, disappearing in the wet season. In general, runoff rate was higher in shrubs patches (0.47 ± 0.67 mm) than in inter-shrub soils (1.54 ± 2.14 mm), but it changed seasonally in different ways, depending on the aspect considered, decreasing in the north-facing hillslope and increasing in the south-facing one. The main factor determining the hydrological and erosive response was the rainfall intensity, regardless of the rainfall depth of the event. This response was modulated mainly by SWR in the north-facing hillslope and the vegetation pattern in the south-facing one.

1 Introduction

It has been widely accepted that the infiltration capacity of soils is higher under dry conditions, owing to the higher matric suction and the action of capillarity forces (Cerdà, 1998; Beven, 2001). This has been demonstrated by means of experiments and measurements in contrasted seasonal climates such as the Mediterranean (Cerdà, 1996, 1997a, 1999). However, this fact has been revoked under certain circumstances by numerous studies in recent years, arguing that repellent soils can have infiltration rates in several orders of magnitude lower than they are supposed to have in hydrophilic conditions (De Bano, 1971; Doerr et al., 2000; Robichaud, 2000; Jordán et al., 2011). Soil water repellency (SWR) has received increasing attention from the scientific community in the last decades and has been reported in several climates and soil types (Doerr et al., 2000; Mataix Solera and Doerr; 2004; Cerdà and Doerr, 2007; Bodí et al., 2011; Jordán et al., 2013; Santos et al., 2013).

The necessary conditions for SWR appearance make it a widespread property under Mediterranean climate. On one hand, Mediterranean climate is characterized by a three-month-long summer drought, between June and September. This prolonged dry period reduces soil moisture to the point where water repellency is triggered (Dekker et al., 2001; Mataix-Solera and Doerr; 2004; Verheijen and Cammeraat, 2007; Martínez-Murillo and Ruiz-Sinoga, 2010; Prats et al., 2013; Martínez-Murillo et al., 2013). On the other hand, summer drought favours the presence of deciduous and semi-deciduous plant species (Orshan, 1964, 1972), which shed their oil- or wax-rich leaves in summer (Moral García et al., 2005), providing hydrophobic compounds to the soil surface. Moreover, in Mediterranean areas there is also a high recurrence of forest fires that are frequently related to SWR appearance (Úbeda and Mataix-Solera, 2008).

One of the main effects of SWR is enhancing overland flow and soil erosion due to the low infiltration capacity of repellent soils (Doerr et al., 2000). However, there are several problems that make it difficult to establish links between SWR and soil erosion (Ritsema and Dekker, 1994; Shakesby et al., 2000; Granged et al., 2011). One of these problems is the effect of SWR on soil erosion, which is hard to isolate from other factors that also change seasonally, such as soil crust formation and litter production. Another problem is scale dependent influence of SWR, changing from plot to catchment measurements due to space discontinuities where generated runoff can reinfiltrate. Lastly, the third problem is that SWR has a seasonal oddity, being more frequent after the drought season, but it can also appear during dry spells in the middle of the wet season (Crockford et al., 1991; Bodí et al., 2013). Furthermore, in Mediterranean areas, there is a high variability of vegetation cover and soil surface components in short spaces (Cerdà, 1997b, 2001; Puigdefábregas, 2005). One of the main factors affecting vegetation is the aspect (Kutiel, 1992), which influences not only the total cover but also the distribution, structure, density and composition of vegetation communities (Kutiel and Lavee, 1999; Gabarron-Galeote et al., 2013; Martínez-Murillo et al., 2013; Prats et al., 2013) and can therefore control soil and water losses.

Moreover, apart from promoting overland flow triggering SWR, vegetation can enhance infiltration, reducing crusting in the soil surface and supplying plants stems, leaves, and roots, all of which enrich the soil and support the microorganisms that transform these remains into soil organic compounds (Puigdefábregas, 2005), favouring the formation of stable aggregates (An et al., 2013; Atucha et al., 2013). Thus, vegetation can influence the soil hydrological response in opposing ways: mostly favouring water infiltration but also triggering runoff when SWR develops.

This study was developed in a small catchment under Mediterranean climate conditions in the South of Spain. The main goal of this paper is to shed light on the relations between SWR, aspect and vegetation, determining the soil hydrological and erosive response throughout the rainy period in different microenvironments. According to this aim, the objectives are (i) to establish relationships between aspect, vegetation cover, SWR and the hydrological and erosive response of soils; (ii) to characterize the seasonality of SWR, runoff and soil loss; and (iii) to establish the relations between precipitation and soil erosion parameters.

Table 1. Topographical and soil characteristics of the studied hillslopes.

	North-facing hillslope	South-facing hillslope
Slope (°)	15°	22°
Aspect (°)	0°	180°
Aspect profile	convex−rectilinear−concave	convex−rectilinear
Soil depth (cm)	30–50	20–30
Coarse fraction (%)	< 10	54–67
Texture	Sandy loam, sandy clay loam	Sandy loam
Organic matter (%)	4–5.2	1.5–3.5

2 Material and methods

2.1 Study area

The experimental area was a small watershed located in southern Spain (36°50′ N, 4°50′ W) (Fig. 1). In general, the area is characterized by a dry Mediterranean climate (mean annual precipitation 576 mm yr^{-1}; mean annual temperature 15.7 °C); the dominance of water erosion processes on steep (> 12.5 °) hillslopes developed on metamorphic rocks (phyllites); and land uses that include rangelands, evergreen forests, abandoned land, and olive and almond orchards. Areas with extensive vegetation cover are characterized by an association of Cambisol and Eutric Regosol soils, whereas in the most degraded areas the soils are Episkeletic Cambisols associated with Haplic Epileptic–Episkeletic Regosols and Eutric Leptosols (IUSS Working Group WRB, 2006) (Gabarrón-Galeote et al., 2013). A north-facing and a south-facing hillslopes were selected. Topographical and soil characteristics are detailed in Table 1.

The north-facing hillslope is characterized by open woodland of cork oak with typical degraded Mediterranean scrubland (*Cistus* spp. *Ulex parviflorus*, *Lavandula stoechas*, *Genista umbellata*). Vegetation cover is rather continuous, with a mean tree cover of 40–50 % and shrub cover > 75 %. *Cistus monspeliensis* and *Cistus albidus* are the dominant shrub species on the hillslope and in adjacent natural areas. The soil surface not covered by shrubs is characterized by the presence of abundant litter from *Cistus* spp. and *Quercus suber*. At hillslope spatial scale, the major soil surface components are patches of *Cistus* spp. (mean size > 2 m^2) and bare soil; in both cases the soil is covered by a thick layer (typically 2–5 cm) of litter.

The south-facing hillslope was previously cultivated with cereals, but abandoned in the mid-1950s. Now it is covered by a patchy vegetation mosaic of bare soil and Mediterranean plant species (60 % vegetation cover, which is similar to that of natural hillslopes in the surrounding area; mean patch size < 2 m^2). *Cistus* spp. are the most common species growing

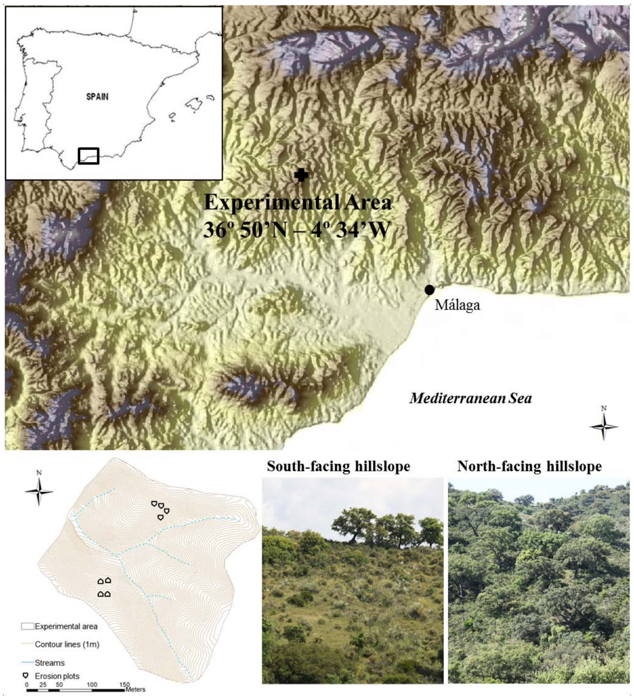

Fig. 1. Location of the experimental area and general view of both north- and south-facing hillslopes.

on the hillslope. In winter, the bare soil area is covered by annual plants, the dead structures of which accumulate on the soil surface during summer.

2.2 Precipitation

Every 10 min, precipitation and rainfall intensity were recorded using a rain gauge of 0.3 mm of precision and expressed in mm h^{-1}. Precipitation data were grouped into two different categories according to the daily mean rainfall intensity (I), the maximum precipitation intensity (in a 10 min basis) of the day (I_{max}), and number of days between precipitation periods. The mean duration of rainy and dry spells was calculated for each period.

2.3 Soil water repellency

Water repellency was measured using the water drop penetration time (WDPT) technique (Van't Woudt, 1959), modified by the addition of eight drops of demineralized water rather than three. The test was applied in the two microenvironments analysed on every hillslope (shrub-covered and inter-shrub soils). Undisturbed soil samples from the 4 microenvironments were collected in 100 cm^3 cylinders and taken to the laboratory. The litter was removed from the surface and then it was smoothed to make it homogeneous. The drops were placed in different places of the soil surface and the time of infiltration noted. The water repellency values obtained with the WDPT were classified according to the classification proposed by Doerr et al. (2006). All the experiments were conducted under controlled laboratory conditions (22 °C; 60 % air relative humidity) to avoid the effects of temperature and humidity in the measurements (Doerr et al., 2002).

2.4 Erosion plots

Eight closed plots were installed in the experimental area distributed as follow: 4 plots on the north-facing aspect (noted as N) and the other 4 on the south-facing one (noted as S), and on each slope 2 of them located in shrub-covered (SC) areas and 2 in inter-shrub areas (IS). These IS areas were often covered by a thick litter layer on the north-facing hillslope and by annual vegetation on the south-facing one. Plots had a surface of 2 m^2 and they were rectangular-shaped and marked out by steel sheets. These steel sheets ended in a funnel shape in order to enable the runoff conduction to reach the collector linked to a deposit of 25 L. The deposits were emptied after every wet spell and the volume collected was noted. The runoff collected was homogenised and a sample of 0.5 L was taken and transported to the laboratory, where it was sieved at a 2 mm mesh and dried in the oven in order to measure the amount of fine sediments transported by the runoff. The parameters calculated were runoff rate (R_r, mm), runoff coefficient (R_c, %), sediment concentration (S_c, g L^{-1}) and soil loss (S_l, g m^{-2}). Although the plots were installed in September 2009, data records were not started until three months later in order to avoid disturbances caused by the soil modifications during the plot installation.

2.5 Statistical procedures

The adjustment of data to normal distribution was tested using the Kolmogorov–Smirnov test, whereas the Barlett test was performed to determine if the data accomplished the homoscedasticity criteria. If these criteria were not satisfied, the logarithmical transformation was attempted. ANOVA test was used if the data were suitable to support parametric statistic and the Mann–Whitney U test was used if they did not. The effects of factors "aspect", "cover" (vegetation cover) and "season" were tested on SWR, runoff and soil loss data using the above-mentioned analyses. Moreover, the relation between precipitation parameters and runoff and soil loss was performed by means of regression models. The significance level was set at 0.05, and all analyses were performed using R software (R Core Team, 2013).

3 Results

3.1 Precipitation analysis

The period analysed was from 15 November 2009 to 15 December 2010. Precipitation during the study period followed the classic trend of Mediterranean climate from the Northern

Table 2. Precipitation characteristics for the whole study period and for each season. P: precipitation; I: mean rainfall intensity; I_{max}: maximum rainfall intensity. Daily maxima in brackets.

	Total	Dry season	Transition season	Wet season
Duration (d)	396	142	104	150
P (mm)	1108.3 (59.2)	21.4 (6.2)	116.8 (41.1)	970.1 (59.2)
I (mm h^{-1})	2.7 ± 1.5 (12.0)	2.4 ± 0.7 (4.0)	3.0 ± 1.9 (9.1)	2.6 ± 1.4 (12.0)
I_{max} (mm h^{-1})	6.6 ± 8.1 (45.6)	4.1 ± 2.8 (9.0)	6.7 ± 8.6 (36.6)	6.9 ± 8.4 (45.6)
Wet spell duration (d)	2.5 ± 2.1	1.7 ± 0.7	1.3 ± 0.4	3.3 ± 2.4
Dry spell duration (d)	6.1 ± 8.2	18.8 ± 13.4	6.2 ± 4.8	2.4 ± 2.2

Hemisphere, with a three-month-long drought between June and September, although precipitation from December 2009 to April 2010 (921.2 mm) was triple the historical average for the corresponding months (306.5 mm).

In order to facilitate analysis, the rainy period was split into three categories named dry, transition and wet seasons. This was done based on the precipitation characteristics more related to the main objective of this study (Table 2). The dry season lasted from 23 April 2010 to 11 September 2010, coinciding with the summer drought. Two transition seasons were differentiated, lasting from 15 November 2009 to 15 December 2009 and from 12 September 2010 to 23 November 2010, respectively. They comprised the isolated precipitation events typical of autumn in the study area. The wet seasons occurred from 16 December 2009 to 22 April 2010 and from 24 November 2010 to 15 December 2010. Both periods were characterized by series of several rainy days separated by short periods without rainfall. Rainfall of 30 mm day^{-1} was frequently exceeded (11 times). The beginning of the wet season in 2009 was provoked by a period of 9 days with a total precipitation of 232.1 mm. This change in 2010 was motivated due to a wet spell of 7 consecutive days with a total precipitation of 80.2 mm.

3.2 Soil water repellency

Figure 2 shows the SWR values measured in every microenvironment and season. SWR data did not accomplish the normality and homoscedasticity criteria required for ANOVA analysis; hence Mann–Whitney U and Kruskal–Wallis tests were performed to compare means taking into account independently aspect, season and cover. Aspect and season had significant effects on SWR ($p < 0.001$), whereas cover did not ($p > 0.05$).

If data were separated by aspect and season, as previous analysis suggests they were, significant differences in SWR between covers in the transition season appeared on both hillslopes ($p < 0.001$); these differences were masked in the general analysis by the data of the wet season, when mean values of SWR remained homogeneous for both hillslopes ($p > 0.05$). There was also significant difference on the north-facing hillslope during the transition season ($p < 0.01$). These facts are clearly shown in Fig. 2 and were corroborated by a

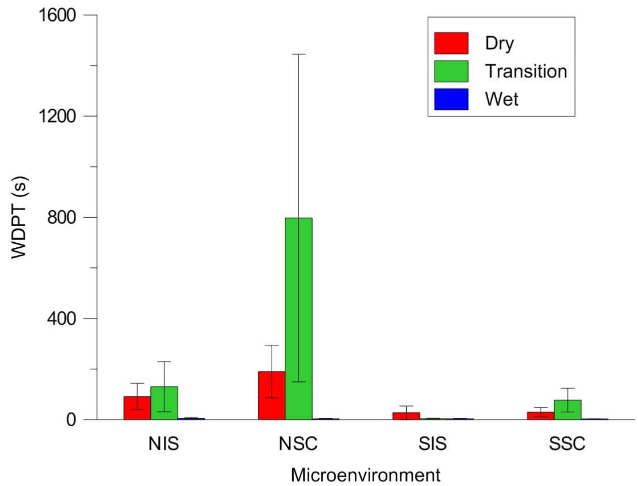

Fig. 2. SWR measured for every microenvironment and season. Error bars represent standard deviation. NIS: north-facing intershrub; NSC: north-facing shrub-covered; SIS: south-facing intershrub; SSC: south-facing shrub-covered.

Kruskal–Wallis analysis of SWR with the variable "microenvironment" (conjunction of aspect and cover) for every season (Table 3). In the transition season, there were significant differences between microenvironments ($p < 0.001$), and the pairwise Mann–Whitney U test showed differences within every hillslope. In the wet season, the soil remained wettable in all the cases but there were quantitative differences between microenvironments ($p < 0.05$). In this period, there were no differences within every hillslope environment. In the dry season there were significant differences between the microenvironments of the north-facing hillslope only.

3.3 Hydrological and erosive response

Table 4 shows means and standard deviations of the hydrological and erosive parameters recorded during the study period. The dispersion of data were large, usually with CV values higher than 100 %. In the transition season NIS plots showed the highest mean values for runoff variables ($R_r = 2.99$ mm, $R_p = 12.22$ %) and SSC showed the lowest ones (0.35 mm, 1.27 %). The maximum event values during

Table 3. Quantitative and qualitative values of SWR. Microenv.: microenvironment; WDPT: water drop penetration time; NIS: north-facing inter-shrub; NSC: north-facing shrub-covered; SIS: south-facing inter-shrub; SSC: south-facing shrub-covered. Different letters denote significant differences between microenvironments in every season.

Microenv.	Dry		Transition season		Wet season	
	WDPT (sg)	Category	WDPT (sg)	Category	WDPT (sg)	Category
NIS	91.1 ± 52.2 b	4 Moderate	130.6 ± 96.2 b	4 Moderate	5.5 ± 3.2 a	0 Wettable
NSC	190.1 ± 104.0 a	5 Moderate	797.0 ± 627.1 a	7 Severe	3.8 ± 1.5 ab	0 Wettable
SIS	27.1.3 ± 26.7 c	2 Slight	4.3 ± 1.7 c	0 Wettable	3.6 ± 1.5 ab	0 Wettable
SSC	29.8 ± 18.1 c	2 Slight	77 ± 46.7 b	4 Moderate	2.8 ± 0.6 b	0 Wettable

this season were also measured in the NIS plots (8.51 mm, 19.33 %) after 44 mm of precipitation with $I = 2.7\,\mathrm{mm\,h^{-1}}$ and $I_{max} = 36.6\,\mathrm{mm\,h^{-1}}$. During the wet season, there was a change of trend and the highest mean values were in SIS plots (1.49 mm, 2.59 %), whereas the lowest occurred in the NSC plots (0.15 mm, 0.23 %). The maximum event values in this season were recorded in the SIS plots (6.34 mm, 11.77 %) after 53.9 mm of precipitation ($I = 2.9\,\mathrm{mm\,h^{-1}}$ and $I_{max} = 44.4\,\mathrm{mm\,h^{-1}}$). No runoff was detected during the dry season, so this season was not taken into account in further analyses of runoff and soil loss.

Regarding the sediment concentration, the highest mean value in the transition season was $0.91\,\mathrm{g\,L^{-1}}$ and it was found both in NIS and SSC plots. On the other hand, the lowest value was $0.25\,\mathrm{g\,L^{-1}}$ in the SIS plots. In the wet season the maximum mean value was $0.59\,\mathrm{g\,L^{-1}}$ in the SSC plots and the lowest one was $0.08\,\mathrm{g\,L^{-1}}$ in the NIS plots. The maximum sediment concentration measured in the transition season was $3.76\,\mathrm{g\,L^{-1}}$ (NIS plots), recorded after a short event of 2.9 mm ($I = 3.6\,\mathrm{mm\,h^{-1}}$, $I_{max} = 6\,\mathrm{mm\,h^{-1}}$). In the wet season it was $2.59\,\mathrm{g\,L^{-1}}$(SSH plots), after 14.7 mm of precipitation ($I = 1.9\,\mathrm{mm\,h^{-1}}$, $I_{max} = 4.8\,\mathrm{mm\,h^{-1}}$).

Lastly, mean soil loss in the transition season was higher in NIS plots ($0.91\,\mathrm{g\,m^{-2}}$) as a result of the high runoff rate and sediment concentration, and lower in the SIS plots. Soil loss in the wet season was higher in the SIS plots ($0.37\,\mathrm{g\,m^{-2}}$) and lower in the NSC plots ($0.02\,\mathrm{g\,m^{-2}}$). The maximum values of soil loss were 2.69 and $2.62\,\mathrm{g\,m^{-2}}$ in the transition and wet seasons, respectively. They coincided with the maximum values of the runoff variables.

3.3.1 Factors affecting runoff

ANOVA analyses showed that the only factor affecting runoff rate was the vegetation cover ($p = 0.009$), whereas aspect and season did not have any significant effect independently. Effectively, runoff rate was clearly different in shrub-covered (0.47 ± 0.67 mm) and inter-shrub soils (1.54 ± 2.14 mm). This confirms the expected trend of more amount of runoff generated in bare soils than in shrub-covered ones. Interestingly, the interaction between aspect and season significantly affected the runoff rate ($p = 0.03$),

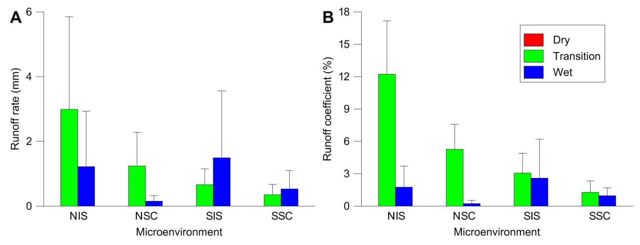

Fig. 3. Mean values of runoff rate and coefficient for every microenvironment and season. Error bars represent standard deviation. NIS: north-facing inter-shrub; NSC: north-facing shrub-covered; SIS: south-facing inter-shrub; SSC: south-facing shrub-covered. No runoff was found in the dry season.

which means that the changes in runoff rate between seasons were different, depending on the hillslope considered. In both microenvironments of the north-facing hillslope, runoff rate was lower during the wet season (Fig. 3a), whereas on the south-facing hillslope this was not observed, being the runoff rate was lower in the transition season (slightly in the inter-shrub plots). Due to the large dispersion of data, only in bare soils of the north-facing hillslope was the difference in runoff rate between seasons significant.

Regarding the runoff coefficient (Fig. 3b), both cover ($p < 0.01$) and season ($p < 0.001$) had significant effects on this property, being R_c was higher during the transition season and in those patches without shrubs. Aspect as a single factor did not have any effect. If the analysis was performed to check the differences between seasons on every microenvironment, it resulted that there were significant differences on both microenvironments of the north-facing hillslope, whereas in the south-facing one the case was the opposite. In spite of having no effect as an individual factor, aspect is clearly an important variable to take into account for the runoff analysis, since R_c is homogeneous during the year on the south-facing hillslope but heterogeneous on the north-facing one. As a consequence, R_c was higher on the north-facing hillslope during the transition season and on the south-facing hillslope during the wet season (Fig. 3b).

Once the differences were analysed in runoff rate and coefficient between aspects, vegetation cover and season, we

Table 4. Summary of precipitation and soil hydrological and erosive response. NIS: north-facing inter-shrub; NSC: north-facing shrub-covered; SIS: south-facing inter-shrub; SSC: south-facing shrub-covered; R_r: runoff rate; R_c: runoff coefficient; S_c: sediment concentration; S_l: soil loss.

		Microenvironments			
Season		NIS	NSC	SIS	SSC
Total	R_r (mm)	1.74 ± 2.26	0.47 ± 0.76	1.31 ± 1.88	0.47 ± 0.51
	R_c (%)	4.83 ± 5.72	1.71 ± 2.63	2.69 ± 3.32	1.06 ± 0.87
	S_c (g l^{-1})	0.32 ± 0.86	0.23 ± 0.29	0.30 ± 0.18	0.66 ± 0.66
	S_l (g m^{-2})	0.32 ± 0.63	0.15 ± 0.31	0.32 ± 0.66	0.28 ± 0.29
Dry	R_r (mm)	0	0	0	0
	R_c (%)	0	0	0	0
	S_c (g l^{-1})	0	0	0	0
	S_l (g m^{-2})	0	0	0	0
Transition	R_r (mm)	2.99 ± 2.86	1.24 ± 1.04	0.66 ± 0.49	0.35 ± 0.32
	R_c (%)	12.22 ± 4.95	5.26 ± 2.33	3.06 ± 1.84	1.27 ± 1.06
	S_c (g l^{-1})	0.91 ± 1.42	0.49 ± 0.38	0.25 ± 0.05	0.91 ± 0.37
	S_l (g m^{-2})	0.91 ± 0.91	0.43 ± 0.45	0.14 ± 0.09	0.58 ± 0.39
Wet	R_r (mm)	1.22 ± 1.71	0.15 ± 0.17	1.49 ± 2.07	0.53 ± 0.57
	R_c (%)	1.75 ± 1.95	0.23 ± 030	2.59 ± 3.61	0.96 ± 0.73
	S_c (g l^{-1})	0.08 ± 0.04	0.12 ± 0.10	0.31 ± 0.20	0.59 ± 0.71
	S_l (g m^{-2})	0.07 ± 0.08	0.02 ± 0.03	0.37 ± 0.73	0.19 ± 0.39

tried to elucidate the precipitation property that correlated best with the overland flow.

Among the rainfall parameters analysed, the best correlation with the runoff rate was found for I_{max}. Remarkably, on the north-facing hillslope runoff generation was different during the transition and the wet seasons (Fig. 4a and b). In inter-shrub soils, the relation between I_{max} and runoff rate was significant ($p < 0.01$) for the whole set of events but it improved when data were split between seasons, turning the R^2 coefficient from 0.49 for the complete data set to 0.93 and 0.61 for the transition and wet season respectively. Moreover, the I_{max} threshold for runoff generation increased from 4.9 mm in the transition season to 6.4 mm in the wet season, whereas the slope of the relation $I_{max} - R_r$ decreased 2.7 times, from 0.254 to 0.093 (Fig. 4a and Table 5). The relation between P and R_r was weaker and it only was significant in the transition season. Beneath *Cistus* spp. the relation between runoff rate and I_{max} was not significant when we took into account the whole study period ($p > 0.05$, $R^2 = 0.08$). However, when we split the data between seasons, this relation became significant only in the transition season ($p < 0.05$, $R^2 = 0.77$), whereas in the wet season it remained not significant ($p > 0.05$, $R^2 = 0.17$). In this case, the relation between P and runoff rate was significant in the wet season ($p < 0.05$, $R^2 = 0.4$), indicating a change in the runoff generation mechanisms.

On the south-facing hillslope (Fig. 4c–d, and Table 5), there was a good and significant relation between runoff rate and I_{max} ($p < 0.001$) in inter-shrub patches as well as beneath shrubs. This relation was consistent throughout the entire study period and the points corresponding to the transition season were straightened to the points of the wet season. In bare soil the R^2 was 0.86 and beneath shrubs was 0.70. As it occurred in the bare soil environment of the north-facing hillslope, the relation of runoff rate with P was weaker than the relation with I_{max}, so the later was the main

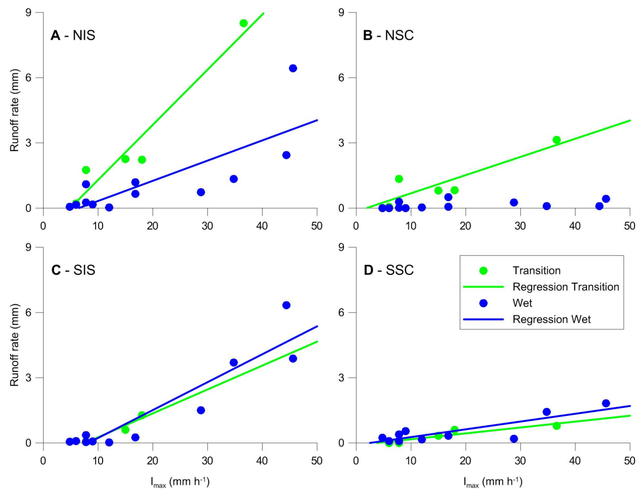

Fig. 4. Relation between I_{max} and runoff rate in every microenvironment. NIS: north-facing inter-shrub; NSC: north-facing shrub-covered; SIS: south-facing inter-shrub; SSC: south-facing shrub-covered.

Table 5. Relevant parameters of the regression models performing the relation between I_{max} and R_r. I_{max} threshold is the I_{max} necessary to generate runoff.

Micro	Transition season			Wet season		
environment	I_{max} threshold	slope	R^2	I_{max} threshold	slope	R^2
NIS	4.88	0.254	0.93*	6.45	0.093	0.61*
NSC	1.86	0.083	0.77*	–	–	0.17
SIS	7.62	0.110	0.91	8.21	0.128	0.86*
SSC	3.74	0.027	0.85*	2.47	0.036	0.71*

* Denotes significance ($p < 0.05$).

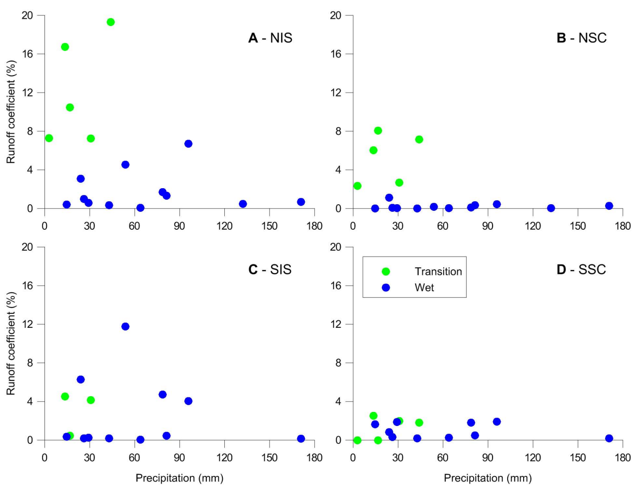

Fig. 5. Relation between runoff coefficient and precipitation. NIS: north-facing inter-shrub; NSC: north-facing shrub-covered; SIS: south-facing inter-shrub; SSC: south-facing shrub-covered.

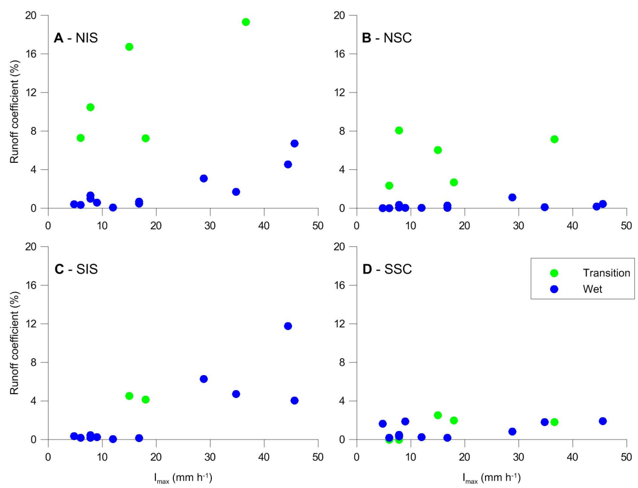

Fig. 6. Relation between runoff coefficient and I_{max}. NIS: north-facing inter-shrub; NSC: north-facing shrub-covered; SIS: south-facing inter-shrub; SSC: south-facing shrub-covered.

controlling rainfall factor affecting the runoff generation. In both microenvironments of the south-facing hillslope, the I_{max} threshold for runoff generation and the slope of the relation $I_{max} - R_r$ only registered slight variations. It is important to highlight that the relation $I_{max} - R_r$ in inter-shrub soils of the south-facing hillslope was not significant during the transition season, in spite of the high R^2 (0.91). This was due to some missing data caused by the effect of grazing on the erosion plots. Nevertheless, since the relation was apparently good, we took into account the parameters of the regression models, although with all due caution.

No significant relation was found between runoff coefficient and precipitation parameters, but when it was plotted against P and I_{max}, two clearly different groups of points according to the season could be observed on the north-facing hillslope, whereas on the south-facing hillslope this different response did not exist (Figs. 5 and 6).

3.3.2 Factors affecting sediment concentration and soil loss

Sediment concentration and soil loss had a similar behaviour. According to the ANOVA test, the only factor that had a statistically significant effect on the erosion variables was season. S_c was $0.66 \pm 0.91\,g\,L^{-1}$ in the transition season and $0.26 \pm 0.41\,g\,L^{-1}$ in the wet season. With regards to S_l, it was $0.55 \pm 0.68\,g\,m^{-2}$ and $0.16 \pm 0.41\,g\,m^{-2}$ in the transition and wet season respectively. As for runoff variables, aspect was an important factor affecting sediment concentration and soil loss, although the effect was masked by the high dispersion of data. If the analysis was performed to check the differences between seasons on every microenvironment, S_c was higher in the transition season on the north-facing hillslope ($p < 0.001$ and $p < 0.01$ in NIS and NSC respectively), whereas there were no differences on the south-facing one ($p > 0.05$). Concerning S_l, results were similar to S_c and it was significantly higher in NIS and NSC ($p < 0.01$ and $p < 0001$ respectively). Contrastingly, in this case the difference between seasons was slightly significant ($p = 0.049$)

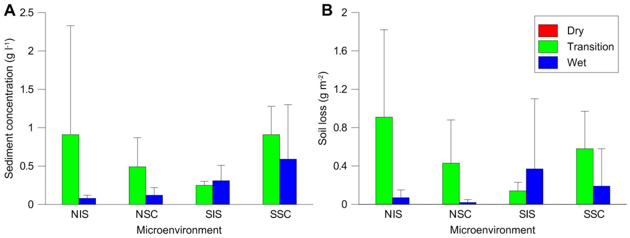

Fig. 7. Mean values of sediment concentration and soil loss in every microenvironment and season. Error bars represent standard deviation. NIS: north-facing inter-shrub; NSC: north-facing shrub-covered; SIS: south-facing inter-shrub; SSC: south-facing shrub-covered. No runoff was found in the dry season.

in SSC. In SIS there was no difference ($p > 0.05$) between seasons. Thus, in spite of the lack of statistically significant differences, it is noteworthy the contrasting behaviour of the sediment concentration and soil loss in the two hillslopes, depending on the season considered (Fig. 7a–b).

Regarding the relations between S_c and S_l with precipitation parameters, S_c did not show any relation with any of them. However, S_l was proportional to I_{max} in the four microenvironments during the transition season, when R^2 ranged from 0.74 in NIS to 0.99 in SSC and SIS, although on the south-facing hillslope only three events were computed. This relation in the wet season was only consistent in the IS microenvironment of both hillslopes, with R^2 of 0.61 in NIS and 0.46 in SIS.

4 Discussion

4.1 Soil water repellency

Repellency was higher on the north-facing hillslope and, in general, its values started to increase in the dry season and were higher during the transition season, decreasing significantly once the wet season started. This reduction of SWR was not observed in the case of inter-shrub areas of the south-facing hillslope, given that soils were already wettable during the transition season. Thus, SWR results highlighted the seasonal character of this property, reported widely in the literature in temperate humid areas as well as in semiarid environments (Witter et al., 1991; Doerr et al., 2000; Kaiser et al., 2001; Benito et al., 2003; Whal, 2008; Zavala et al., 2009). SWR is commonly associated to dry soils and it is supposed to disappear when soil water content increases to a critical soil moisture threshold (Crockford et al., 1991; Imeson et al., 1992; Ritsema and Dekker, 1994; Doerr et al., 2000; Moody et al., 2009; Santos et al., 2013). SWR results were consistent with this statement and after the summer drought, three out of four microenvironments showed hydrophobicity and only one of them remained wettable, whereas during the wet season all the microenvironments were wettable. The SWR measurements corresponding to the transition season were done just after the 2009 dry season and, in consequence, soil moisture was clearly below the wilting point at that time. However, soil drying by itself is not enough to restore soil water repellency and the addition of fresh hydrophobic compounds is also needed (Doerr and Thomas, 2000; Rillig et al., 2010). In the study area the dominant species were *Cistus albidus* and *Cistus monspeliensis*. They are seasonal dimorphic species (Aronne and De Micco, 2001), an adaptation to the Mediterranean summer drought (Orshan, 1964, 1972) that involves the cessation of dolichoblast growth at the end of spring, flower formation, and leaf abscission in order to avoid transpiration water loss. Hence, abundant litter accumulates on the topsoil beneath the shrubs and in surrounding areas during summer (Gabarrón-Galeote et al., 2013). Additionally, this litter is rich in wax and oil compounds, frequently associated to SWR appearance (Verheijen and Cammeraat, 2007). The SWR measurements corresponding to the dry season were done in June, so SWR was starting to increase after the wet season.

The differences in litter input would explain the contrasts between and within hillslopes. On one hand, on the north-facing hillslope shrubs covered approximately 75 % of the hillslope, consequently there were no true bare soil areas because of the great amount of litter produced that covered the patches between shrubs (Gabarrón-Galeote et al., 2012). Thus, there was a high input of hydrophobic compounds, more abundant in the shrub covered areas, that triggered SWR when soils became drier. On the other hand, on the south-facing hillslope shrub-cover was rather discontinuous and there were large patches where the litter layer was absent. These areas were covered by annual vegetation during the wet season. We expected to find SWR on the SIS microenvironment due to the annual vegetation growth, as it was reported by Martinez-Murillo and Ruiz-Sinoga (2007) for the same study site, but the values obtained in the present study were lower. This might have beeb caused by an extremely rainy year previous to their measurements (1081 mm) that caused an extraordinary vegetation growth and a higher than average amount of litter production during that summer. In contrast, precipitation during the year previous to our study was 528 mm.

The values of SWR in the wet season are consistent to the seasonal behaviour of SWR. Crockford et al. (1991) reported that only 9 days without rain during the wet season were enough to trigger repellent conditions in the soil. However, the relation between antecedent rainfall and SWR depends on vegetation type. Keizer et al. (2008) found that only 6 days were enough to detect dramatic changes of SWR in a eucalypts forest, whereas Santos et al. (2013) detected clearly different patterns between soils under pines and under eucalypts. The wet season in our study was rainier than usual and the mean duration of dry spells was 2.5 days, so we can expect permanent wettable conditions throughout this season. Thus, there was a heterogeneous pattern of soil water repellency related to vegetation cover and litter input (Doerr et al., 1998) during the transition season, which turned into homogeneous and wettable during the wet season.

4.2 Runoff generation

During the transition season, the maximum values of runoff rates took place in the north-facing hillslope in both environments, whereas in the wet season the maximum values took place in the vegetated areas, independently of aspect. This suggests a change in the factor controlling runoff generation. As for SWR, runoff generation was different between hillslopes. Soil water repellency has been proven to have significant effects on the soil hydrological response, on the runoff generation as well as on soil erosion (Doerr et al., 2003; Shakesby et al., 2000; Prats, 2012). However, these effects are not always of the same magnitude and they are strongly dependent on the continuity of the repellent layer and the cracks and pores on the soil surface (Granged et al., 2011). During the dry season no runoff was detected because the rainfall events were of low magnitude and intensity, and the SWR was not fully developed when these events occurred, which was in May and the beginning of June.

On the north-facing hillslope, overland flow was higher in the bare patches than beneath shrubs, and two clearly contrasting soil responses were observed throughout the hydrological year. At a plot scale, all the hydrological variables (R_{r}, R_{p}, S_{c} and S_{l}) were significantly higher in the transition season. The change of conditions was observed not only in the mean values of rate and runoff coefficient, but in the correlation of these properties with precipitation. On one hand, the slope of the relation between runoff rate and I_{max} was clearly different between seasons in both microenvironments. On the other hand, the events with higher R_{c} occurred in the transition season, being independent of precipitation. This seasonal behaviour of overland flow in Mediterranean conditions could be related to soil crust formation (Nunes et al., 2010), but soil surface layer on the north-facing hillslope had more than 5 % of organic matter, so surface crusting was not the reason for the enhanced overland flow (Hillel, 1998; Beven, 2001). This suggests SWR as the more probable cause (Doerr et al., 2003). The strong influence of SWR on runoff generation during the transition season was studied on the same hillslope by Gabarron-Galeote et al. (2012) by means of rainfall simulations. They obtained runoff in 100 % and 60 % of the experiments developed for bare soil and beneath shrubs respectively. When runoff is a consequence of SWR, it is generated by Hortonian mechanisms, since the wettability of the soil surface decreases dramatically (DeBano, 1971). Indeed, the significant relation between I_{max} of the event and the runoff rate suggests that runoff is mainly generated by Hortonian mechanisms on the north-facing hillslope during the transition season. The fact that the R_{c} was higher in NIS (12.22 %) than in NSC environments (5.26 %), whereas SWR was moderate and severe respectively, was probably caused by the presence of more macropores due to root development of shrubs in NSC patches. These macropores caused discontinuities in the repellent layer and allowed the runoff generated to reinfiltrate within the plot and reach the hydrophilic layer beneath the repellent one. These kinds of discontinuities, due to macropores as well as to a patchy pattern of SWR, are the cause of the low response to runoff generated in repellent conditions at the catchment level (Doerr et al., 2003). In the study mentioned above, Gabarron-Galeote et al. (2012) found that macropores were the main infiltration way during rainfall simulations when soil surface is repellent. The I_{max} threshold for runoff generation was higher in the bare patches, a result consistent with the lower SWR.

SWR disappeared in the wet season and the hydrological response also changed clearly. Relations between runoff rate and I_{max} were weaker, which suggested that under hydrophilic conditions the formation of Hortonian overland flow was prevented; therefore the lower runoff of this season was produced by saturation of the shallow soil (Shakesby et al., 2000), favoured by the extremely wet season of the year 2009–2010. In fact, in the NSC patches the relation of runoff with I_{max} disappeared, whereas the relation with P became significant. In a study of Doerr et al. (2003), developed in an area with similar topographical and geological characteristics but significantly more rainy, the hydrological response at plot scale during the wet season was similar to the one reported here on the north-facing hillslope. They detected only 1 out of 60 events with more than 3 % of runoff during the wet season, whereas our maximum value was 2.26 %. Doerr et al. (2003) also pointed out that only in very wet conditions could saturation overland flow be developed, caused by the saturation of the relatively shallow soil. This statement is also applicable to the north-facing hillslope of our experimental area.

On the south-facing hillslope there were no significant differences in rate and coefficient of runoff between seasons, and neither in the relation between I_{max} and runoff rate. However, there were some remarkable differences between microenvironments that are important to highlight. In the transition season, the runoff was 3.06 % and 1.27 % in inter-shrub and vegetated patches respectively. These values were both lower than the corresponding ones on the north-facing hillslope. In the bare patches this fact seems reasonable since soils are wettable even in the transition season. Therefore, although in absence of SWR, soil conditions of this layer are less favourable to promote infiltration as they are on the north-facing hillslope (soils less developed, with low organic matter content and hydraulic conductivity, Martinez-Murillo et al., 2007), where a lower overland flow was detected. In addition, annual vegetation created paths that favour infiltration of the generated runoff. Regarding the shrub covered areas, they showed moderate SWR during the transition season but, surprisingly, the lower overland flow was measured here. This can be explained by the vegetation allocation on the south-facing hillslope. The non-uniform distribution of vegetated areas promotes the spatial concentration of soil moisture, nutrients, biological activity and sedimentation beneath shrubs (Cammeraat, 2004; Ludwig et al., 2005; Puigdefábregas, 2005; Martinez-García et al., 2011; Espigares et al., 2013). At the same time, soil fertility is reduced in inter-shrub areas because of erosion and gas emission processes. This generates a feedback process (Pugnaire et al., 1996; Cerdá, 1997; Holmgren et al., 1997) that continuously improves the soil properties of so-called fertility islands (Schlesinger et al., 1990). Due to the good soil conditions and the biological activity, Hortonian overland flow generated by repellent conditions was rapidly re-infiltrated through animal burrows (Garkaklis et al., 1998), root channels and macropores (Sevink et al., 1989; Doerr et al., 2003), and there was no connectivity between the small patches source of runoff, even at a plot scale.

During the wet season no SWR was detected and runoff was 2.59 % in bare patches and 0.96 % in vegetated areas. These values are consistent with the fertility island theory formerly explained, and they are a direct consequence of the infiltration capacity, the quality of soils and the control of the soil erosion (Cerdà, 1998).

It is difficult to elucidate the runoff generation mechanism on south-facing hillslope of the study area. In similar conditions, Martinez-Murillo and Ruiz-Sinoga (2007) found differences in runoff rate generated as well as in the mechanisms between seasons on south-facing exposures. The differences in runoff generated were justified because they found water repellency in the transition season in both microenvironments. They stated that during the wet season runoff was produced by saturation mechanisms. In this study, the consistent relation between $I_{\max}$ and runoff rate could suggest Hortonian runoff generation, but in the absence of soil, water repellency overland flow by saturation of the shallow soil cannot be discarded (Shakesby et al., 2000).

To sum up, during the transition season, SWR was the main factor controlling overland flow generation, especially on the north-facing hillslope; whereas in the wet season runoff generation depended mainly on the soil properties that favour infiltration (e.g. organic matter, aggregate stability), which is determined by the vegetation cover (Cerdá, 1996; Mataix-Solera et al., 2011).

4.3 Sediments and soil loss

Sediment transport variables (S_c and S_l) had a similar behaviour to the ones reported by runoff variables, showing larger differences between seasons on the north-facing hillslope than on the south-facing one. The first point to be highlighted is that SWR significantly affected the Sc of the runoff generated. In the three microenvironments where conditions shifted from repellent to wettable conditions when wet season started, a decrease of S_c was also detected. The change of S_c was significant on NIS and NSC. In SSC, although mean S_c was 0.91 g L^{-1} in the transition season and 0.59 g L^{-1} in the wet one, the difference was not significant because of the large data dispersion. The higher S_c in the transition season can be explained by the effect of SWR in soil surface. According to Ahn et al. (2013), soil water repellency increases the distance of ejection of particles after a drop impact, which in hillslopes with a certain degree of inclination involves greater net downslope movement and, hence, net erosion of particles. Shakesby et al. (2000) reported that in hydrophilic soils the wetting provoked an increase in the particles cohesion and, in consequence, a compact surface seal that limited the amount of splashed sediments was developed. On the contrary, in hydrophobic soils, particles remained dry and easily detachable. For NIS and NSC, the higher S_c together with higher runoff coefficient and rate in the transition season made reasonable that sediment losses were also larger. In a study conducted in burnt soils, Sheridan et al. (2007) also detected, under repellent conditions, a higher S_l. This fact was explained by an increase of the S_c that in turn was due to the higher soil erodibility and the loss of vegetation cover. In our case, vegetation cover remained rather constant, so changes in S_c in repellent conditions were due to the increase of soil erodibility. In the case of the SSC microenvironment, contrastingly to what occurred on the north-facing hillslope, the higher S_l was only explained by the increase in S_c since no difference in R_r and R_c were detected. In this microenvironment, in addition to the increase of soil erodibility promoted by SWR, the high S_c was promoted by the higher sediment availability. The factors causing high availability of sediments in shrub-covered plots were, firstly, that the inter-shrub areas are more frequently washed by runoff and, secondly, that the washed sediments are deposited beneath shrubs and they are only transported when the precipitation event is deep or intense enough (Martínez-Murillo and Ruiz-Sinoga, 2007). Similar spatial relationships between sediment yield, vegetation and bare soil were found by Puigdefábregas and Sánchez (1996), Puigdefábregas (1998) and Sheridan et al. (2007). Under Mediterranean climate, Nunes et al. (2010) also detected more erosion in the dry period in herbaceous, shrubland and oak-tree areas, although they attributed this fact to crust formation instead of soil water repellency.

It is noteworthy that during the transition season the changes in SWR were not proportional to the changes in soil loss. In fact, sediment transport does not have to be necessarily proportional to SWR (Shakesby et al., 2000) since it also depends on the availability of sediments and the capacity of water to move them. Different studies have reiterated that SWR has a relative importance in the erosion processes, but other properties such as rainfall depth, rainfall intensity or litter cover have usually a bigger impact (Prats et al., 2012; Malvar et al., 2013). In this sense, Robichaud et al. (2013) pointed out that due to the combined effect of different variables, such as vegetation cover, the apparently consistent relation between SWR and erosion could not be assured in that particular case. In our case, I_{max} proved to be a significant influence on S_c during the transition season, even in the SIS microenvironment, which remained wettable. This suggests that SWR is an important property modulating soil erosion but, ultimately, it is more strongly determined by rainfall characteristics. Robichaud et al. (2013) also found that rainfall intensity was the main property determining sediment yield. During the wet season I_{max} had only significant influence on S_l in the inter-shrubs patches. A potential explanation for this is the combination of the absence of SWR combined with the thick layer of litter in the shrub-covered patches, which prevented the sediment movement since the energy of raindrops decreases before impacting soil particles (Casermeiro et al., 2004; Prats et al., 2012).

5 Conclusions

This paper contributes to understand that (i) rainfall intensity was the main property determining overland flow and sediment transport. In general, the events that generated more runoff and erosion were those with a higher I_{max}, independent of the rainfall depth. Only in the shrub-covered patches during the wet season this relation was weaker due to the effect of the litter cover and to the absence of SWR. (ii) Soil water repellency was an important ecological factor in the study area, especially on the north-facing hillslope, where it determined a dramatic change in the hydrological response between repellent and wettable conditions. A decrease of overland flow and erosion was detected, and even a change in the runoff generation mechanism. Also, vegetation pattern was an important factor, especially on the south-facing hillslope where overland flow generation was determined. It was higher in the inter-shrubs patches throughout the year, independent of the season considered, and the feedback process of enrichment in the shrub-covered patches mitigated the effect of SWR in the transition season.

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