TITLE: IMPACT OF LOW PRESSURE GRAZING IN THE HYDROLOGICAL AND SEDIMENT CONNECTIVITY IN HILLSLOPES UNDER CONTRASTED MEDITERRANEAN CLIMATIC CONDITIONS (SOUTH OF SPAIN).

SHORT TITLE: GRAZING AND CONNECTIVITY IN MEDITERRANEAN HILLSLOPES.

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ABSTRACT

Many areas from the Mediterranean region are characterised by steep slope gradient, patchy vegetation cover and soil surface conditions prone to overland flow generation and sediment transport. This study evaluated the hydrological and sediment connectivity between sections (top, middle and bottom-channel) from three low pressure grazed hillslopes located under contrasted Mediterranean climatic conditions in southern Spain. The aim was performed by installing rain-gauge stations and opened-plots in order to register overland flow and sediment concentration from Feb-2008 to Jan-2010. The results indicated that: i) major volumes of overland flow and sediment transport occurred more frequently in the humid and semiarid; ii) the more frequent hydrological connectivity was observed between the middle and bottom-channel sections, though the major values of overland flow and sediment concentration were registered in the upper sections; iii) it was found very frequent those rainfall events in which all sections contributed with overland flow and sediment to the channel; iv) the factors controlling hydrological and sediment connectivity varied from one site to another depending on the rainfall regime and vegetation cover, though the soil surface conditions (rock fragment cover either embedded or not embedded, crusts, annual plants, among others) were found a key factor in all of them. In summary, the grazing activity, even

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being of low pressure, contributes to distance the hydrological and sediment connectivity from the response expected in the field sites, especially, in that of humid Mediterranean climate: more overland flow and less sediment concentration and, vice versa, when becomes arid.

KEYWORDS: hydrological connectivity, overland flow, sediment, grazing, Mediterranean hillslopes.

INTRODUCTION

Up-to 11 definitions of hydrological connectivity were compiled by Ali and Roy (2009) making evident the lack of consensus in its definition (Bracken *et al*., 2013). Most of those definitions relate the linkages between those elements, which define the eco-geomorphologic landscape (relief, climate, vegetation cover and land use, and human infrastructures, among others), and the energy and matter transfer that occurs from hillslopes to riparian zones and channels as well. From all those definitions the presence of two types of connectivity arises: structural and functional. According to Turnbull *et al.* (2008), the former corresponds to the spatial patterns in the landscape, such as the spatial distribution of landscape units which influence water transfer patterns and flow paths, whilst the latter refers to how these spatial patterns interact with catchment processes to produce runoff, connected flow and hence water transfer in catchments. Thus, according to Masselink *et al*. (2016), the concept of connectivity addresses the spatial and temporal variability in runoff, sediment transport and associated substances such as pollutants and how these move through the catchment. Sediment connectivity explains which sediment sources contribute and where (semi-) permanent sinks and pathways of sediment are (Bracken & Croke, 2007).

The Mediterranean eco-geomorphological landscape is highly dependent on the climatic and topography conditions. The elements forming the spatial patterns of landscapes which control the structural connectivity may vary in time and space. Indeed, the existence of rainfall gradients in the Mediterranean region has been well-documented (Imeson *et al*., 1996; Lavee *et al*., 1998; Ruiz-Sinoga *et al*., 2011, 2015; Marchamalo *et al*., 2016) along which those elements are modified by the spatio-temporal variability of rainfalls. Consequently, the characteristics of those elements are modified from the rainiest to the driest regions following a positive feedback process that leads the system to eco-geomorphologic conditions prone to soil erosion and degradation (Lavee *et al*., 1998).

As the climate becomes less rainy, the patchy vegetation pattern becomes more frequent and the bare soil areas along hillslopes can be easily connected whether the magnitude and intensity of rainfall exceed a certain threshold (Beven & Kirkby, 2002; Cammeraat, 2004; Ruiz-Sinoga *et al*., 2010a; Ruiz-Sinoga *et al*., 2010b). The interaction between topography and processes occurring within catchments is key to understanding dynamics of hydrological connectivity (Bracken & Croke, 2007; Turnbull *et al*., 2008; Wainwright *et al*, 2011). Thus, it becomes transcendent to characterize and evaluate the elements which forms the eco-geomorphologic landscape to apprehend as much as possible the interaction between them with catchment and hillslope processes to produce runoff, connected flow and hence water transfer as well as sediment. Focussing on Mediterranean eco-geomorphologic landscapes characterised by patchy vegetation patterns, especially frequently in southfacing hillslopes (Dickie & Parsons, 2012; Saco & Moreno-De las Heras, 2013; Okin et al., 2015), the hydrological response becomes highly difficult to model due to the coexistence of very different interaction within the catchments: vegetation acts as sink and barrier areas for overland flow, which usually is generated in the bare soil ones and thus sediment as well (Puigdefábregas *et al*., 1999; Ruiz-Sinoga *et al*., 2010c). In this conditions, connecting overland flow and hence sediment from the top of hillslopes to other sections as well as to the channel depends on the magnitude and frequency of rainfalls. This is especially characteristic in the rainiest sites and, thus, the frequency of connecting hillslopes and channels decreases along the rainfall gradients towards the driest sites where only the most extreme events can make to interact all hillslope sections with channels (Puigdefábregas, 2005). In Mediterranean regions, with rainfall gradients and changes in the structural connectivity, a decreasing trend in the functional one can be pointed out towards the most semiarid sites as biotic factors (vegetation, organic matter content in the soil, litter among other) become less frequent (Ruiz-Sinoga *et al*., 2010b).

However, in some cases, the eco-geomorphologic landscape from rainier regions may become very similar to that from drier ones due to grazing as dominant land use reducing vegetation cover (Ruiz-Sinoga *et al*., 2010a; Pulido *et al*., 2016) and, as consequence, soil erosion and degradation are enhanced (Palacios *et al*., 2014). Run-off generation can be favoured where scrub growth is prevented by over-grazing (Boix *et al*., 1995). Thus, where grazing becomes very dominant, soil degradation phenomena by water erosion have been reported in rangelands from Mediterranean environments (Schnabel, 1997; Gómez Gutiérrez *et al*., 2009; Ruiz-Sinoga et al., 2010a). The vegetation cover is reduced due to the cattle harvesting and, consequently, the connections between hillslopes sections and channels are enhanced during the rainfall events promoting sediment exportation (Kakembo, 2009; Teztlaff et al., 2012; Arnáez et al., 2015)

The aim of this study is the assessment of hydrological and sediment connectivity in hillslopes affected by grazing of low pressure, and located in very contrasted climatic conditions along a Mediterranean mountainous region. Namely, the objectives are to: i) characterize overland flow and sediment movement along southfacing hillslopes; ii) evaluate hydrological and sediment connectivity between the hillslope sections; and iii) corroborate the most controlling factors in accordance to previous studies performed in the experimental sites.

MATERIALS AND METHODS

Study area

The study covers a geographical area in South of Spain including the Cordillera Bética along which a rainfall gradient is observed (Fig. 1). Considering this geographical area, in accordance to the methodology proposed by Imeson & Lavee (1998), three field sites were selected taking into account that all of them had to be characterized by similar topography, geology and land use, but different climatic conditions: humid (HU), dry (DY) and semiarid (SM) Mediterranean climate. Table I compiles the most important eco-geomorphologic characteristics from the three field sites. According to the map of annual rainfall including in Figure 1, HU, DY and SM areas were representative from those geographical areas above 900, between 450 and 900, and below 450 mm, respectively, Water erosion was the most relevant geomorphic process in all of them: washed bare soil areas with high rock fragment content on the top of soil, mainly, as well as areas concentrating overland flow with incipient rills.

The three field sites share similar human activity: grazing. In the three cases, the cattle were of goats (20-25 individuals) grazing either one or two day per week, depending on the season and the growth of therophytic plants. Although the recurrent period of grazing was not very frequent, it was enough to maintain the vegetation cover in lower levels than expected without that activity, especially in the humid and dry-Mediterranean sites. In different field surveys, conducted before the installation of plots, as consequence of the grazing activity, it was estimated the vegetation cover was reduced in at least 30-40%, 25-30% and 20% in the humid, dry and semiarid sites, respectively, by comparison to other similar hillslopes free of this human activity.

Plots

Figure 1 also shows the experimental design with the set of opened plots, which was replicated at each field site. In the HU and DY sites, a paired-set of one-metre width opened plots were installed in every section (top, middle and bottom-channel) of a hillslope with

South facing exposure, whilst three of them were built in SM site (SM in advance) in South facing exposure as well; one plot more in SM because the rainfall variability and scarcity was higher in the semiarid one. Totally, there were 6-opened plots in HU and DY and 9 in SM. In all cases, the plots were oriented parallel to the line of the maximum slope and enclosed in their lower parts using strips inserted 10 cm into the soil. At the bottom of each plot, a container of 250 L was installed for collecting overland flow and sediment. Table II compiles the main eco-geomorphologic characteristics from the opened plots. Plot length and slope gradient slightly differed between field site but the topographic profile was similar in all of the cases: concave-rectilinear-concave. This type of profile is very frequently observed in relieves of metamorphic rock as parent material, which enhances water erosion and incision processes. In any case, the comparison between sites and plots was made according to the section within the hillslope: top, middle and bottom-channel.

Measurements

In the three field sites, rainfall was monitored using a tipping-bucket rain gauge (0.2 mm accuracy) with recordings made at 15 min intervals. Overland flow and sediment yield was measured from February 2008 to January 2010 and were measured after each rainfall event; one rainfall event was defined as that separated by 24 hours from the next one. In order to register total overland flow and sediment concentration, an erosive event was defined as that rainfall event which generated overland flow. Total overland flow for each rainfall event was registered by inserting a ruler into the containers; before the final installation, the calibration method consisted in adding known volumes of water and measuring the level with the ruler. Suspended solids were measured in homogenous solution for each event by means of suspending settled material within the containers. Due to constraints in measuring accurately the contribution area to each plot, overland flow was related to the plot length (L m^{-1}). The sediment concentration (g L^{-1}) was also calculated after drying and evaporating the water completely from the overland flow samples in a laboratory heater.

Statistical analysis

The statistical analysis was performed in order to evaluate the difference in connectivity between hillslope sections considering the whole dataset (regional approach) as well as each field site dataset (local approach). To do this, the differences in overland flow and sediment were analysed in order to assess that connectivity between sites and hillslope section, assuming those differences can be considered an approach to it. Descriptive statistical tests, as mean, standard deviation and coefficient of variation, were calculated. Differences in overland flow and sediment yield were tested using analysis of variance (one-way ANOVA). The normality and homogeneity of variance were assessed by means of the Shapiro-Wilk test (number of samples <50) and Levene's test, respectively. In case of non-homocesdasticity (Levene's test; $p<0.05$), non parametric test were used. Mean differences between the various experimental sites and hillslopes sections were determined using Tukey test or Games-Howell test when data were either parametric or non-parametric, respectively. Overland flow data responded to a parametric distribution, whilst the sediment data to one non-parametric. In all the analyses the selected significance limit was 0.05.

In order to characterize the correlation between overland flow and sediment delivery with eco-geomorphologic drivers (rainfall, length, slope gradient, and vegetation cover): Pearson´s and Spearman´s coefficient were applied whether the data were parametric or not, respectively. Also, one regression analysis was performed in order to estimate the relationships among variables, including the modelling (adjustment of an equation: linear, polynomial, logarithmic, etc.) focussed on the relationship between the considered independent variables overland flow and sediment concentration) and the dependent one (plot length).

Regarding the frequency of connectivity between hillslope sections and channel, the number of erosive events in which overland flow and, thus sediment, was registered at the same time in the top, middle and bottom sections was evaluated. For this purpose, several types of connections were previously defined as follows: type 0, no overland flow; type 1, overland flow solely generated either in the sections 'top' or in the 'middle'; type 2, connectivity between sections 'top' and 'middle'; type 3, connectivity between sections 'middle' and 'bottom-channel'; type 4, overland flow solely registered in the section 'bottom-channel'; type 5, connectivity between all sections.

The statistical analysis was performed using SPSS version 24 for Windows.

RESULTS

Rainfall, overland flow and sediment transport

Rain-gauge stations recorded rainfalls consistent with the position of the field site within the rainfall gradient observed in the study area. Table III shows the general statistic of rainfall data from the three field sites. Totally, 80, 84 and 117 events of rainfalls, generating overland flow or not, were registered in HU, DY and SM, respectively. From all of them, as it is addressed in Table III, only 47, 27 and 16, generated overland flow in HU, DY and SM, respectively, being considered as erosive events. This occurred because events with shorter duration were more frequently in DY and SM than in HU, where events were longer in time as well as higher values in mean and median indicated a major occurrence of extreme rainfall events. Between HU and SM, there were a clear decreasing trend in the rainfall depth, number of rainy days and rainfall intensity as well. The rainfall events with intensity of less than 5 mm h^{-1} were the most frequent in the three field sites: 78.9, 85 and 90% of the total events in HU, DY and SM, respectively. Conversely, the rainfall events with intensity major than 15 mm h^{-1} did not exceed 5% of frequency (3.4, 1.3 and 1.1% in HU, DY and SM, respectively). The lower frequency of rain events as well as rainfall intensity were more remarkable in SM where the number of events with rainfall exceeding 15 mm h^{-1} was extremely low (2 of 180 events). The frequency of the most intense rainfall events were larger in autumn than in winter and spring, especially, in HU and DY. Table IV shows the most rainfall events during the study period, which declining in depth, duration and intensity from the rainiest site to the driest one. The kinetic energy was also higher in HU, but did not follow the similar clear trend. In SM, some extreme rainfall events exceeded or equalled the highest one in kinetic energy from DY.

Table V compiles the descriptive statistic of overland flow and sediment concentration from the three field sites. The frequency with rain events generating overland flow and thus sediment transport was of 31.7, 23.3 and 29.9% in HU, DY and SM, respectively, considering the whole database per site. This meant the database included 124, 59 and 106 plot-event data in HU, DY and SM, respectively, whether all sections and plots were taking into account. HU and SM registered the major values either in overland flow generation and sediment concentration compared to DY. Overland flow was one order of magnitude major in HU and SM than in DY as well as in the case of sediment concentration, though it was up-to seven points major in SM than in HU. The maximum values of overland flow and sediment concentration did not usually coincide during the same rainfall event. In general, maximum values of overland flow were significantly affected by the depth of rainfall (r=0.48; p=0.00) and rainfall intensity (r=0.46; p=0.00), but not sediment concentration (r=0.08; p>0.05) and (r=0.16; p>0.05).

Differences between sites and hillslope sections

The significant differences in the mean values of overland flow and sediment concentration were evaluated between sites and hillslope sections. Overland flow data were parametric whilst sediment non-parametric in all cases. Neither mean nor maximum overland flows were statistically and significantly different (p>0.05). In the case of sediments, there were significant differences between DY and SM when means and maximum sediment concentration were compared: p=0.019 and p=0.023, respectively. When sections were taken into account, certain significant differences arose in overland flow. These differences were statistically significant in the case of mean and maximum overland flow (Table VI). However, it was not found significant differences in the case of sediment concentration in none of the hillslope sections.

At local scale, when the hillslope sections were compared, significant differences were found in HU and SM but not in DY (Fig. 2). In HU, only mean overland flow significantly differed between the top and middle sections as well as between the top and bottom-channel one. In SM, similar results were found for the mean overland flow and in the case of the maximum overland flow as well. Mean and maximum sediment concentration did not significantly differed in both previous sites. Finally, in DY, neither overland flow nor sediment concentration was found statistically different between the sections.

The results of statistical tests indicated, in general, overland flow may differ in more cases than sediment concentration between sites as well as between hillslope sections. Plots from the three field sites produced overland flow when certain thresholds of rainfall depth and intensity were exceeded: >10 mm and 5 mm h^{-1}, respectively, for all of them. Regarding the rainfall intensity, the threshold observed was of 4.8 mm h^{-1}. If the hillslope section was considered, similar values were obtained for the middle one, but not in the case of the others, top and bottom-channel sections, where the rainfall depth threshold needed were of 15 mm. However, in the case of the sediment transport, plots from DY differed to SM plots. In the former, the sediment concentration was one order of magnitude lower than in the latter.

Fig. 3 shows the distribution of overland flow and sediment concentration in the different considered sections. At a glance, as it was shown in Table IV with the coefficients of variation, the variability was high as well as the range wide in all cases. In general, the magnitude of overland flow decreased from the top to the bottom-channel section in the three field sites, especially, in the transitional site (DY). The equation of adjustment varied between sites: logarithmic, polynomial and logarithmic in HU, DY and SM, respectively. The equation slope indicated that overland flow magnitude decreased more rapidly in SM, HU and DY, following this order. Regarding sediment concentration, the trend along the hillslopes was unclear. Taking into account that sediment concentration was usually one order of magnitude major in SM than in HU and, especially, than in DY, the sediment transport differed from one site to another. In HU, it was found sediment concentration diminished from the top to the middle section but decreased towards the channel. In DY, the sediment concentration decreased from the top to the bottom-channel section, though it must be pointed out its magnitude was almost negligible in most events with less than 1 g L^{-1}. Finally, the most effective overland flow transporting sediments was registered in SM, the driest site, as the sediment concentration highly increased from the top to the bottom-channel section indicating very active transfer of sediment from the hillslope to the channel system.

Frequency of connectivity between hillslope sections and channel

The frequency of connectivity between hillslope sections and channel was evaluated as well. In the material and method section, the type of defined connectivity between sections was addressed. As Fig. 4 shows, the type 0 was dominant whether the whole database was taken in consideration: more than 50% of events did not generate overland flow. Regarding the type of connectivity, the connection between all sections and channel presented the major frequency with more than 20%. The other types dropped below 10% of frequency.

At local scale, there were some common trends between the three field sites, though somehow it differed. The rainfall events generating overland flow were dominant in DY and SM, but not in HU. The disconnection between sections and the overland flow generated only in either the top or middle sections increased from the driest to the rainiest site. The connectivity solely between the top and middle section of hillslopes were found the less frequent type. Unexpectedly, the type 3 (connectivity between middle and bottom-channel section) was the one which occurred with less frequency in HU, whilst it exceeded 10% in DY and SM. On the contrary, the type 4 which occurred when overland flow was generated in the bottom section and reached the channel increased in the rainiest site. Finally, the connectivity between all sections and channel (type 5) was the dominant process in HU as well as in SM when overland flow was registered, but not in DY where the most frequent type of connectivity was the type 3 of connectivity: connectivity of middle section with the bottom-channel one.

DISCUSSION

The overland flow and sediment data recorded at three field sites (differing in climatic conditions only) and hillslope sections (top, middle and bottom) corroborated that the rainiest and semiarid sites registered major overland flow and sediment transport, respectively, whilst the dry site was intermediately positioned. Rainfall intensity (in the rainiest site) and soil surface conditions (in both transitional and driest sites) become important structural factors controlling the functional connectivity among hillslope sections during the erosive events in the three grazed field sites. Another remarkable finding was overland flow and sediment concentration were larger in the upper sections of hillslopes than in the others. Notwithstanding, the connectivity between the middle and bottom-channel sections as well as the whole hillslope with the channel showed the most frequent hydrological and sediment connectivity, especially, in the rainiest and driest sites.

Cammeraat (2002) indicates three main factors influencing diffuse connectivity at hillslope scale: i) soil surface irregularity (roughness), which could be very low on the patch scale, but higher at the hillslope and catchment scales, ii) spatial organization of the vegetation on the hillslope scale and the spatial arrangement between land units at the catchment scale, and iii) rainfall intensity, event duration and thus the effective rainfall.

Rainfall regime is a key control factor in the overland flow generation and, thus, in the sediment connectivity along hillslopes and between hillslopes and channels. The reported data of rainfalls in this study, especially, that related to the frequencies of rainfalls with certain magnitude, even for the semiarid site, were substantially different from those previously reported for Mediterranean climatic conditions (Marqués *et al*., 2008; De Luís *et al*., 2010). Bull & Kirkby (2002) addressed a rainfall intensity of 15 mm h^{-1} as the limit to consider a rainfall event as erosive, especially, in semiarid regions; in our study, those rainfall events exceeding 15 mm h^{-1} were of very low frequency. It is not evaluated what is defined as an erosive event and how they contribute to soil erosion in this research, though it can be pointed out what was exposed by González-Hidalgo et al. (2009) that the largest events represent a high percentage of total soil erosion – the largest 10% of events account for at least 50% of total erosion, independently of the length of record, soil characteristics, plant cover or farming practices. These considerations as well as the variability of what is considered an erosive event and its effects on the connectivity between hillslope sections and channels requires further investigations.

In these semiarid regions, as the vegetation cover is decreased and the most extreme rainfall events become less frequent, the duration of rainfalls arises as one fundamental factor (Puidefábregas, 2005). In this study, the major rainfall events in depths and duration were registered in the most rainy site rendering into a more frequent connectivity between the three hillslopes sections considered as well as with the channel. At the most driest site, the entire connection between hilllslope sections and channel remained as the most frequent as well, but here the rainfall intensity and other factors, latter discussed, may play a major influence in overland flow and sediment transport than rainfall duration. In the transitional site (DY), it was clearer the absence of longer rainfall events: the partial connectivity of middle section with the bottom-channel was the most frequent one.

Generally speaking, along the rainfall gradient observed in the study area, a decrease in vegetation cover would be expected (Lavee *et al*., 1998), being major in HU and lower in SM. Vegetation is a key factor in connectivity: it influences surface roughness and local capacity to store sediments and water (Puigdefabregas *et al.*, 1999) and, also, increasing infiltration (Bochet *et al*., 1999; Cammeraat, 2004; Ruiz-Sinoga *et al*., 2009a). Hence, vegetation contributes towards disconnecting upstream and downstream areas (Borselli *et al*., 2008).

However, the human activity can impact the vegetation cover through cultivation, abandonment of agricultural lands as well as grazing activity, for instance, reducing the vegetation cover to unexpected levels coverage whether rainfall supplies are considered (Pulido *et al*., 2016). This is especially transcendent in Mediterranean southfacing hillslopes where the major radiation increases the evapotranspiration process leading to less water holding into the soil and, consequently, less available water for the growth of plants (Gabarrón-Galeote *et al*., 2013). In consequence, as result, the reduction of vegetation cover is enhanced and more surface of bare soil is exposed to raindrop impacts and hence source areas of overland flow and sediment are increased.

In our study, the three sites were affected by low pressure grazing but sufficient to reduce the vegetation cover, especially, in HU and DY. Areas between shrubs in HU and SM were nearly completely uncovered, but not in DY where those areas were mostly covered by annual vegetation from December to June due to a lower pressure of grazing. In fact, the presence of this type of vegetation played a key role in retaining soil particles despite the generation of overland flow (Martínez-Murillo & Ruiz-Sinoga, 2007; Ruiz-Sinoga *et al*., 2010a; Gabarrón-Galeote *et al*., 2013) and the sediment concentration registered in DY were almost negligible in many rainfall events that generated overland flow. Another important factor related to vegetation to explain our results were the relative position of vegetation within the plots. All plots had shrub patches not located just in their lowest part and in contact with the collector, but at least 1-metre up in order to better evaluate the effect of grazing.

Thus, our results are well-explained when soil surface conditions are considered at patch scale. In fact,the eco-geomorphologic conditions were more different between sites when soil surface conditions were analysed. In previous studies, Ruiz-Sinoga & Martínez-Murillo (2009b), Ruiz-Sinoga *et al*. (2010b) and Ruiz-Sinoga *et al.* (2010c) reported the impact of soil surface conditions in the hydrological response of soils from the same sites. Plots in HU presented soil surface conditions prone to overland flow generation: the presence of rock fragments embedded into the soil surface with some crusts due to the coexistence of high gravel content and clay-silty texture. Thus, in absence of vegetation cover and organic matter supply, bare soils becomes excellent sources of overland flow and sediment in HU. In fact, that soil surface condition has been widely proposed as a key factor in soil erosion (Poesen & Ingelmo, 1992; Poesen & Lavee, 1994; Martínez-Murillo *et al*., 2010). These soil surface conditions added to steep slope gradients and patchy vegetation patterns implies grazed southfacing hillslopes may be characterised by a remarkable structural connectivity which become functional very frequently during the abundant and longer period rainfalls under humid Mediterranean climate.

In the case of SM, Martínez-Murillo *et al*. (2010) and Ruiz-Sinoga *et al*. (2010b) reported a condition mainly characterised by very high rock fragment cover (over 70%) disposed on the surface of soil, not embeded, which was extremely shallow (less than 10 cm of depth). This is a very common feature from Mediterranean soils affected by old cultivation activity and water erosion from semiarid Mediterranean mountains and, in some cases, it has been pointed out that such high rock fragment cover, when it is not embedded, play a key role in reducing soil erosion (Shakesby, 2011). However, this were not the case of SM, where the short but intense rain storms and the very low vegetation cover generated very efficient overland flow transporting sediment along the whole hillslope towards the channel system connecting with certain frequency the middle and bottom section to the channel.

Finally, in DY, rock fragments partially embedded into as well as partially on the soil surface mainly featured the soil surface conditions. Besides, annual plants seasonally covered areas between shrubs. All these elements may produce a more complex response in the hydrology of soils and thus of the hillslope, especially, when water repellency have been reported in this field site as well making possible even the generation of overland flow from vegetated areas (Martínez-Murillo & Ruiz-Sinoga, 2010). Nevertheless, in this field site, during the study period, the major vegetation cover and the absence of either longer rainfalls in duration or greater depths may influence the very low generation of overland flow and thus the sediment transport.

In summary, the impact of grazing promoted similar eco-geomorphologic conditions in the studied hillslopes, especially in both rainiest and driest sites, what rendered in certain spatial patterns of vegetation and soil surface conditions (structural connectivity) that, jointly the rainfall regime, controlled the fluxes of water and sediment along the hillslope sections towards the channel system (functional connectivity).

CONCLUSIONS

The hydrological and sediment connectivity was evaluated in three Mediterranean hillslopes with similar eco-geomorphologic conditions, affected by low pressure grazing and located under different climatic conditions: humid, dry and semiarid. After this evaluation, the conclusions are the following:

i) Overland flow was up-to 2-fold more frequent in the humid site and almost two and four times major in volume respect the semiarid and dry ones, respectively. However, the sediment transport was up-to 7 and 20 fold major in the semiarid site than in the humid and dry ones, respectively.

ii) In general, the up-slope sections contribute with major volume of overland flow and sediment due to the scale dependency (shorter distance from the water division). However, the connectivity between the middle and bottom-channel sections as well as the whole hillslope with the channel showed the most frequent hydrological and sediment connectivity, especially, in the rainiest and driest sites.

iii) The reduction in vegetation cover by the cattle exposes more bare soil to rainfall, especially, in the humid and dry site. Thus, the soil surface conditions becomes extremely influential in the overland flow and sediment transport and, consequently, in the connectivity between hillslope sections and channels. Those sites with soil surface conditions prone to overland flow and, thus, to transport more soil particles, presented more frequent connectivity: rock fragment embedded in crusts as well as shallow soils with high rock fragment cover played a key role.

iii) In presence of steep slope gradients and similar vegetation patterns as consequence of the low pressure grazing, the rainfall depth and duration, in the case of the humid site, and the rainfall intensity, in the case of both dry and semiarid ones, jointly the soil surface conditions (all of them defining the structural connectivity), become important factors of the functional connectivity during the rainfall events controlling whether the considered hillslope sections are connected between them and with the channel.

To sum up, the grazing activity contributed to distance the hydrological and sediment connectivity processes of three hillslopes located under contrasted Mediterranean climatic conditions from the response expected for all of them: decreasing sediment transport from the semiarid to the humid site as the rainfalls and vegetation cover increase.

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Table I. Eco-geomorphological characteristic of field sites. Abbreviations: P, annual rainfall; T, annual temperature; HU, site under humid Mediterranean climate; DY, site under dry Mediterranean climate; SM, site under semiarid Mediterranean climate; OM, organic matter content; BD, bulk density; ASF, aggregate stability fraction.

Site	**Humid (HU)**	**Dry (DY)**	**Semiarid (SM)**
Climate	Humid Mediterranean (P: 1,010.0 mm y^{-1}; T: 14.6ºC)	Dry Mediterranean (P: 518.3 mm y^{-1}; T: 15.9ºC)	Semiarid Mediterranean (P: 293.8 mm y^{-1}; T: 10.9ºC)
Topography	680 m.a.s.l. Slopes > 25% Southfacing	580 m.s.a.l. Slopes >25% Southfacing	1,150 m.s.a.l. Slopes 20-25% Southfacing
Geology	Schists and phyllites	Phyllites and grauwacs	Mica-schists
Land use and vegetation cover (VC)	Rangeland (opened oakland with shrubs). Not intensive grazing. VC = 70%	Rangeland (opened oakland with shrubs). Not intensive grazing. VC = 55%	Rangeland (shrubs). Not intensive grazing. VC = 25%
Soil classification (FAO 2014)	Eutric Cambisol/Leptic Regosol	Ochric Cambisol/Leptic Regosol	Skeletic Leptosol
Soil properties	Gravel content = 52.6% Texture: silty loam Clay content: 22.7% pH = 5.9 OM = 11.6% BD = 1.08 g cm^{-3} ASF = 86.6%	Gravel content = 63.0% Texture: loam Clay content: 20.4% pH = 6.4 OM = 5.9% BD = 1.13 g cm^{-3} ASF = 77.9%	Gravel content = 57.6% Texture: sandy loam Clay content: 12.9% pH = 7.2 OM = 1.6% BD = 1.44 g cm^{-3} ASF = 50.5%
Soil surface conditions	Annual vegetation and bare soil partially covered by embedded rock fragment and litter.	Annual vegetation and bare soil partially covered by embedded rock fragment and litter.	Bare soil with rock fragments on the top.

Table II. Eco-geomorphologic conditions of the opened-plots.

Site	**Plot**	**Slope (%)**	**Length (m)**	**VC (%)**	**Soil surface conditions**
HU	T1	15	3	45	Embedded rock fragments (cover<20% of soil surface), crusts and annual vegetation.
	T2	15	3	45	Embedded rock fragments (cover<20% of soil surface), crusts and annual vegetation.
	M1	20	25	55	Embedded rock fragments (cover<20% of soil surface), crusts and annual vegetation.
	M2	20	25	50	Embedded rock fragments (cover<20% of soil surface), crusts, annual vegetation and litter.
	B1	25	50	60	Embedded rock fragments (cover<20% of soil surface), crusts and annual vegetation.
	B2	25	50	60	Embedded rock fragments (cover<20% of soil surface), crusts, annual vegetation and litter.
DY	T1	8	3	50	Rock fragment on top (cover 20-70%), annual vegetation and litter.
	T2	8	3	60	Rock fragment on top (cover 20-70%), annual vegetation and litter.
	M1	22.5	15	60	Rock fragment on top (cover 20-70%), annual vegetation and litter.
	M2	22.5	15	65	Rock fragment on top (cover 20-70%), annual vegetation and litter.
	B1	25	30	55	Rock fragment on top (cover 20-70%), annual vegetation and litter.
	B2	25	30	65	Rock fragment on top (cover 20-70%), annual vegetation and litter.
SM	T1	10	3	20	Rock fragment on top (cover >70%).
	T2	10	3	10	Rock fragment on top (cover >70%).
	T3	10	3	5	Rock fragment on top (cover >70%).
	M1	25	30	25	Rock fragment on top (cover >70%).
	M2	25	30	25	Rock fragment on top (cover >70%).
	M3	25	30	25	Rock fragment on top (cover >70%).
	B1	30	55	30	Rock fragment on top (cover >70%).

B2	30	55	30	Rock fragment on top (cover >70%).
B3	30	55	30	Rock fragment on top (cover >70%).

Table III. General statistic of rainfall events in the three field sites. Abbreviations: HU, humid Mediterranean site; DY, dry Mediterranean site; SM, semiarid Mediterranean site; Max, maximum; Min, minimum; Sd, standard deviation; I30, rainfall intensity in 30 minutes; EI30, kinetic energy in 30 minutes.

	HU	**DY**	**SM**
Total depth Feb08-Jan09 (mm)	858.7	506.5	341.2
Total depth Feb09-Jan10 (mm)	1269.6	758.3	424.9
Number of events	232	226	180
Mean depth/event (mm)	9.2	5.6	4.3
Median depth (mm)	2.5	2.0	1.5
Max depth in one event (mm)	174.4	64.4	47.7
Min depth in one event (mm)	0.2	0.2	0.2
Sd (mm)	18.8	10.1	7.8
Erosive events	47	27	16
Mean depth/event (mm)	33.3	26.1	25.5
Median depth/event (mm)	22.3	19.6	22.0
Max depth/event (mm)	174.4	59.5	47.7
Min depth/event (mm)	6.6	13.0	13.5
Sd (mm)	31.4	13.4	11.0
Mean I30 (mm h^{-1})	9.5	6.7	8.4
Max I30 (mm h^{-1})	38.1	17.4	29.7
Mean EI30 (MJ mm ha^{-1} h^{-1})	37.9	20.2	30.8
Max EI30 (MJ mm ha-1 h-1)	180.4	89.7	212.9
Factor R Feb08-Jan09	511.2	326.5	258.3
Factor R Feb09-Jan10	1269.5	530.8	349.3

Table IV. Most extreme rainfall events in the three field sites. Abbreviations: HU, humid Mediterranean site; DY, dry Mediterranean site; SM, semiarid Mediterranean site; D, depth (mm); T, duration (h); I30max, maximum rainfall intensity in 30 minutes (mm h^{-1}); EI30, kinetic energy (MJ mm ha^{-1} h^{-1}).

	Date	**D**	**T**	**I30**	**EI30**
HU	1/11/08	148.0	27.5	15.8	180.4
	21/12/09	174.4	46.3	9.9	176.7
	23/12/09	24.3	3.3	38.1	146.3
	24/12/09	62.3	20	18.3	124.2
	19/12/09	41.5	11.8	22.8	114.3
DY	1/2/09	64.4	20.3	14.4	99.8
	26/1/10	47.9	16.5	17.4	89.7
	23/9/08	49.2	9	12.9	68.9
	21/10/09	28.6	3.8	17.4	59
	31/10/09	59.5	19.8	7.5	43.2
SM	20/6/09	47.7	5.7	29.7	212.9
	10/10/08	42.3	5.3	19.2	96.8
	25/9/08	22.1	5	14.4	34.8
	24/9/08	17.6	1.2	13.8	31.6
	26/1/10	38.1	8.7	5.4	20

Table V. General statistic and maximum event in overland flow and sediment concentration. Abbreviations: OF, overland flow (L m^{-1}); SC, sediment concentration (g L^{-1}); m, mean; SD, standard deviation; VC, variation coefficient; max, maximum value; R, rainfall depth (mm); I, rainfall intensity in 30 minutes (mm h^{-1}).

	Site	**m**	**SD**	**VC**	**max**	**R**	**I**
OF	HU	2,1	2,29	0.93	18.2	362.8	22.8
	DY	0,51	1,02	0.50	7.2	127.1	28.8
	SM	1,43	1,64	0.87	16.7	156.3	10.8
SC	HU	1,25	2,63	0.48	29.8	43.5	42.6
	DY	0,33	0,3	1.10	1.12	31.0	34.8
	SM	7,08	18.26	0.39	113.6	58.6	38.4

Table VI. Significant p-values ($p<0.05$) comparing hillslope sections from all sites. Abbreviations: OF, mean overland flow; OF_{max}, maximum overland flow; SC, mean sediment concentration; SC_{max}, maximum sediment concentration.

	Comparison of hillslope sections		
	Top-Middle	Top-Bottom	Middle-Bottom
OF	0.07	0.06	-
OF_{max}	0.06	0.03	-
SC	-	-	-
SC_{max}	-	-	-

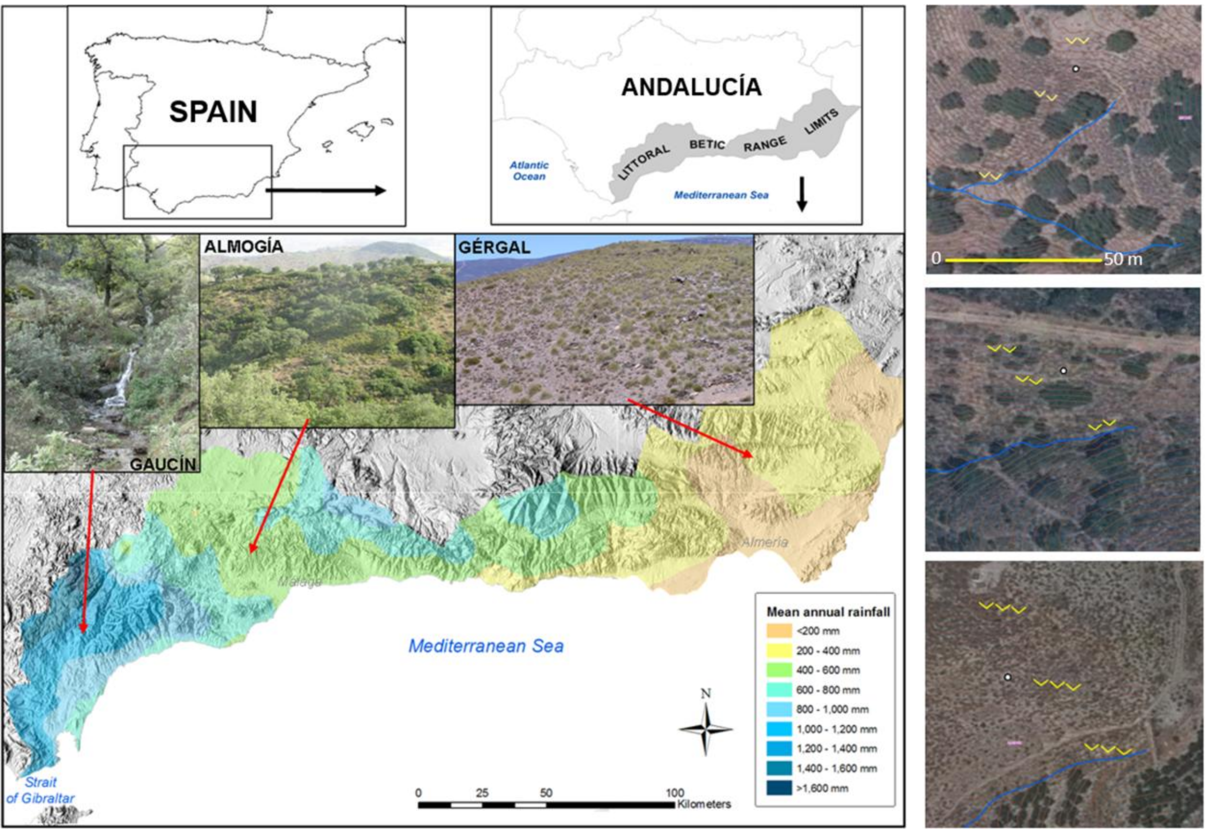

Figure 1. Rainfall gradient observed in the study area and location of field sites and detailed of aerial photos including the location of the opened plots in the three field sites (top, humid field site; middle, dry field site; bottom, semiarid field site). The scale bar is equal for the three field sites.

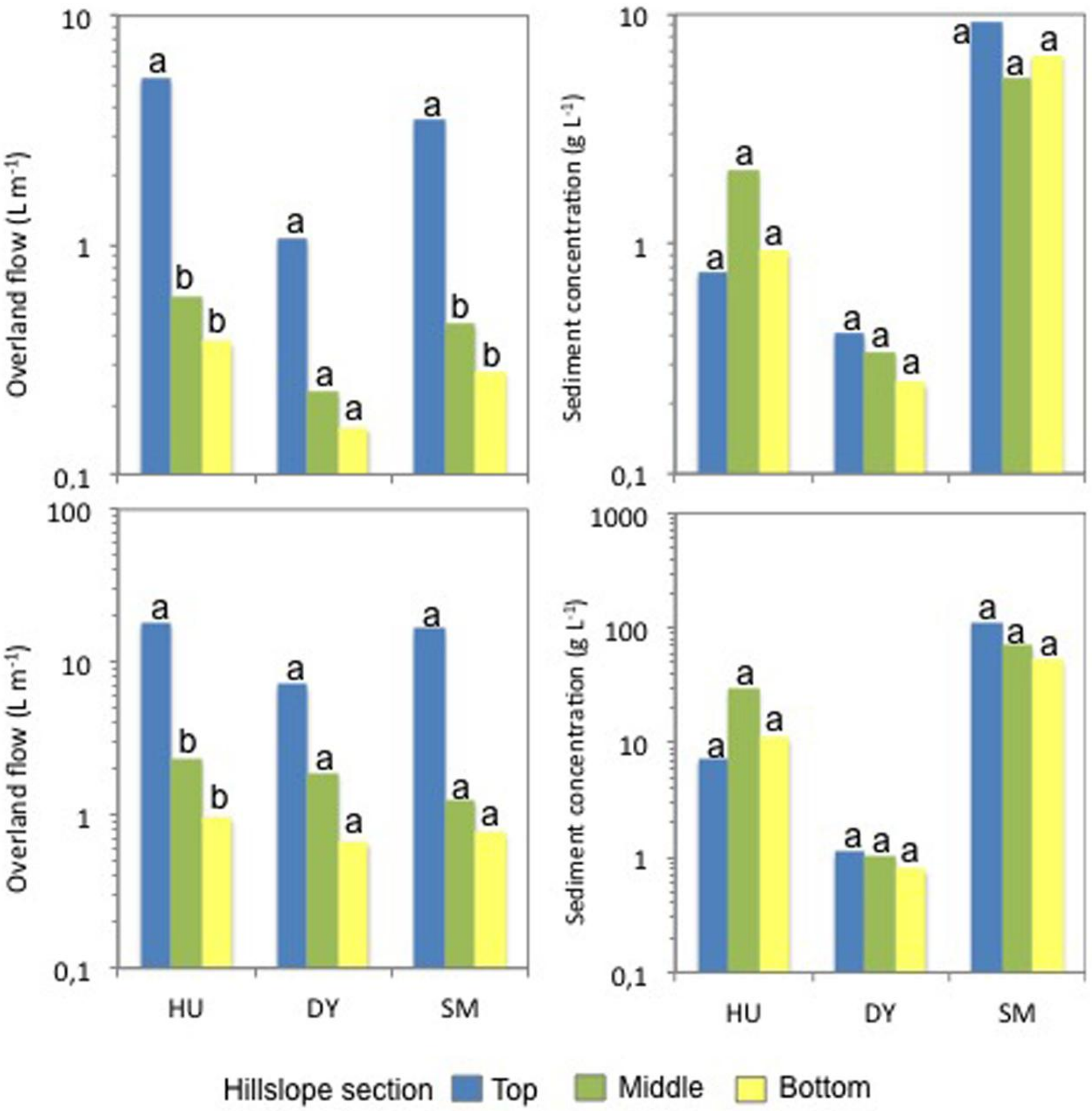

Figure 2. Mean and maximum of overland flow and sediment concentration in every hillslope secition. Means and maximum within a column for each hillslope section that do not have a common letter are significantly different using Tukey's test ($p<0.05$).

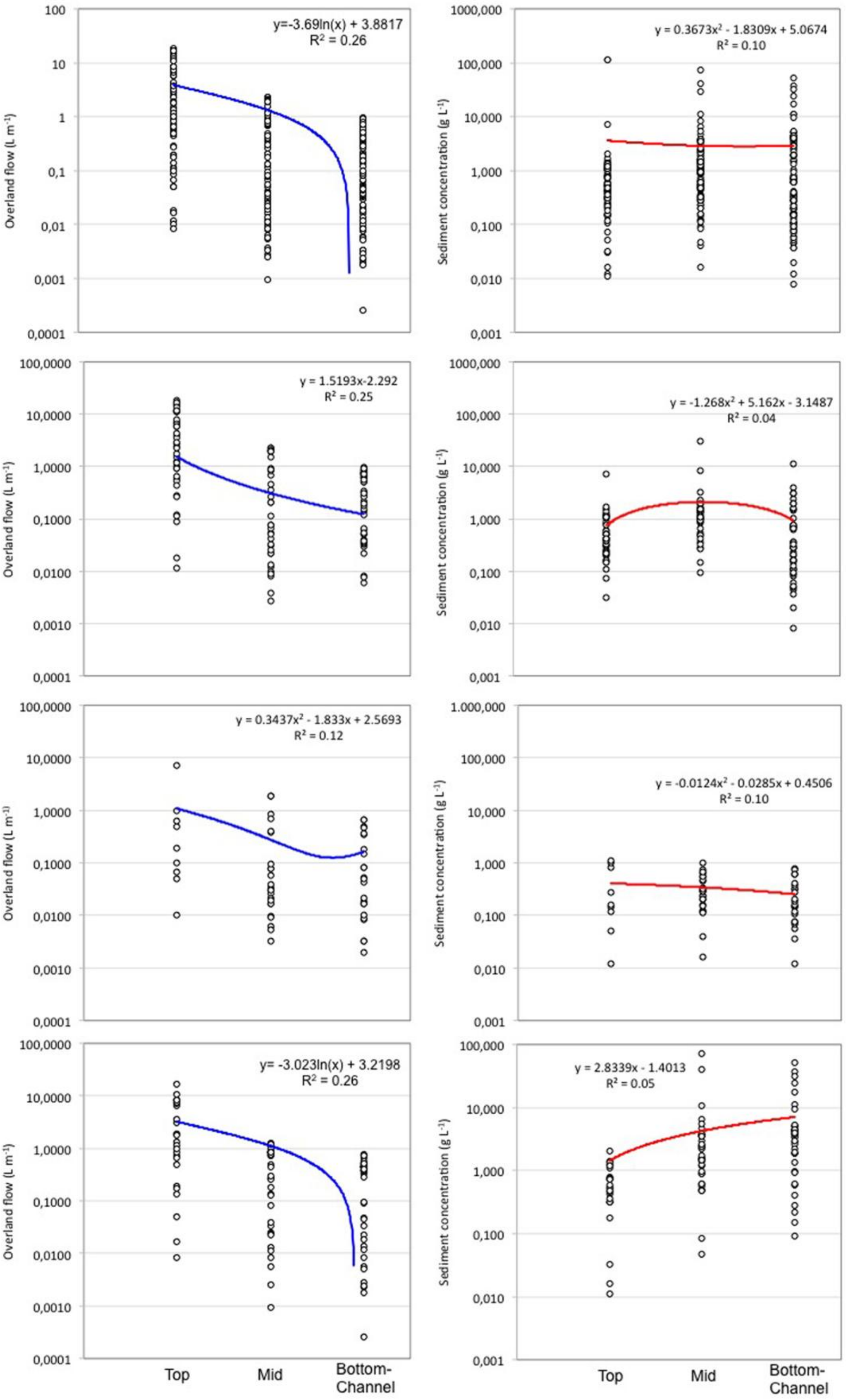
100
10
1
0,1
0,01
0,001
0,0001
Overland flow (L m^{-1})
y=-3.69ln(x) + 3.8817
R² = 0.26
1000,000
100,000
10,000
1,000
0,100
0,010
0,001
Sediment concentration (g L^{-1})
y = 0.3673x² - 1.8309x + 5.0674
R² = 0.10
100,0000
10,0000
1,0000
0,1000
0,0100
0,0010
0,0001
Overland flow (L m^{-1})
y = 1.5193x-2.292
R² = 0.25
1000,000
100,000
10,000
1,000
0,100
0,010
0,001
Sediment concentration (g L^{-1})
y = -1.268x² + 5.162x - 3.1487
R² = 0.04
100,0000
10,0000
1,0000
0,1000
0,0100
0,0010
0,0001
Overland flow (L m^{-1})
y = 0.3437x² - 1.833x + 2.5693
R² = 0.12
1.000,000
100,000
10,000
1,000
0,100
0,010
0,001
Sediment concentration (g L^{-1})
y = -0.0124x² - 0.0285x + 0.4506
R² = 0.10
100,0000
10,0000
1,0000
0,1000
0,0100
0,0010
0,0001
Overland flow (L m^{-1})
y= -3.023ln(x) + 3.2198
R² = 0.26
Top
Mid
Bottom-Channel
100,000
10,000
1,000
0,100
0,010
0,001
Sediment concentration (g L^{-1})
y = 2.8339x - 1.4013
R² = 0.05
Top
Mid
Bottom-Channel

Figure 3. Scatter-plots of hillslope section vs. mean overland flow and sediment concentration and adjustment of equation regression. The significance level of R2 is $p<0.05$. Abbreviation: T, top section; M, middle section; B, bottom-channel section.

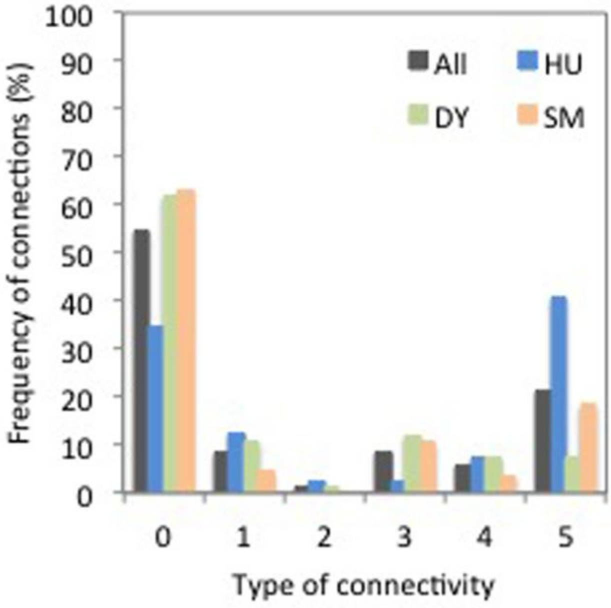

Figure 4. Frequency of connections and disconnections between hillslope sections and channel. Abbreviations: HU, humid Mediterranean field site; DY, dry Mediterranean field site; SM, semiarid Mediterranean field site; No OF, event not generating overland flow; T, overland flow only in top section; M, overland flow only in middle section; B, overland flow only in bottom-channel section; T-M, overland flow only in top and middle section; T-B, overland flow only in top and bottom-channel section; M-B, overland flow only in middle and bottom-channel section; T-M-B, overland flow in the three sections.