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Hydrological heterogeneity in Mediterranean reclaimed slopes: runoff and sediment yield at the patch and slope scales along a gradient of overland flow

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Abstract

Hydrological heterogeneity is recognized as a fundamental ecosystem attribute in drylands controlling the flux of water and energy through landscapes. Therefore, mosaics of runoff and sediment sinks and source patches are frequently identified in these dry environments. There is a remarkable scarcity of studies about hydrological spatial heterogeneity in restored slopes, where ecological succession and overland flow are interacting. We conducted a field research to study the hydrological role of patches and slopes along an overland flow gradient in three reclaimed slopes coming from mining reclamation in a Mediterranean-continental climate. We found that runoff generation and routing in non-rilled slopes showed a pattern of source and sink areas of runoff. Such hydrological microenvironments were associated to seven vegetation patches (characterized by plant community types and cover). Two types of sink patches were identified: shrub *Genista scorpius* patches could be considered as a "deep sink", while patches where the graminoids *Brachypodium retusum* and *Lolium perenne* dominate were classified as "surface sinks" or "runoff splays". A variety of source patches were also identified spanning from "extreme sources" (*Medicago sativa* patches; equivalent to bare soil) to "poor sources" (areas scattered by dwarf-shrubs of *Thymus vulgaris* or herbaceous tussocks of *Dactylis glomerata*). Finally, we identified the volume of overland flow routing along the slope as a controlling major factor of hydrological diversity: when overland flow increases at the slope scale hydrological diversity diminishes.

1 Introduction

Spatial heterogeneity is a fundamental ecosystem attribute in drylands, controlling the flux of resources and energy through landscapes (Noy-Meir, 1973; Schlesinger et al., 1990). Indeed, water-limited landscapes are generally arranged in a mosaic of patches with diverse hydrological role, where surface fluxes of water runoff and sediments interact with vegetation dynamics (Lavee et al., 1998; Puigdefábregas, 2005). The Trigger-Transfer-Reserve-Pulse (hereafter TTRP) conceptual model developed by Ludwig et al. (1997, 2005) represents a useful framework for the understanding of these systems. This approach suggests that these ecosystems are structured as a mosaic of densely vegetated patches, with resource-sink hydrological role, interspaced within a bare soil or scarcely vegetated component, with resource-source hydrological role. The transfer of water runoff and sediments from the bare source areas to vegetated patches (i.e. sinks) maximizes the use of resources, producing pulses of vegetation growth, which increase the ability of vegetation patches to capture surface resource fluxes and hence, enhance water and soil conservation at the landscape level.

Several studies have highlighted the operation of coupled eco-hydrological processes described by the TTRP conceptual framework in many semiarid and arid ecosystems throughout the world, including Niger (Seghieri et al., 1997; Bromley et al., 1997), Jordan (White, 1969), Australia (Dunkerley and Brown, 1995), USA (Reid et al., 1999) and Spain (Calvo-Cases et al., 2003). Further work refined the principles of this approach, explaining that the sink-source hydrological role of vegetation patches does not only depend on vegetation density, but also on the specific traits of the dominant plant species growing in them (Bochet et al., 2006; Garcia-Estringana et al., 2010; Vasquez-Mendez et al., 2010).

The effects of disturbance on these resource-conserving natural ecosystems are well known: rises in runoff generation and soil erosion, frequently associated to the development of rill or gully networks (Davenport et al., 1998; Ludwig and Tongway, 2000; Wilcox et al., 2003). Under these conditions, vegetation patches are not able to capture water and sediments efficiently, causing a significant loss of resources at the landscape scale. These losses reduce vegetation growth and, in consequence, could cause the activation of a long-term self-reinforced degradation process. Similar mechanisms operate in degraded human-made slopes under Mediterranean-dry climate (Nicolau, 2002). The dynamics of these reclaimed ecosystems are modulated by the amount of overland flow routed through the slopes, which in some cases is very

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high, favoured by structurally poor soils, rough topographical designs, and occasionally, the presence of runoff contributing areas (e.g. steep berms, tracks, etc.) located at the top of slopes (Moreno-de las Heras et al., 2008; Hancock and Willgoose, 2004). When the amount of overland flow is high, intense soil erosion processes develop, rill erosion being the most significant phenomenon. Rill networks drain runoff away from slopes efficiently, reducing water infiltration, thus increasing the water deficit (Moreno-de las Heras et al., 2010). As a result, vegetation dynamics is affected, constraining seed germination, plant establishment and development, and seed production (Espigares et al., 2011). These mechanisms drive the reclaimed ecosystem towards a highly degraded state, in which a very costly intervention is required to facilitate vegetation recovery (Nicolau, 2003; Merino-Martín et al., 2011).

To date, the study of the interactions between the dynamics of overland flow and vegetation has focused on degradation processes affecting both natural and reclaimed semiarid environments. Notably lacking are studies that focus on the opposite ecosystem recovery phenomenon. Reclaimed mining environments offer excellent opportunities for the elucidation of the structural and functional dynamics of ecological systems, where soils and vegetation are in general very simple, so that plant communities and hydrological processes represent early stages of ecosystem organization (Aronson et al., 1993). In this study, we analyze hydrological processes (i.e. runoff generation and routing and sediment yield) acting at both the patch and slope scales in Mediterranean-dry reclaimed mining slopes with sparse vegetation and with absent or poorly developed (i.e. spatially discontinuous) rill networks. Previous work carried out in the same study area (Moreno-de las Heras et al., 2009, 2010) indicated that under these conditions overland flow is not routed by rill networks, running mostly as sheet flow over the surface, so the vegetation is able to establish successfully on slopes, promoting a wide diversity of vegetation patches dominated by a variety of plant species with different cover. We specifically aimed to (a) evaluate the heterogeneity of hydrological roles developed at the patch and slope scales in water-limited reclaimed slopes under the perspective of the ecosystem recovery processes, and (b) analyze the interaction of this hydrological heterogeneity with the amount of overland flow routed along the slopes.

We state as a fundamental assumption that the different vegetation patches developed in these Mediterranean-dry reclaimed slope systems have a diverse hydrological role that can be functionally categorized as sources or sinks of resources, in accordance with the TTRP conceptual framework (Ludwig et al., 1997, 2005). Furthermore, we hypothesize that the hydrological heterogeneity of these reclaimed ecosystems is modulated by the amount of overland flow running at the slope scale. This overland flow will increase the complexity of surface hydrological role as it decreases, as that would indicate efficient runoff redistribution across the slope between different patches fulfilling different hydrological roles. In addition, we hypothesize that we can find two mosaic-generating processes along the overland flow gradient: mosaics driven by differential erosion (i.e. Wainwright et al., 2002), where plant cover plays a passive role, and mosaics driven by vegetation (i.e. Puigdefábregas, 2005), where vegetated patches become hot-spots of soil and vegetation change.

2 Methods

2.1 Study area

The study site is located within the *Utrillas* coalfield (~1100 m a.s.l. above sea level) in the Iberian Mountain Chain (Spain). This work was carried out in three reclaimed mining slopes located at *El Moral* spoil bank (40°47′50′′ N, 0°50′26′′ W) that were selected to span a gradient of overland flow. The climate is Mediterranean-Continental with mean annual temperature of 14 °C (ranging from a minimum mean daily temperature of 6.7 °C in December and a maximum mean daily temperature 23.1 °C in July), with air frost period between October and April. The local moisture regime can be classified as dry Mediterranean (Papadakis, 1966) with mean annual precipitation of 466 mm (mainly concentrated in spring and autumn) and potential evapotranspiration

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of 759 mm, yielding a hydrological deficit of 292 mm running from June to October. The mean number of annual rainfall events in the area is ∼50, with some convective rainstorms occurring especially in summer, characterized by high rainfall intensities of up to 100 mm in 24 h (Peña et al., 2002).

The slopes were built between 1987 and 1988 by the *Minas y Ferrocarril de Utrillas S.A.* mining company, with between 18° and 20° inclinations and a layer of 100–250 cm of a clay-loam overburden substratum free of major physicochemical constraints (see Table 1 for a detailed description of slopes). Revegetation of slopes was implemented after cross-slope ploughing by sowing a mixture of perennial grasses (*Festuca rubra*, *Festuca arundinacea*, *Poa pratensis* and *Lolium perenne*) and leguminous herbs (*Medicago sativa* and *Onobrychis viciifolia*). Although the slopes were restored using the same general procedures, they differed in their subsequent evolution (i.e. rilling, vegetation development), due to differences in their geomorphological design, chiefly in the upper part (Moreno-de las Heras et al., 2008, 2009). Indeed, a 40° steep berm (barely covered; <3%) integrated at the top of some slopes (Fig. 1a and b) acts as a water-contributing area, generating important amounts of overland flow and promoting rill erosion processes. This situation gave us the opportunity to select three reclaimed scenarios subjected to a variable amount of overland flow routed along the slopes since their construction. Although there are no significant differences in soil traits between slopes (Table 1), differences in the size of the up-slope water contributing area and its associated erosion processes (discontinuous rilling on slope 1 and sheet flow on slopes 2 and 3) have promoted large differences in vegetation development.

2.2 Hydrological measurements

Runoff and sediment yield at slope and patch scales were monitored on the three experimental slopes from October 2007 to December 2008. The hydrological year in the study site lasts from early autumn to the end of the next summer; however, due to the scarcity of rain events during the autumn of 2007, the sampling period was extended until December 2008, so we included the autumn of 2008.

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At the slope scale, naturally delimited catchments (unbounded plots) were selected (Fig. 1a–c). Therefore, the area of the slope-scale plots differed between the three slopes (see Table 1). At the foot of each slope catchment two plastic collectors were installed and a central cemented outlet fed into these collectors. From the outlet, runoff was guided through a pipe into two 200-l storage tanks connected by a ten-slot runoff divider.

At the patch scale, a variable number of Gerlach plots were installed, encompassing the different vegetation patches present in slopes. In total, we found seven different types of vegetation patches dominated by different plant species (see Table 2 for a detailed description of vegetation cover and soil structural properties of patches): scattered clumps of legumes (*M. sativa*) and grasses (*Dactylis glomerata*) in a matrix of bare soil, scattered dwarf shrubs (*Santolina chamaecyparissus* and *Thymus vulgaris*) in a matrix of bare soil, and finally, patches densely covered by grasses (*L. perenne* and *Brachypodium retusum*) and shrubs (*Genista scorpius*). Three unbounded Gerlach plots 0.5 m wide (connected to 100 l runoff storage drums) per cover type were established in each slope (Fig. 1e). Catchment areas of Gerlach plots were visually delimitated on the basis of surface microtopography, and ranged from 1 to 16 m^2. For *M. sativa* patches, bounded 3 m long Gerlach plots were used (0.5 m wide; Fig. 1d), since the high runoff volumes produced by these patches – located on the steep berm integrated at the top of slopes – compromised the operability of the experimental design. A 3 m length Gerlach plot was selected for these patches according to previous results obtained in the study site, which showed a low scale-dependency of hydrological responses in plots of this length (Moreno-de las Heras et al., 2010). Runoff collected from plots was measured after each runoff event (runoff-producing events occurring within a 24 h period were considered the same event). Runoff was determined by measuring water level in the container and calculating final volume using the relevant geometric equations. During the study period, no runoff event exceeded the storage capacity of tanks and drums, nor were there any significant losses from tanks attributable to evaporation. The stored runoff was stirred, and a representative

1 l sample was taken by filling a 1 l plastic bottle from the bottom up in order to obtain an integrated sample. Sediment concentrations were determined by oven-drying (at 105 °C) the collected runoff sample until constant weight was achieved. Precipitation amount and characteristics were measured using an automatic recording rain gauge (GroWeather, Davis®) located about 500 m from experimental slopes. Total precipitation was also recorded using three pluviometers, each located on one experimental slope. According to pluviometer data, spatial variations in precipitation during the study period were negligible.

2.3 Topographic and microtopographic measurements

A total station was used to carry out a topographical survey by tacheometry, defining the surface of the vegetation patches. Filling points and break lines were defined in order to determine slope topography. In each slope, the presence of micro-topographic structures and species vegetation cover was registered in 35 50 × 50 cm plots (seven plots regularly distributed in five transects along the slope).

2.4 Soil moisture measurements

To test differences in soil water content between patches, TDR (Time Domain Reflectometry) sensors were installed horizontally at 25 cm into the soil in four replicates of each vegetation patch. A TDR cable tester (Tektronix® 1502C), was used to collect the data, following the methodology proposed by Cassel et al. (1994), with an accuracy of 94 % in soil moisture determination. Soil water content data were collected within 5 days after each precipitation event.

2.5 Data analyses

Differences in runoff and sediment yield at the slope scale were analysed using Kruskal-Wallis and *post-hoc* Mann-Whitney non-parametric tests. Differences in runoff,

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sediment yield and soil water content at the patch scale were analysed using non parametric tests for repeated measures (Friedman test and post-hoc Wilcoxon-Nemenyi-McDonald-Thompson test; Hollander and Wolfe, 1999). In order to analyze the influence of rainfall characteristics on the hydrological role of the different patches, we used linear regressions to relate runoff and sediment yield with rainfall properties (depth and intensity). Runoff, soil moisture and sediment yield data were used to perform a cluster analysis (Tryon, 1939) to separate out groups of patches with homogeneous hydrological role. The linkage rule employed was Ward's method and City-block (Manhattan) as distances measures. We used Chi-Square test to analyze if there were significant relationships between vegetation patch hydrological behaviours and micro-topographic structures.

We estimated the "hydrological diversity" of each slope by computing the Shannon diversity index, for which we included the hydrological groups obtained from the cluster analysis as species. This diversity index is dependent of both the richness and abundance (vegetation patch) of each hydrological group.

Statistical analyses were performed using STATISTICA (Statsoft, 2001). *Post-hoc* Wilcoxon-Nemenyi-McDonald-Thompson tests were performed with the "coin" and "multcomp" packages of the R program (R_Development_Core_Team, 2009) using the code of "Tal Galili", published on r-statistics.com (http://www.r-statistics.com/2010/02/post-hoc-analysis-for-friedmans-test-r-code).

3 Results

3.1 Rainfall characteristics

A total of 74 rainfall events were registered during the study period, accounting for a total rainfall of 703 mm. During the 2007 hydrological year a total of 550.7 mm were registered, which was above the historical average of 466.2 mm reported by Peña et al. (2002) for the study area. Seventeen events (23 % of the total number of events)

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produced runoff at the slope scale. Characteristics of the runoff-producing rainfall and hydrological responses to these events are shown in Table 3. Average duration and depth of runoff-producing events was 233.8 min and 36.7 mm, respectively. Intensity of maximum single event varied from 2.5 mm h^{-1} to 24.8 mm h^{-1}.

3.2 Runoff, erosion and soil moisture at the patch scale

Total runoff, runoff coefficients and sediment yield differed significantly between cover types ($p < 0.0001$, Friedman test, Fig. 2). Multiple comparisons between vegetation patches shown in Fig. 2 suggest that there is a gradient with two extremes: one patch (*Genista*) showing lower runoff and sediment production and higher soil moisture and another patch (*Medicago*) with higher runoff and sediment production rates and lower soil water content.

3.3 Hydrological role of vegetation patches vs. rainfall characteristics

Significant linear relationships between runoff and rainfall depth within each patch were obtained, showing a variable effect of the amount of rain on runoff (Fig. 3a) depending on patch. The slope of the regression equation can be used as a parameter to measure the effect of the different vegetation patches on hydrological processes (Fig. 3b). In accordance with runoff yield results, the lowest slope of the regression equation corresponded to the vegetation patch with lowest runoff rates and sediment production (*Genista* patches), and the highest slope of the regression to the *Medicago* patches (which had highest runoff and sediment yield rates).

3.4 Hydrological groups

Classification of vegetation/cover patches based on hydrological properties (runoff, runoff coefficient and soil moisture) using cluster analysis resulted in 4 groups (Fig. 4). Together with previous results, we related the resulting groups to four main hydrological roles. One group (runoff sinks) included three patches (*Genista, Brachypodium,* *Lolium*) with lower runoff and sediment production rates and higher soil water content (Fig. 2). It was possible to distinguish two kind of sinks within this group; deep sinks (*G*) and surface sinks (*B*, *L*), which appeared slightly different in the cluster classification dendrogram. In contrast with this sink group there were two groups with the highest amounts of runoff and sediment yield (*Santolina* and *Medicago*), which were assigned to moderate and extreme runoff sources, respectively. Between these contrasting roles, a fourth group was found (low runoff response) which included two patches (*Dactylis* and *Thymus*) that played the role of poor runoff sources.

Runoff and sediment yield were only recorded for rainfall events that delivered runoff at the foot of slopes (slope-scale runoff producing events). In addition, we used unbounded gerlach plots to describe actual hydrological role of these patches; this approach assumes the fact that some high-intensity precipitation events may have connected a greater surface than the estimated catchment areas for each patch. These two design constraints explain the counterintuitive result of classifying as a runoff sink a surface patch in which some (though very low) amounts of runoff and erosion were recorded.

3.5 Micro-topographic forms

We found seven micro-topographic forms in the three slopes under study: flat areas, steep flat (flat forms with gradient of 40 %), concave/convex, preferential sheet-flow, rills, rill fans/splays (where a rill interrupts) and runoff splays (deposition areas formed by water accumulation in micro-terraces built during restoration practices). In general, slopes 1 and 2 had many of these micro-topographic forms while slope 3 was mainly dominated by flat areas (Fig. 5a).

There was a significant relationship between the hydrological groups and the micro-topographic structures found on the three slopes (Chi-Square = 75.59; $df = 27$; $p < 0.001$, Fig. 5b). On the basis of the differences between observed and expected frequencies, surface sinks were associated with rill fans/splays and microterraces. In contrast, extreme sources appeared associated with steep flat micro-topographic forms and deep sinks (G) appeared more frequently in flat forms.

3.6 Hydrological heterogeneity at the slope scale

Runoff coefficient and sediment yield differed significantly between the three slopes ($p < 0.0001$, Kruskal-Wallis test, Fig. 6a and b), showing a gradient of soil erosion from slope 1 to slope 3. Significant linear relationships were found between runoff and rainfall depth at the slope scale, differences in the equation slope suggest a different behavior for each of the three slopes (Fig. 6c).

When the abundance of each of the four hydrological groups of patches obtained from the cluster analysis in the three slopes were compared (Fig. 6d), extreme sources were found to be absent in slope 3, which was characterized by a fairly homogeneous abundance of moderate and poor sources and sinks. On the contrary, slope 1 was characterized by a dichotomous hydrological role (with extreme and moderate sources and sinks) but without poor source patches, which were most abundant in slope 2. Hydrological diversity increased as overland flow decreased (Fig. 6e).

4 Discussion

Our results showed that patterns of runoff generation, infiltration and routing in reclaimed slopes are highly dependent on the patch covering the soil, controlling the final role as a runoff source or sink. The cluster analysis applied to field data of runoff and erosion rates and soil water content in the seven patches allowed us to identify four "micro-environments" with different hydrological role: (1) sinks (*Genista, Brachypodium, Lolium*), (2) poor sources (*Dactylis, Thymus*), (3) moderate sources (*Santolina*) and (4) extreme sources (*Medicago*). These findings are supported by comparisons of runoff, sediment yield rates and soil water content, and by the identification of different hydrological responses of patches to rainfall characteristics.

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Our results suggest that the general model developed for semi-arid areas (TTRP) describing two main types of hydrological microenvironments (sources and sinks) should be delved into in the case of constructed slopes. Bare patches between plants – characterised by a poor soil structure and a low infiltration capacity – act as runoff generating areas; while areas under plant clumps function as runoff sinks, where organic matter contents are higher, favouring soil aggregation and soil faunal activity, hence increasing macro-porosity and infiltration rates (Calvo-Cases et al., 2003; Ludwig and Tongway, 1995; Sánchez and Puigdefabregas, 1994). In our study, we have also identified the type of plant assemblages that play either role, as well as the intensity of that role in each case.

In the studied slopes, sinks were associated with the production of very low amounts of runoff and sediments collected down slope from the patch. Furthermore, these low runoff and sediment yield rates were relatively constant in these patches, even under high precipitation or intense rainfall conditions. These patches are soil surface areas densely covered by grasses (*L. perenne*, *B. retusum*) or shrubs with a dense herbaceous understory (*G. scorpius*). *B. retusum* is a common species following disturbance in Mediterranean environments (Bautista et al., 1996; Cerdà, 1998). It has been described as a good soil protector, with a high erosion control capacity (De Baets et al., 2007) thanks to a dense root system and the consolidation of soil aggregates (Cerdà, 1998). We found that runoff and erosion rates where low for *B. retusum*, contrasting with the low amounts of soil water content after rainfall at 25 cm, which could suggest that this species is highly efficient in obstructing runoff and sediments although it is not so efficient infiltrating water in depth. In fact, results and field observations showed *B. retusum* clumps splaying rather than retaining the water and sediment flow. Ryegrass (*L. perenne*) is not a characteristic species of Mediterranean degraded environments; it was introduced during revegetation practices. The effects of ryegrass in reducing runoff and erosion rates have been broadly described (Zhou and Shangguan, 2007). It has been found that canopies of ryegrass usually contribute to runoff declines to a greater extent than roots, whereas roots contributed mainly to a strong

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decrease in sediment yields (Zhou and Shangguan, 2008). We also found that this patch was highly efficient in obstructing runoff and sediments, although it is the sink with the highest runoff and erosion rates and the most precipitation-dependent hydrological behaviour. *Genista* patches had the significantly lowest runoff and erosion rates and highest soil water content. Soil moisture content after rainfall, which is a good indicator of a runoff sink role, suggests that this patch is not only efficient in obstructing runoff and sediments; it also incorporates water at depth. We found that the soil characteristics of *G. scorpius* understorey are significantly different, with lower bulk density and surface strength. The deeply infiltrated water is easily conserved against evaporation and used by *G. scorpius* and associated plants during dry periods. Molinillo et al. (1997) found also that under a dense *G. scorpius* cover, both runoff and sediment yield are strongly controlled.

Briefly, our results emphasize the presence of a variety of sink roles dependent on plant community characteristics; *G. scorpius* patch could be considered as a "deep sink", while *B. retusum* and *L. perenne* could be described as "surface sinks" or "runoff splays".

Our results suggest an interrelation between micro-topographic structures and vegetation patches present on these microstructures. The three selected slopes represent a gradient of overland flow from discontinuous rilling to very low amounts of runoff routing as sheet flow along the slopes. This gradient generated different micro-topographies through soil erosion: rills and rill-fans in the slope with highest runoff volumes (slope 1), splays when runoff volumes decreased (slope 2), and absence of micro-topographic structures in the slope with low runoff volumes (slope 3). These results are supported by the fact that two of the three types of sink patches described (*Lolium* and *Brachypodium*) are related to microterraces and splays forms (field observations related *Lolium* to rill fans and *Brachypodium* to splays). Thus, we suggest that the proliferation of these cover types was related, in the early stages of succession, to the existence of these micro-structures. In fact, the characteristic species *L. perenne* is a residual species from initial revegetation practices subsisting under favourable

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conditions generated by rill fans. On the other hand, *B. retusum*, which is a pioneer species typical in degraded environments, would have colonized only the splays where it can persist. These findings are in accordance with Wainwright et al. (2002), who worked in flows with a discontinuous pattern, with alternating areas of channelization and deposition, and found that rill fans (they called these areas "beads") were areas with higher concentrations of nutrient, water and seed resources, finding these sites favourable for the growth of "islands of fertility" (Garner and Steinberger, 1989). A different situation is found in slope 3, where different runoff volumes have not eroded the surface differentially and did not generate different micro-structures. Therefore, we suggest that the colonization of *Genista* in this slope is independent of the generation of favourable hydric microenvironments and their initial spatial distribution was conditioned by other abiotic and biotic factors. Thus, we can say that we found the two mosaic-generating processes named by Puigdefábregas (1999): mosaics driven by differential erosion, where plant cover plays a passive role (slopes 1 and 2), and mosaics resulting from "nucleation" processes (slope 3), where vegetated patches become hot-spots of soil and vegetation change. Besides, we found that the gradient of overland flow routing along the slope influences these mosaic generation processes, shifting the driving force of mosaic generation towards an abiotic control under higher overland flow volumes.

In contrast with the sink roles described, *Medicago* and *Santolina* patches played an obvious role as sources. *Medicago* patches had the highest runoff rates and sediment yield (considered extreme sources of runoff), followed by *Santolina* (moderate runoff source). *Medicago* patches have a high bare soil cover (vegetation cover <3 %) while *Santolina* patches include vegetated interpatches of scattered dwarf-shrubs (vegetation cover ≈20 %). Similar runoff and erosion rates to those obtained for *Medicago* plots were obtained in bare soil by other authors (Cerdà, 1997).

Within these contrasting hydrological roles we found two patches (*Thymus* and *Dactilys*) which belong to vegetated inter-patches areas with cover ranging from 15 to 25 %. These areas are covered by scattered dwarf shrubs (*T. vulgaris*) or tussocks of orchardgrass (*D. glomerata*). Both species are characteristic of semi-natural Mediterranean environments. *T. vulgaris* develops on relatively erodible soils (Cerdà, 1998), whereas the growth of *D. glomerata* has been described as good for erosion control, although not as good as *L. perenne* (Gokbulak, 2003). However, they play a similar hydrological role which could be explained by differences in cover (23.33 % for *T. vulgaris* and 17.33 % for *D. glomerata*).

Our results confirm that not only plant cover plays a main role for hydrological control in inter-patch areas, but plant morphology is also important. Although *Santolina* patches had a similar vegetation cover to those of *Thymus* or *Dactylis*, they have significant higher erosion rates. This result agrees with those of Bochet et al. (2006), who found that rates of soil loss and runoff reduction varied strongly between three different Mediterranean species because of different plant morphology and features.

Our experimental design, which included three slopes subjected to the influence of a range of upslope runoff generation, allowed us to evaluate the effect of overland flow on hydrological heterogeneity. The particular influence of runon (in this case runoff contributions from upslope structures) on the ecohydrology of these constructed systems must be taken into account. Moreno-de las Heras et al. (2009) reported a trend towards hydrological and ecological simplification when run-on cause the development of dense rill networks. Our results, referred to non-concentrated overland flow regimes, illustrate how when the amount of overland flow routing along slopes decreases, hydrological heterogeneity increases. We obtained the highest runoff and erosion rates for slope 1, which developed some discontinuous rills, finding significant differences with the other two non-rilled slopes. Moreover, we obtained very different rainfall-runoff relationships for the set of experimental slopes, with slope 1 being highly dependent on rainfall volume, which together with the previous result, suggests a greater hydrological connectivity of this slope compared with slopes 2 and 3. In fact, these results can be explained as a consequence of the development of discontinuous rills, which increase runoff connectivity and consequently, runoff and soil erosion rates (Nicolau, 2002; Bracken and Croke, 2007).

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The proportion of runoff sources decreased along the overland flow gradient represented by the slopes, the extreme sources being absent in slope 3, with the lowest runoff coefficient. Moreover, this slope presented the highest values of "hydrological diversity" (an index influenced by both the richness and proportion of each hydrological group). This slope hosts conditions for the development of a very efficient sink, clumps of *G. scorpius* with a dense understorey of grasses and forbs. This sink shows a remarkable capacity for overland flow interception as well as for increasing soil water content at 25 cm depth. These properties facilitate the development of vegetation and the spread of plant cover, leading the reclaimed ecosystem towards more complex states. Thus, we can say that as upslope generation of overland flow becomes less important in theses slopes, hydrological heterogeneity increases and is driven by vegetation, promoting a variety of sinks and low runoff production areas. Moreover, hydrological connectivity decreases and water availability for plants increases, reinforcing the trend towards the biological control of the hydrological processes.

Our experimental design also allows us to discuss these results under the perspective of the temporal evolution of sink-source patterns as ecological succession proceeds in these reclaimed ecosystems. This phenomenon has been scarcely analysed: most previous studies depict hydrological heterogeneity for stable systems throughout the world where sources and sinks are coupled under a dynamic equilibrium state (Ludwig et al., 1997, 2005), or address the stability of coupled systems under several types of disturbances, mainly fires and overgrazing, which reduce vegetation cover, and thus runoff obstruction, increasing runoff and erosion rates (Wilcox et al., 2003; McIvor et al., 1995; Scanlan et al., 1996). Our research describes the variation of the sink-source pattern in a gradient of ecological recovery after slope reclamation. Thus, when upslope runoff generation decreases and the vegetation is able to reach a higher level of complexity, a new type of sink develops: the *Genista scorpius* deep sink, with a dense plant understorey. These sink patches significantly increase the biological control of hydrological processes in reclaimed slopes. Therefore, we found that the TTRP framework proposed by Ludwig et al. (2005) could be useful for the further understanding of the ecology of these slopes, although more research is needed to investigate whether the water accumulated in the patches provides a pulse for vegetation growth.

5 Conclusions

Runoff generation and routing in constructed slopes that have not developed continuous rill networks revealed a pattern of source and sink areas. Such hydrological microenvironments were associated to seven patches (characterized by different plant communities and cover). Two types of sink patches were identified: *G. scorpius* community, considered as a "deep sink"; *B. retusum* and *L. perenne* described as "surface sinks". Surface sinks were related to previous micro-structures while the deep sinks were not related to a previous microtopography. A range of sources were also identified, spanning from "extreme sources" of *M. sativa* (equivalent to bare soil) to "poor sources": areas with scattered dwarf shrubs (*Thymus vulgaris)* or herbaceous orchardgrass tussocks (*Dactylis glomerata)*.

The volume of overland flow routing along the slope controls hydrological diversity. As overland flow at slope scale increases, hydrological diversity decreases and it is driven by overland flow, developing contrasted hydrological roles (extreme sources and sinks). In fact, when runoff generation in the upper part of the slope stops, the tempered roles (poor sources) become more abundant and a qualitative change occurs as the deep sink formed by patches of *G. scorpius* emerges, hydrological diversity being driven by vegetation in this case. This trend towards an increase in hydrological diversity and the development of deep sinks reflects the evolution through time of the constructed slopes when ecological succession is not "arrested" by overland flow. Thus, in this case, the described pattern of runoff sinks and sources is not stable, but evolves towards a greater biological control of hydrological processes.

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Table 1. Descriptive features for the three experimental slopes (mean ± SE).

	N	Slope 1		Slope 2		Slope 3	
Date of reclamation		1988		1988		1987	
Topography							
Slope area (m^2)		497.5		510.6		1474.3	
Slope gradient (°)		20		20		20	
Area of *Water-Contributing Area* (m^2)		50.4		22.7		0	
Aspect		North		North		North	
Soil traits[1]							
Stoniness (%)	9	39.17 ± 4.54	a	40.50 ± 3.16	a	41.91 ± 3.36	a
Sand (%)	9	44.75 ± 2.64	a	45.56 ± 2.68	a	43.95 ± 2.98	a
Silt (%)	9	28.68 ± 0.27	a	25.19 ± 1.07	a	29.75 ± 1.23	a
Clay (%)	9	26.57 ± 2.38	a	29.25 ± 1.61	a	26.30 ± 1.76	a
Texture	9	Clay loam		Clay loam		Clay loam	
pH-H_2O; *w*/*v*: 1/2-	9	8.38 ± 0.25	a	8.32 ± 0.15	a	8.01 ± 0.22	a
EC-*w*/*v*: 1/2- ($dS\,m^{-1}$)	9	0.31 ± 0.06	a	0.31 ± 0.01	a	0.68 ± 0.42	a
Organic matter (%)	9	1.18 ± 0.25	a	1.55 ± 0.34	a	1.99 ± 0.37	a
$CaCO_3$ (%)	9	7.34 ± 0.44	a	6.17 ± 0.38	a	6.84 ± 0.28	a
Bulk density[2] ($g\,cm^{-3}$)	27	1.48 ± 0.08	a	1.52 ± 0.03	a	1.43 ± 0.01	a
Cover features[3]							
Bare soil cover (%)	105	44.6 ± 3.1	a	32.3 ± 3.9	b	23.7 ± 2.8	b
Stone cover (%)	105	25.5 ± 3.0	a	22.7 ± 1.6	a	21.1 ± 2.6	a
Litter cover (%)	105	5.4 ± 1.8	a	1.1 ± 0.4	b	4.0 ± 1.9	ab
Vegetation cover (%)	105	24.4 ± 2.8	a	43.9 ± 4.1	b	51.2 ± 4.2	b
Plant traits[3]							
Species Richness	105	3.83 ± 0.28	a	6.43 ± 0.44	b	9.26 ± 0.55	c
Shannon's index	105	0.80 ± 0.08	a	1.21 ± 0.08	b	1.30 ± 0.08	b
Erosion features							
Sheet Erosion Index[4]	9	0.70 ± 0.09	a	0.59 ± 0.05	a	0.52 ± 0.06	a
Rill density[5] ($m\,m^{-2}$)	3	0.58		0.00		0.00	
Rill erosion rate[4,6] ($t\,ha^{-1}\,yr^{-1}$)	3	8.41		0.00		0.00	

See footnote on next page.

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Table 1.

Footnote:

Abbreviations: N: Number of samples; EC: Electrical conductivity; w/v: relation weight (soil)/volume (water).

[1] Measured in three composite samples (each formed by three subsamples) from the first 10 cm in three transects regularly distributed along the slope.

[2] Measured in nine randomly distributed unaltered soil cores (3 cm height by 5 cm diameter).

[3] Cover, visually estimated in 35 regularly distributed 0.25 m^2 plots per slope during spring 2006.

[4] Measured by the relationship: stone cover/stoniness; following Moreno-del Heras et al. (2008).

[5] Linear rill length (m) measured per surface area (m^2).

[6] Measured from rill network dimensions following Morgan (1997).

Values with the same letters (a–c) within rows do not differ significantly at $\alpha = 0.05$. Tested using Kruskal-Wallis and Mann-Whitney post-hoc tests.

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Table 2. Characteristics of each patch present in the slopes under study.

	Vegetation patch	Cover[1] (%)	Bulk Density[2] (g/cm^3)	AWC[3] (%)
	*Genista*	81.3 a	1.13 a	6.40 a
	*Brachypodium*	93.7 a	1.30 ab	8.52 a
	*Lolium*	67.3 a	1.41 bc	8.07 a
	*Thymus*	23.3 ab	1.55 cd	6.92 a
	*Dactylis*	17.3 ab	1.41 bc	9.01 a
	*Santolina*	19.3 ab	1.42 bc	8.79 a
	*Medicago*	2.7 b	1.61 d	9.09 a

Abbreviations: AWC = Available Water Content. Values with the same letters (a–d) within rows do not differ significantly at $\alpha = 0.05$. Analyzed with Kruskal-Wallis and Mann-Whitney U *post-hoc* tests.

[1] Cover, visually estimated in six 0.25 m^2 plots per vegetation patch in spring 2008.

[2] Measured in unaltered soil cores (3 cm height by 5 cm diameter) in fifteen samples in each vegetation patch.

[3] Measured, as the difference between volumetric water content at field capacity ($\psi = -0.03$ MPa) and wilting point ($\psi = -1.5$ MPa) in three samples (each formed by three subsamples) from the top 10 cm.

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Table 3. Rainfall characteristics, runoff and sediment yield of slopes.

Event	Date	Depth (mm)	I_{30}[1] (mm h^{-1})	Duration[2] (min)	Rf (mm) SL 1	Rf (mm) SL 2	Rf (mm) SL 3	Sy (g m^{-2}) SL 1	Sy (g m^{-2}) SL 2	Sy (g m^{-2}) SL 3
1	9 Mar 2008	28.86	5.5	90	0.01	0.00	0.00	1.93	0.00	0.00
2	13 Apr 2008	24.22	6	45	0.01	0.01	0.00	0.00	0.57	0.00
3	9 May 2008	120.11	15	30	17.18	1.01	0.18	187.23	3.06	0.18
4	16 May 2008	18.77	12	285	4.35	0.36	0.04	82.53	2.90	0.26
5	17 May 2008	73.68	12	105	9.72	3.94	1.19	125.41	2.71	0.89
6	23 May 2008	36.34	9.5	90	5.36	0.49	0.05	151.03	20.33	0.29
7	31 May 2008	27.25	3.5	210	1.35	0.08	0.00	73.40	0.64	0.00
8	9 Jun 2008	48.45	9	555	13.82	2.60	1.33	13.82	8.53	1.01
9	29 Jun 2008	45.42	24.8	270	4.96	0.25	0.03	93.14	1.64	0.43
10	17 Jul 2008	32.50	4.4	210	4.15	0.82	0.02	619.81	26.82	0.18
11	31 Aug 2008	16.05	4	60	0.84	0.42	0.01	214.64	6.37	0.24
12	10 Sep 2008	23.01	2.5	90	2.72	0.19	0.01	22.60	1.88	0.01
13	12 Oct 2008	13.93	7	120	1.33	0.09	0.00	22.07	0.41	0.03
14	18 Oct 2008	20.79	5.5	30	2.71	0.17	0.01	12.76	0.38	0.08
15	24 Oct 2008	17.56	8	180	6.36	0.71	0.03	63.71	3.32	0.08
16	28 Oct 2008	28.87	4.5	765	7.47	0.67	0.03	8.67	0.32	0.06
17	2 Nov 2008	48.24	7	840	19.76	2.78	0.22	131.77	1.20	0.17

[1] I_{30} = 30 min maximum rainfall intensity.
[2] Duration of maximum rainfall intensity precipitation. Rf: Runoff (mm). Sy: Sediment yield (g m^{-2}). SL: slope.

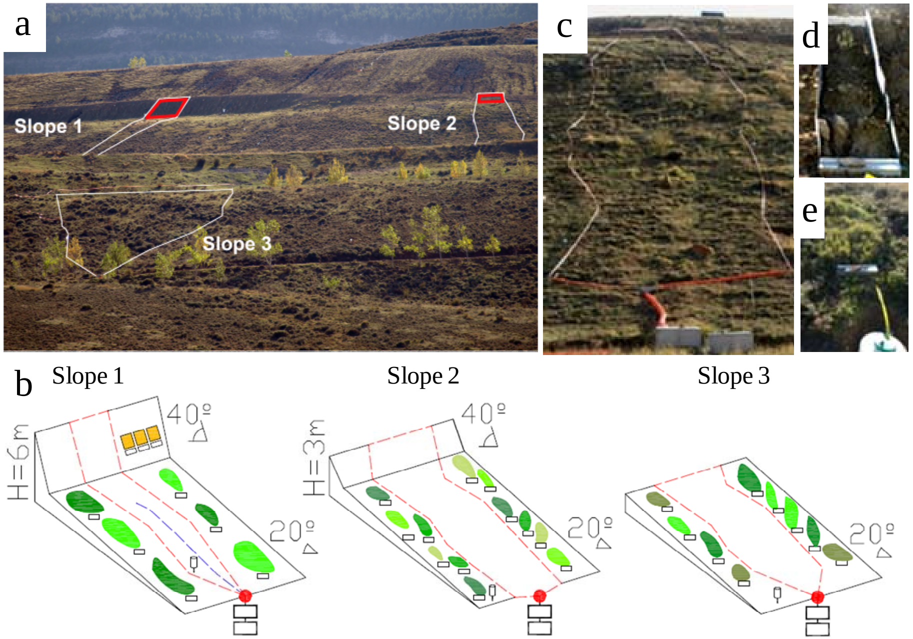

Fig. 1. **(a)** Location of the three experimental slopes at the El Moral spoil-bank (in red colour water contributing areas); **(b)** schematic representation of the experimental layout at slopes; **(c)** example of a slope plot on Slope 2. **(d)–(e)** examples of gerlach plots on slopes.

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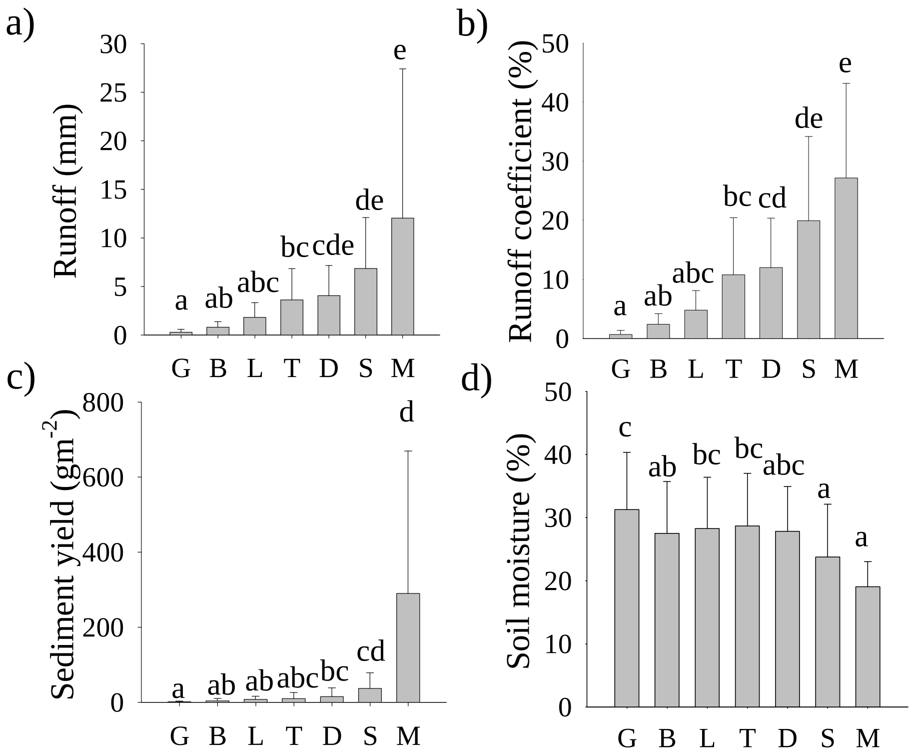

Fig. 2. Hydrological behavior of different vegetation patches. G: *Genista*; B: *Brachypodium*; L: *Lolium*; T: *Thymus*; D: *Dactylis*; S: *Santolina*; M: *Medicago*. Letters indicate significant differences between groups of patches (post-hoc Wilcoxon-Nemenyi-McDonald-Thompson test, $p < 0.05$).

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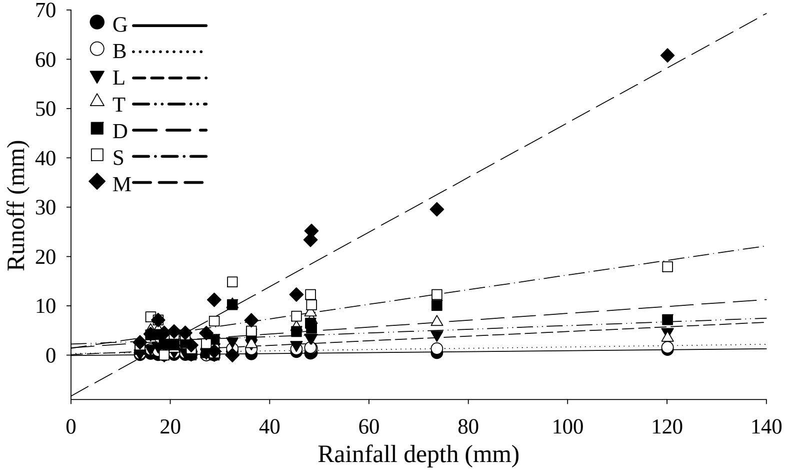
a)



b)

Vegetation patch	Equation	p	r^2
	Runoff (lm^{-2}) against Depth (mm)		
G. scorpius	y = -0.0702 + 0.0096*x	0.00006	0.6678
B. retusum	y = 0.3052 + 0.0134*x	0.00920	0.3734
L. perenne	y = 0.0797 + 0.0469*x	0.00007	0.6621
T. vulgaris	y = 2.2381 + 0.0374*x	0.23000	0.0945
D. glomerata	y = 1.4735 + 0.0698*x	0.01240	0.3496
S. chamaecyparissus	y = 1.397 + 0.1483*x	0.00060	0.5575
M. sativa	y = -8.3062 + 0.554*x	0.00000	0.9043

Fig. 3. (a) Runoff-rainfall depth relationships obtained for the different patches during the study period (2007–2008). G: *Genista*; B: *Brachypodium*; L: *Lolium*; T: *Thymus*; D: *Dactylis*; S: *Santolina*; M: *Medicago*. **(b)** Linear regression equations relating rainfall depth (mm) with runoff (mm) in the different patches.

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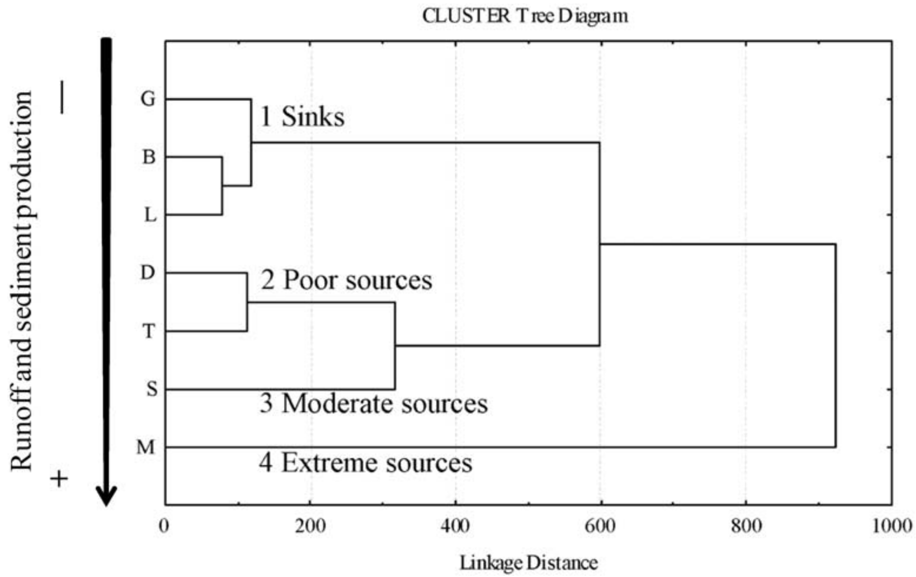

Fig. 4. Dendogram of the cluster classification analysis with hydrological data of the different patches. G: *Genista*; B: *Brachypodium*; L: *Lolium*; T: *Thymus*; D: *Dactylis*; S: *Santolina*; M: *Medicago*.

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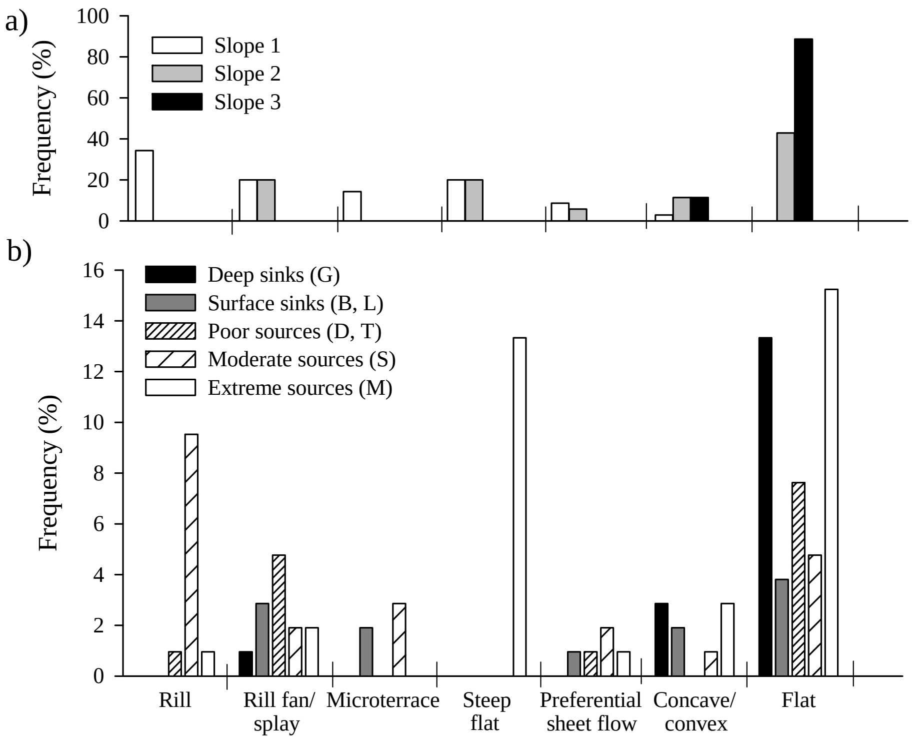

Fig. 5. Micro-topographic structures found on the three slopes under study **(a)** and relationships to hydrological behavior of vegetation patches **(b)** ($Chi^2 = 86.22$; $df = 34$; $p < 0.001$). G: *Genista*; B: *Brachypodium*; L: *Lolium*; T: *Thymus*; D: *Dactylis*; S: *Santolina*; M: *Medicago*.

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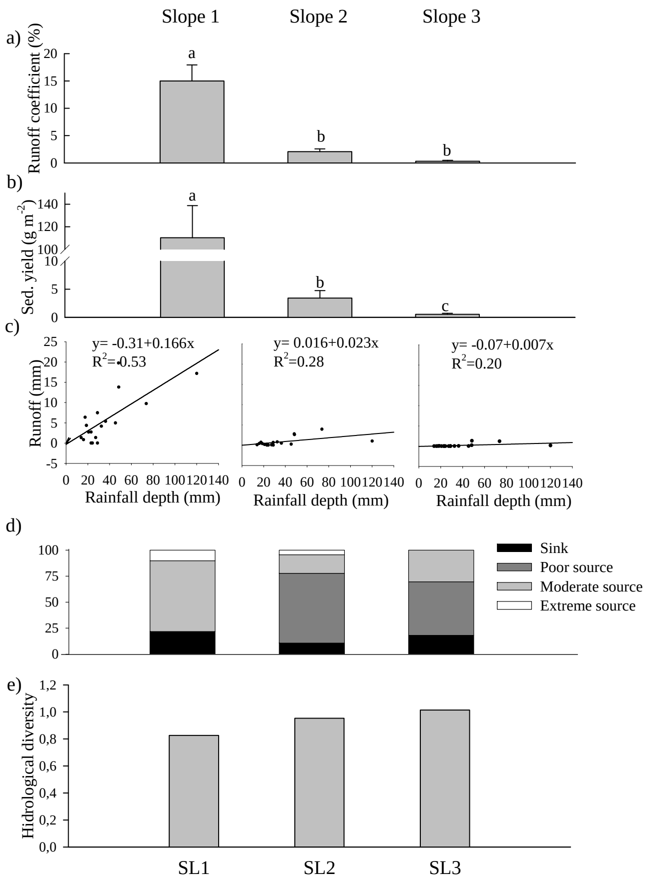

Fig. 6. Slope hydrology and hydrological heterogeneity. **(a)** Runoff coefficient (%) , **(b)** sediment yield (g m^{-2}), **(c)** runoff-rainfall depth relationship, **(d)** hydrological group abundance, **(e)** hydrological diversity. G: *Genista*; B: *Brachypodium*; L: *Lolium*; T: *Thymus*; D: *Dactylis*; S: *Santolina*; M: *Medicago*.

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