WATER RESOURCES RESEARCH, VOL. 46, W04503, doi:10.1029/2009WR007875, 2010

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Plot-scale effects on runoff and erosion along a slope degradation gradient

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Received 17 February 2009; revised 31 October 2009; accepted 16 November 2009; published 6 April 2010.

[1] In Earth and ecological sciences, an important, crosscutting issue is the relationship between scale and the processes of runoff and erosion. In drylands, understanding this relationship is critical for understanding ecosystem functionality and degradation processes. Recent work has suggested that the effects of scale may differ depending on the extent of degradation. To test this hypothesis, runoff and sediment yield were monitored during a hydrological year on 20 plots of various lengths (1–15 m). These plots were located on a series of five reclaimed mining slopes in a Mediterranean-dry environment. The five slopes exhibited various degrees of vegetative cover and surface erosion. A general decrease of unit area runoff was observed with increasing plot scale for all slopes. Nevertheless, the amount of reinfiltrated runoff along each slope varied with the extent of degradation, being highest at the least degraded slope and vice versa. In other words, unit area runoff decreased the least on the most disturbed site as plot length increased. Unit area sediment yield declined with increasing plot length for the undisturbed and moderately disturbed sites, but it actually increased for the highly disturbed sites. The different scaling behavior of the most degraded slopes was especially clear under high-intensity rainfall conditions, when flow concentration favored rill erosion. Our results confirm that in drylands, the effects of scale on runoff and erosion change with the extent of degradation, resulting in a substantial loss of soil and water from disturbed systems, which could reinforce the degradation process through feedback mechanisms with vegetation.

Citation: Moreno-de las Heras, M., J. M. Nicolau, L. Merino-Martín, and B. P. Wilcox (2010), Plot-scale effects on runoff and erosion along a slope degradation gradient, *Water Resour. Res.*, *46*, W04503, doi:10.1029/2009WR007875.

1. Introduction

[2] Understanding the influence of scale on hydrological and ecological processes has been an active area of research for at least the last several decades, but remains a significant challenge [*Cammeraat*, 2002; *Yair and Raz-Yassif*, 2004; *Newman et al.*, 2006]. In particular, the analysis of variations in runoff and sediment yield in plots of different sizes has been recognized as a vital task for modeling hillslope hydrology [*Boardman*, 2006; *Bracken and Croke*, 2007]. In addition, the redistribution of water and sediment fluxes has been stressed as a fundamental process for the comprehension of ecosystem organization and land degradation in water-restricted environments, where ecological and hydrological processes are tightly coupled [*Wilcox and Newman*, 2005; *Okin et al.*, 2009].

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0043-1397/10/2009WR007875

[3] Hydrological studies that focus on the scale issue have documented that runoff per unit area generally decreases as plot size increases, as a result of reinfiltration in the downslope areas [*Yair and Lavee*, 1985; *Kirkby*, 2002; *Gomi et al.*, 2008]. Runoff reinfiltration has been linked primarily with the spatial variability of infiltration [*Yair and Kossovsky*, 2002; *Cerdan et al.*, 2004]. Furthermore, variations in the timing of rainfall and surface runoff play a significant role affecting active reinfiltration processes, even in the absence of spatial variability [*Wainwright and Parsons*, 2002; *van de Giesen et al.*, 2005; *Reaney et al.*, 2007].

[4] Soil erosion also depends on scale. Polynomial techniques have been used to describe and predict overall increases in soil erosion with slope length [*Wischmeier and Smith*, 1978], but there is evidence that no single relationship exists [*Morgan*, 1995]. Several studies have even indicated reductions in soil erosion with length [*Evans*, 1995; *Wilcox et al.*, 2003; *Parsons et al.*, 2006]. *Parsons et al.* [2004] suggest that the role played by scale will depend on the degree of sheet and rill erosion.

[5] The way in which scale affects slope runoff and soil erosion is a major ecological issue in water-restricted environments, because it governs the spatial redistribution of the main limiting resources for vegetation (e.g., water, nutrients) [*Puigdefábregas and Sánchez*, 1996]. For example, vegetation cover in drylands is usually sparse and spatially

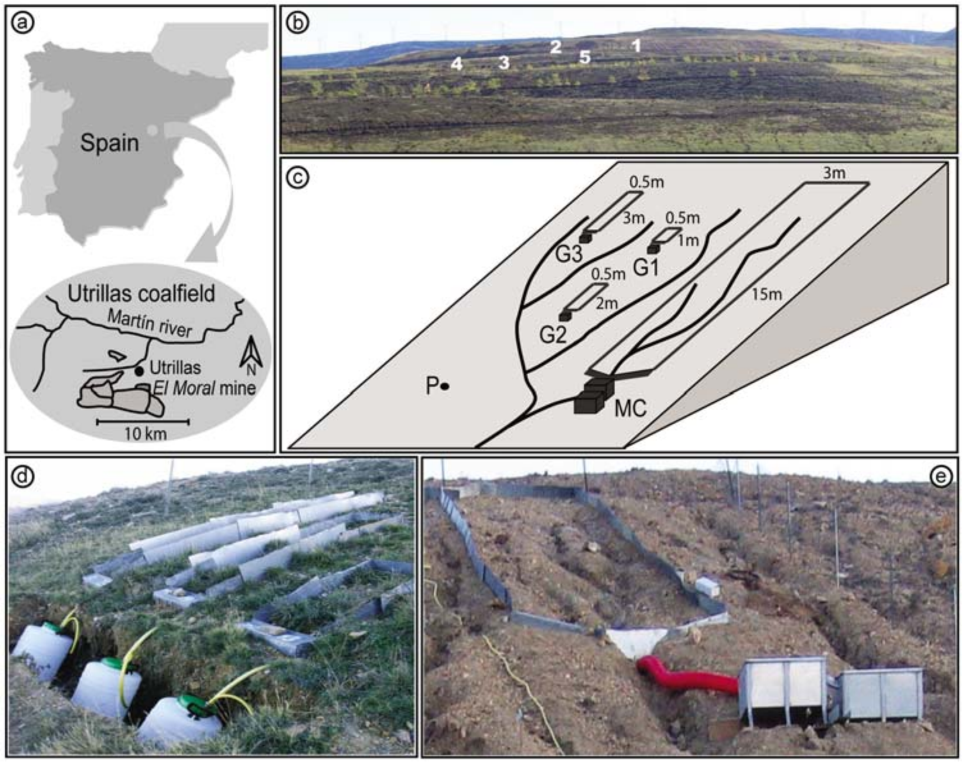

Figure 1. Site diagram: (a) regional location, (b) situation of the five experimental slopes in El Moral spoil bank, (c) schematic representation of the experimental layout in a representative slope, (d) Gerlach plots located on slope 5, and (e) microcatchment plot located on slope 1. Abbreviations: G1, 1 m long plot; G2, 2 m long plot; G3, 3 m long plot; MC, 15 m long microcatchment plot; P, pluviometer.

heterogeneous due to both climatic and edaphic limitations [*Deblauwe et al.*, 2008]; and the maintenance of vegetation cover depends on favorable redistribution of water and sediments [*Saco et al.*, 2007]. At the same time, vegetation distribution (i.e., the amount and spatial organization of vegetation cover) strongly influences the pattern and extent of water and sediment redistribution [*Puigdefábregas*, 2005]. In other words, resources in these systems are efficiently controlled by positive feedback mechanisms between water and vegetation [*Ludwig et al.*, 2005].

[6] If the distribution of vegetation is altered by disturbance and degradation, the effects of scale on hydrological processes will be altered and, thereby, ecosystem function will be affected [*Turnbull et al.*, 2008]. For this reason, *Wilcox et al.* [2003] hypothesized that the effects of scale on runoff and erosion will differ greatly depending on the degree of disturbance. In undisturbed hillslope systems, one would expect strong and nonlinear decreases in unit area runoff and erosion as slope length increases, owing to the spatial redistribution of water and sediments; whereas in disturbed systems, one would expect less pronounced reductions (or even increases in sediment yield when rill erosion occurs). The loss of soil and water from highly disturbed systems could enhance the degradation process, limiting vegetation growth and, consequently, increasing water runoff and soil erosion from the hillslope system [*Zehe and Sivapalan*, 2009].

[7] The objective of this work is to document how the interaction between degradation and scale (plot length) affects runoff and sediment yield. We state as a fundamental assumption the above hypothesis of *Wilcox et al.* [2003], which posits very different scale effects depending on degradation extent. Our assessment was based on a multiple-scale runoff and sediment yield data set (field plots measuring 1–15 m in length) covering a 12 month period. This data set was obtained from reclaimed mining slopes of varying degrees of degradation in Mediterranean-dry Spain.

2. Materials and Methods

2.1. Site Description

[8] This work was carried out in the Utrillas field site (Figure 1a), an experimental station located in El Moral, a reclaimed coal mine in central eastern Spain (40°47′24″ N, 0°49′48″ W, 1100 m). The climate is Mediterranean-continental, with a mean annual air temperature of 11°C (6.8°C in December and 23.5°C in July); the air frost period runs from October to April. The local moisture regime can be classified as Mediterranean-dry [*Papadakis*, 1966]. Mean potential evapotranspiration is 758 mm and annual precipitation, most of which occurs in spring and autumn, is 466 mm. Especially remarkable in the area is the erosion potential of some events (late spring and summer rainstorms in particular), the intensities of which occasionally reach 100 mm in 24 h [*Peña et al.*, 2002].

[9] For this study, five 30 m wide slopes in the reclaimed mining area were monitored (Figure 1b). These slopes are all north facing and have a rectilinear shape with a slope gradient of 20°. They were restored during 1988–1989 by the Minas y Ferrocarril de Utrillas S.A. company, through a

Table 1. Basic Characteristics of the Five Experimental Slopes[a]

	Number of Samples	Slope 1	Slope 2	Slope 3	Slope 4	Slope 5
Date of reclamation		1989	1989	1988	1988	1988
Topography						
Slope length (m)		55	50	75	75	60
Slope width (m)		30	30	30	30	30
Slope gradient (°)		20	20	20	20	20
Length of water-contributing area (m)		8.0	8.0	6.5	4.0	0.0
Aspect		north	north	north	north	north
Soil traits						
Stoniness[b] (%)	25	22.2 ± 2.2	24.7 ± 3.5	26.2 ± 4.1	25.2 ± 2.6	24.5 ± 3.3
Sand[b] (%)	25	33.6 ± 3.6	33.5 ± 3.7	33.8 ± 3.0	39.9 ± 1.8	36.3 ± 2.7
Silt[b] (%)	25	26.9 ± 2.8	33.8 ± 1.6	30.8 ± 1.8	26.4 ± 2.9	26.6 ± 4.5
Clay[b] (%)	25	39.5 ± 2.2	32.8 ± 2.9	35.4 ± 2.1	33.8 ± 2.1	37.1 ± 2.9
Texture[b]	25	clay loam	clay loam	clay loam	clay loam	clay loam
pH-H_2O; w/v 1/2[b]	25	8.0 ± 0.1	8.0 ± 0.1	8.0 ± 0.1	8.0 ± 0.1	7.9 ± 0.1
EC; w/v 1/2[b] (dS m^{-1})	25	0.24 ± 0.13	0.26 ± 0.14	0.20 ± 0.10	0.19 ± 0.03	0.23 ± 0.03
CEC[b] (cmol kg^{-1})	25	29.5 ± 0.9	23.3 ± 3.3	28.3 ± 1.0	26.0 ± 0.5	22.1 ± 3.5
ESP[b] (%)	25	0.68 ± 0.46	0.27 ± 0.11	0.13 ± 0.01	0.12 ± 0.01	0.18 ± 0.03
Bulk density (g cm^{-3})	75	1.51 (a) ± 0.14	1.49 (a) ± 0.12	1.39 (a) ± 0.17	1.39 (a) ± 0.12	1.23 (b) ± 0.17
Organic matter[b] (%)	25	0.58 (a) ± 0.20	0.56 (a) ± 0.23	1.27 (a, b) ± 0.35	1.46 (a, b) ± 0.83	2.00 (b) ± 0.74
fc[c] (mm h^{-1})	75	11.5 (a, b) ± 6.3	10.1 (a) ± 5.7	20.5 (a, b) ± 7.6	22.7 (b) ± 9.3	36.7 (c) ± 6.9
Surface traits						
Roughness index[d]	60	1.04 (a) ± 0.01	1.05 (a) ± 0.01	1.10 (a, b) ± 0.01	1.15 (b, c) ± 0.03	1.23 (c) ± 0.01
Vegetation cover (%)	150	1.1 (a) ± 2.0	8.2 (a, b) ± 5.5	27.8 (b) ± 9.9	44.3 (b, c) ± 16.2	59.4 (c) ± 20.8
Erosion features						
Rill density[e] (m m^{-2})		0.95	0.78	0.58	0.30	0.00

[a]Basic characteristics include topography, soil, surface traits, and erosion features. Mean ± standard deviation values are shown. Abbreviations: EC, electrical conductivity; w/v, relation weight (soil)/volume (water); CEC, cation exchange capacity; ESP, exchangeable sodium percentage. Values with the same letters (a, b, or c) within rows do not differ significantly at $\alpha = 0.05$. Analyzed with Kruskal-Wallis ANOVA and post hoc Mann-Whitney U tests.

[b]Data from *Moreno-de las Heras* [2009].

[c]Final infiltration rate from rainfall simulations. Data from *Moreno-de las Heras et al.* [2009].

[d]Roughness tortuosity index; following *Kamphorst et al.* [2000].

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

series of procedures: first, a 100 cm thick layer of overburden, from the *Utrillas* cretacic formation of *Albian* age, was spread over the spoil bank; this overburden has a clay-loam texture (kaolinitic-illitic mineralogy) with a basic pH (Table 1) that can be classified as nonsaline and nondispersive according to *Rengasamy et al.* [1984]. Next, the soil was prepared for revegetation by cross-slope plowing, to create a transversal pattern of surface roughness that would inhibit rapid overland flow and facilitate water storage. Finally, the slope was sown with a mixture of perennial grasses and leguminous herbs (*Festuca rubra*, *Festuca arundinacea*, *Poa pratensis*, *Lolium perenne*, *Medicago sativa* and *Onobrychis viciifolia*, nomenclature following *Tutin et al.* [1964–1980]).

[10] In the years following the restoration of these slopes, degradation has taken place (cover, surface, and soil features), to varying degrees of intensity. Rill erosion has accelerated, mainly because a flawed geomorphological design has enabled excessive amounts of overland flow to be generated from upslope water contributing areas of different length [*Moreno-de las Heras et al.,* 2009]. A previous study carried out on this experimental site [*Espigares et al.*, 2010] found that reduced amounts of plant-available water (attributable in large part to accelerated drainage via the densely developed rill networks) was mainly responsible for the differences among the experimental slopes with respect to vegetation development and associated surface conditions.

2.2. Hydrological Measurements

[11] From October 2005 to October 2006, runoff and sediment yield were monitored on the five experimental slopes. A number of plots, delimited by 20 cm high metallic sheets inserted 10 cm into the soil, were established on each slope (Figure 1c). In the interrill areas of the slope, three small Gerlach plots were established, each measuring 0.5 m wide: one plot 1 m long (G1), one 2 m long (G2), and one 3 m long (G3). At the downslope end of each plot was a trough, connected to a 50 L drum for storage of runoff (Figure 1d). In addition, a microcatchment plot (MC), 15 m long by 3 m wide, was established on each slope to encompass a representative rill network. At the foot of each microcatchment plot, two 1.5 m wide metallic collectors were installed; a cemented central outlet directly connected to the principal rill fed into these collectors. From the collectors, runoff was guided through a pipe into two 200 L storage tanks connected by a ten-slot runoff divider (Figure 1e).

[12] Runoff collected from the plots was manually measured within a day after each runoff event (runoff-producing events occurring within a 24 h period were considered the same event). During the study, no runoff event exceeded the storage capacity of the tanks and drums, nor were there any significant losses from the tanks attributable to evaporation. The stored runoff was stirred and 1 L samples were taken. Sediment concentrations were estimated by first oven drying (at 105°C) the collected runoff samples and then weighing the sediment. Precipitation amounts and characteristics were directly measured by an automatic recording rain gauge (GroWeather, Davis®) located about 400 m from the experimental slopes. Total precipitation was also recorded from five pluviometers, one located on each experimental slope (Figure 1c). According to the pluviometer data, spatial

variations in precipitation during the study period were negligible.

2.3. Soil and Surface Characteristics

[13] For each experimental slope, vegetation cover was visually estimated on twenty 0.25 m^2 quadrats distributed over the runoff plots (one on the G1 plot; two on the G2 plot; three on the G3 plot; and 14 on the MC plot). Vegetation cover was also measured in ten additional 0.25 m^2 quadrats randomly located outside the runoff plots.

[14] Soil surface roughness was characterized for each experimental slope by delineating twelve 1 m long linear transects in each plot (one for each G1 plot, two for each G2 plot, three for each G3 plot, and six for each MC plot). A 1 m long pin frame having 50 aligned, mobile needles was used to transfer the soil microtopography in two dimensions onto paper, following the methodology of *Bochet et al.* [2000]. The ratio of the surface profile length of each transect to the length of the straight line formed by its projection was then used to calculate a simple surface roughness tortuosity index [*Kamphorst et al.*, 2000]. This index ranges from a minimum value of 1 for ideal smooth surfaces to 1.5 for extremely rough soil surfaces.

[15] Soil bulk density was determined from fifteen undisturbed soil cores (3 cm long by 5 cm in diameter) collected from each slope at random. In addition, the total length of the rills on each slope was measured, by stretching a tape along the entire rill network. Rill density was subsequently calculated as the ratio of the total linear length of the network to the surface area of the slope.

[16] Two publications were used as sources of additional information on soil physicochemical characteristics and soil infiltration capacity [*Moreno-de las Heras*, 2009; *Moreno-de las Heras et al.*, 2009]. Physicochemical soil traits were determined for each slope from five composite samples (each consisting of six subsamples from the top 10 cm of the soil profile). The soil sampling procedure was designed to obtain the best possible picture of the soil spatial variability on each slope [*Moreno-de las Heras,* 2009]. The soil analyses followed standardized procedures described by *Ministerio de Agricultura, Pesca y Alimentación* [1994]. Finally, soil infiltration capacity was depicted as the final infiltration rates (*f*c) from rainfall simulation experiments carried out on the five experimental slopes (75 experiments, each at least 30 min long, on 0.24 m^2 plots at 63 mm h^{-1}) [*Moreno-de las Heras et al.*, 2009]. Final infiltration rates were calculated by fitting the instantaneous infiltration rates of the rainfall simulations to the Horton-type function described by *Borselli et al.* [1996].

2.4. Statistics

[17] We explored the differences in general surface conditions among the five slopes through nonparametric statistical tests (Kruskal-Wallis ANOVA and post hoc Mann-Whitney U tests). To identify which precipitation events caused erosion, cluster analysis was used to group rainfall events according to their characteristics (depth, I_1, I_{30} and duration). Data from the larger (MC) plots of all experimental slopes were averaged to obtain a mean hydrological response for the study site.

[18] Scale effects on runoff and erosion in natural hillslopes generally involve changes in slope steepness and aspect and hence become a two-dimensional process [*Kirkby et al.*, 2005]. Nevertheless, our experimental layout (field plots in artificial slopes of uniform gradient and aspect) allows a simplified one-dimensional analysis based on flow length within the plot scale. Thus, to analyze how plot-scale influences annual cumulative runoff and sediment yield for each of the five slopes, the best fitting regression functions for plot length were determined. In addition, differences in both runoff and sediment yield between plots of different lengths were analyzed for each experimental slope by applying Kruskal-Wallis and Mann-Whitney U tests. We used rainfall events grouped as different precipitations types (those previously identified via cluster analysis) as replicates [*Lal*, 1997].

[19] Finally, to analyze how the varying surface conditions of experimental slopes may modify the effects of scale, we carried out a two-step analysis. First, the spatial connectivity of both runoff and sediment flow was determined as the runoff and sediment yield ratios for pairs of plots with consecutive sizes: one plot of a certain length versus the consecutive smaller plot (G2/G1, G3/G2 and MC/G3). These ratios can mean decreasing (values < 1), no scaling effect (values = 1) or increasing (values > 1) of runoff and sediment yield as plot length increases. Further, we obtained Spearman's rank correlation coefficients between runoff and sediment yield ratios and surface characteristics (vegetation cover, surface roughness and rill density). Thus, positive Spearman's coefficients identify the surface characteristics which could contribute to increase spatial connectivity, while negative values identify those surface characteristics which could contribute to reduce the spatial connectivity of the flow. Rainfall events were also grouped as different precipitation types for this two-step analysis, in order to detect variations caused by the type of rainfall event.

3. Results

3.1. Surface Conditions

[20] The five experimental slopes represent a gradient of degradation associated with the degree of development of rill networks (Table 1). Two of the slopes (1 and 2) exhibit dense, well-developed rill networks (rill density > 60 m m^{-2}). On these slopes the soil surface is bare or sparsely covered (total cover < 10%) and has lost most of its original roughness. The soils of these highly degraded slopes have a massive and very dense (approximately 1.50 g cm^{-3}) structure and very low organic matter content (approximately 0.50%), making their infiltration capacity rather low (*f*c < 15 mm h^{-1}). In contrast, slope 4 has a discontinuous and poorly developed rill network (0.30 m m^{-2}), and slope 5 is devoid of rills. Slopes 4 and 5 also have more cover (45–60% total cover, although spatially heterogeneous), and retain their original surface roughness. The soils of slopes 4 and 5 have a lower bulk density (1.23–1.39 g cm^{-3}) and higher infiltration capacity (*f*c: 23–37 mm h^{-1}), influenced by the presence of herbaceous roots and higher amounts of organic matter (1.5–2.0%). Considering the conditions represented by the highly eroded versus the most vegetated slopes (slopes 1 and 2 versus slopes 4 and 5), slope 3 represents a transitional position in the degradation gradient.

Table 2. Summary of the Different Categories of Precipitation and Average Runoff and Sediment Yield Responses at the Utrillas Field Site for the 2005–2006 Hydrologic Year[a]

	Number of Events	Precipitation (mm)				I_{30} (mm h^{-1})		Duration (h)		Runoff (mm)				Sediment Yield (g m^{-2})			
		Mean	SD	CA	Percent	Mean	SD	Mean	SD	Mean	SD	CA	Percent	Mean	SD	CA	Percent
Nonerosive	56	0.5	0.5	26	4	0.6	0.5	0.5	0.5	0.0	0.0	0	0	0	0	0	0
Nonactive Atlantic fronts	11	9.8	5.3	108	18	2.6	1.3	5.3	3.8	0.4	0.6	4	4	4	10	43	1
Active Atlantic fronts	8	34.7	27.2	277	45	9.5	2.6	14.3	16.6	4.2	6.8	34	38	144	420	1157	23
Convective thunderstorms	4	50.9	15.5	204	33	30.2	16.4	15.8	8.5	12.8	10.3	51	58	947	1227	3786	76
Total	79			615	100							89	100			4986	100

[a]Averaged from MC plots: 3 × 15 m microcatchments on all slopes for each event. Abbreviations: SD, standard deviation; CA, cumulative amount; Percent, relative percentage amount.

3.2. Categories of Precipitation Events

[21] Total rainfall during the 2005–2006 hydrologic year was 615 mm, about 32% above the annual average. About 30% of rainfall events produced runoff, but most of the runoff and erosion was generated by relatively few events (Table 2). Three categories of runoff-producing rainfall events were identified: (1) low-intensity rains occasioned by nonactive Atlantic fronts, beginning in the autumn and lasting until the early spring (these rains were the most common); (2) more intense events caused by active Atlantic fronts, occurring during the same period (these rainfall events were an important source of runoff, responsible for about 38% of the annual total); and (3) high-intensity convective thunderstorms, occurring during late spring and summer (these events produced 58% of the runoff and 76% of the erosion).

3.3. Runoff

[22] Runoff displayed great variability, both among and within the five experimental slopes (Table 3). Variability among the slopes was related to the extent of degradation, and these differences increased with scale (plot length): for the G1 plot on the most densely rilled slope (slope 1), runoff was 1.4 times higher than that of the G1 plot on the most vegetated slope (slope 5); for the G2, G3 and MC plots, runoff amounts from slope 1 were 3.2, 3.8 and 4.9 times higher than those from slope 5, respectively.

[23] The relationship between plot length and runoff variability among the slopes reveals a pronounced effect of scale within each slope: unit area runoff declined as plot length increased (Table 3). Nevertheless, the magnitude of this decline varied greatly depending on slope conditions (Figure 2a). Indeed, the decline in runoff was more sensitive

Table 3. Annual Cumulative Amounts of Runoff, Sediment Yield and Runoff Coefficient for the 2005–2006 Hydrologic Year[a]

	Cumulated Runoff (mm)	Annual Runoff Coefficient (%)	Cumulated Sediment Yield (g/m^2)
		Slope 1	
G1	181	30	5218
G2	159	26	5219
G3	138	22	6207
MC	132	21	12161
Mean ± SD	153 ± 22	25 ± 4	7201 ± 3339
		Slope 2	
G1	161	26	5264
G2	143	23	5127
G3	128	21	6495
MC	129	21	8061
Mean ± SD	140 ± 16	23 ± 3	6237 ± 1363
		Slope 3	
G1	144	23	2824
G2	117	19	2654
G3	102	17	2762
MC	98	16	3270
Mean ± SD	115 ± 21	19 ± 3	2653 ± 201
		Slope 4	
G1	128	21	2018
G2	65	11	1515
G3	59	10	1162
MC	57	9	1217
Mean ± SD	77 ± 34	13 ± 6	1478 ± 392
		Slope 5	
G1	132	22	1261
G2	50	8	427
G3	37	6	279
MC	27	4	228
Mean ± SD	62 ± 48	10 ± 8	549 ± 482

[a]Abbreviations: G1, 1 m long plot; G2, 2 m long plot; G3, 3 m long plot; MC, 15 m long microcatchment plot; SD, standard deviation.

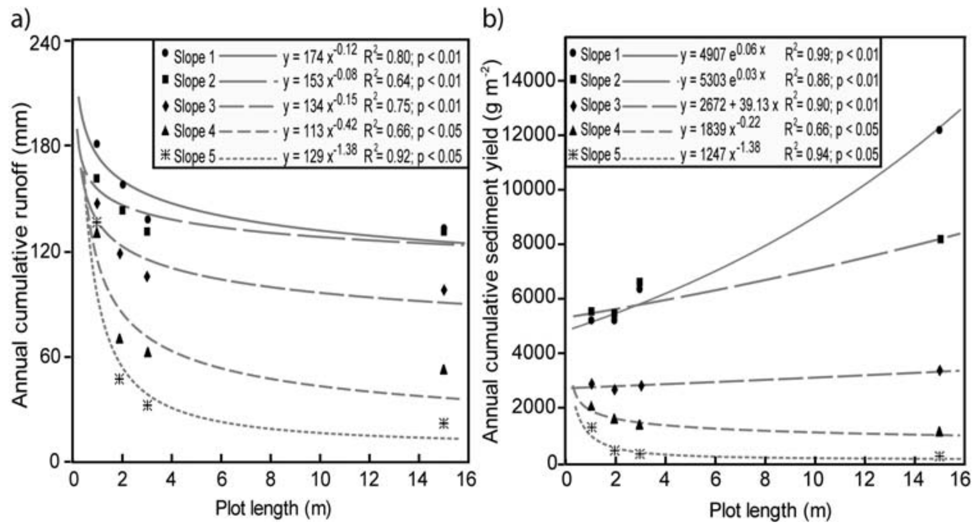

Figure 2. Relationship between scale (plot length) and annual cumulative amounts of (a) runoff and (b) sediment yield.

to plot length at the most vegetated slopes (a reduction of 55–79% for slopes 4 and 5) than at the most degraded ones (a reduction of 20–32% for slopes 1, 2, and 3).

[24] The effect of scale on runoff also varied with precipitation category (Figure 3). In the case of low-intensity, nonactive Atlantic front events, unit area runoff differed significantly with plot length (Figure 3a). In contrast, the effect of plot length on runoff was less pronounced under both active Atlantic front events and convective thunderstorms (Figures 3b and 3c). For these two categories, the effect was significant only in the case of slope 5, the nonrilled and most vegetated slope.

[25] The analysis of the spatial connectivity of runoff showed that the influence of surface conditions on scale effects varied depending on the category of precipitation event (Table 4). For both nonactive and active Atlantic events, the differences in the degree of degradation of surface features among the experimental slopes played a significant role only at the smallest scales (the transition between G1 and G2 plots), at which increased vegetation cover and surface roughness correlated with decreased runoff connectivity. For high-intensity convective storms, this correlation was also observed, and, in general, was even more pronounced, at the larger scales. For example, increased vegetation cover and surface roughness were correlated with decreased runoff connectivity at the transition between the G3 and MC plots. It is noteworthy that at this large scale, increased rill density strongly correlated with increased runoff connectivity under high-intensity storms.

3.4. Erosion

[26] Erosion was also highly variable among and within slopes (Table 3). Annual sediment yield from the most degraded slope (slope 1) was 4 to 53 times higher than from the most vegetated slope (slope 5), a difference that becomes larger with increasing scale from the G1 to the MC plots (Table 3). Indeed, the degree to which plot length affected sediment yield varied depending on the extent of degradation (Figure 2b). For highly degraded slopes (slopes 1 and 2) sediment yield increased substantially with plot length; the largest amounts came from the longest plots (15 m long MC plots), directly influenced by continuous rill networks (rill density > 0.60 m m^{-2}). In the case of the most severely degraded slope (slope 1), sediment yield from the MC plot was 133% greater than that from the G1 plot. The opposite relationship was found for the less degraded slopes (slopes 4 and 5), where rill networks are discontinuous or even absent (rill density: 0.00–0.30 m m^{-2}), and sediment is deposited between rills and in microtopographical depressions (generated by cross-slope plowing) in which vegetation is densely developed. On these two slopes, sediment yield from the MC plots was 39% to 81% lower than that from the G1 plots.

[27] The effect of scale on erosion varied with category of precipitation event depending on the degree of degradation (Figure 4). For the least degraded slope (slope 5), sediment yield declined as plot length increased, irrespective of the category of precipitation. Conversely, for the most degraded slope (slope 1), sediment yield did not show clear trends with respect to plot length for both nonactive and active Atlantic events, but it increased significantly with plot length under high-intensity convective storms.

[28] The influence of surface conditions on the connectivity of the sediment fluxes also varied with category of precipitation event (Table 4). For nonactive Atlantic events, a decline in the continuity of sediment yield was correlated with increasing vegetation cover and soil roughness at the smallest scales (the transition between G1 and G2 plots). For the other types of precipitations (active Atlantic and convective events), the influence of these two factors (vegetation cover and surface roughness) on the connectivity of sediment fluxes was stronger and also relevant at larger scales. In fact, for active Atlantic events, increased vegetation cover and surface roughness were correlated with decreased continuity of sediment yield at both small and intermediate scales (the transitions between G1 and G2 plots and between G2 and G3 plots). For convective precipitation events these relationships were observed even at the largest scales (the transition between G3 and MC plots). In addition, for these high-intensity convective precipitations the rill density strongly affected the connectivity of sediment fluxes: increased rill density was strongly correlated with

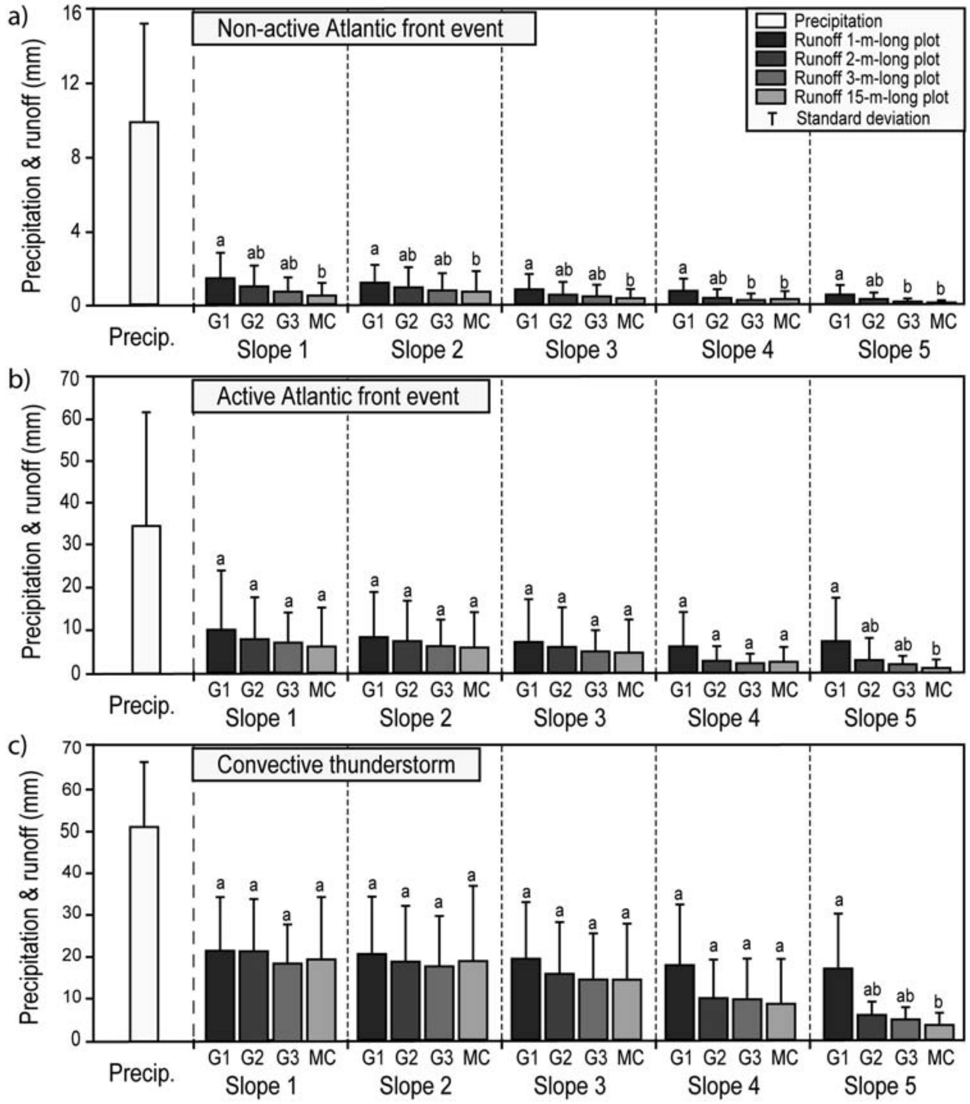

Figure 3. Mean runoff generated from the different plots by runoff-producing events of the various precipitation categories: (a) nonactive Atlantic front, 11 events; (b) active Atlantic front, 8 events; and (c) convective thunderstorm, 4 events. For comparison, corresponding mean precipitation amounts are shown on the left-hand side. Bars with the same letters (a or b) within slopes do not differ significantly at $\alpha = 0.05$. Runoff was analyzed using nonparametric Kruskal-Wallis and post hoc Mann-Whitney U tests. Detailed information on the three most typical runoff events for each precipitation category is available in the auxiliary material.[1]

increased continuity of sediment yield at the largest scales (the transition between G3 and MC plots).

4. Discussion

4.1. Runoff

[29] As was hypothesized by *Wilcox et al.* [2003], our results showed that unit area runoff is much less sensitive to plot length under degraded conditions: for the most degraded slopes (1, 2, and 3), unit area runoff from the 15 m long plots (MC) showed a 20–32% decrease compared with the 1 m long plots (G1), whereas for the less degraded slopes (4 and 5), the corresponding decrease was 55–79% (Table 3). These findings are consistent with previous results obtained in this Mediterranean-dry study area: under bare and rilled conditions, unit area runoff from 35 m long plots showed a 26–35% decrease compared with 1.5–3.0 m long plots, whereas under vegetated conditions the corresponding decrease was 66% [*Nicolau*, 2002]. Similar trends (less sensitivity to scale under degraded conditions) were reported in subhumid regions of West Africa: under bare and crusted conditions, unit area runoff showed a 40% decrease in 12 m long plots, compared with 1.25 m long plots, whereas an 80% decrease was observed under vegetated conditions [*van de Giesen et al.*, 2000].

[30] Reductions in unit area runoff can be attributed to both spatial variability of soil infiltration and temporal

[1]Auxiliary materials are available at ftp://ftp.agu.org/apend/wr/2009wr007875.

Table 4. Spearman's Rank Correlation Coefficient Between the Spatial Connectivity of Both Runoff and Sediment Flow and Surface Traits for Runoff Events Produced Under the Three Precipitation Categories[a]

	Vegetation Cover	Roughness Index	Rill Density
	Nonactive Atlantic Front Event (N = 11)		
G2/G1 runoff ratio	−0.38**	−0.33*	NA
G3/G2 runoff ratio	−0.22	−0.22	NA
MC/G3 runoff ratio	0.03	0.24	−0.05
G2/G1 sediment yield ratio	−0.48**	−0.47**	NA
G3/G2 sediment yield ratio	−0.27*	−0.24	NA
MC/G3 sediment yield ratio	0.07	−0.01	−0.08
	Active Atlantic Front Event (N = 8)		
G2/G1 runoff ratio	−0.73**	−0.72**	NA
G3/G2 runoff ratio	−0.25	−0.22	NA
MC/G3 runoff ratio	0.06	0.21	−0.03
G2/G1 sediment yield ratio	−0.69**	−0.68**	NA
G3/G2 sediment yield ratio	−0.41**	−0.40**	NA
MC/G3 sediment yield ratio	−0.20	−0.14	0.18
	Convective Thunderstorm (N = 4)		
G2/G1 runoff ratio	−0.92**	−0.93**	NA
G3/G2 runoff ratio	−0.37	−0.38	NA
MC/G3 runoff ratio	−0.58**	−0.50*	0.64**
G2/G1 sediment yield ratio	−0.60**	−0.63**	NA
G3/G2 sediment yield ratio	−0.62**	−0.61**	NA
MC/G3 sediment yield ratio	−0.68**	−0.60**	0.73**

[a]The spatial connectivity of both runoff and sediment yield is depicted as the runoff and sediment yield ratios for pairs of plots with consecutive sizes. Surface traits include vegetation cover, surface roughness, and rill density. Abbreviations: N, number of events; G1, 1 m long plot; G2, 2 m long plot; G3, 3 m long plot; MC, 15 m long microcatchment plot; NA, not applicable. Significance: *, significant at $\alpha = 0.05$; **, significant at $\alpha = 0.01$.

runoff dynamics [*Wainwright and Parsons*, 2002; *Yair and Raz-Yassif*, 2004; *Boix-Fayos et al.*, 2007]. The residence time of overland flow on each slope (time required for movement from top to bottom) plays a central role in the efficiency of the process, controlling the time that surface runoff has to recharge soil water stores as it moves down the slope [*Tongway and Ludwig*, 2001; *Joel et al.*, 2002; *van de Giesen et al.*, 2005]. The extent of degradation of the vegetation strongly influences the capacity of slope systems to slow, retain, and store overland flow. In fact, in the case of the most degraded slopes in our study (1, 2, and 3), the scarce vegetation cover (less than 30%) meant that surface crusts were well developed, limiting soil infiltration capacity and hence point infiltration [*Moreno-de las Heras et al.*, 2009]. Even more interestingly, the residence time of overland flow on slopes like these is much shorter (owing to the inability of the scant vegetation to intercept and slow down the flow), which greatly reduces the efficiency of runoff reinfiltration as the flow moves down the slope.

[31] Microtopographical alterations caused by accelerated erosion (the development of rill networks and reduction of surface roughness) also play an important role in runoff reinfiltration processes, by limiting the residence time of flow on the slope. Those experimental slopes that had well-developed rill networks and rather limited surface roughness (slopes 1, 2 and 3) showed a low reinfiltration efficiency. A lack of surface roughness offers little resistance to flow, thus severely restricting surface storage [*Stomph et al.*, 2002]. In addition, the presence of dense rill networks increases runoff connectivity; the rills route the flow throughout the slope very efficiently [*Nicolau*, 2002; *Bracken and Croke*, 2007].

[32] The low efficiency of runoff reinfiltration processes under degraded conditions was particularly noticeable for those categories of precipitation producing the most runoff (Figure 3). For low-intensity precipitation events (nonactive Atlantic front events), unit area runoff was scale-dependent for all five experimental slopes. For these small precipitation events, reinfiltration processes on the most degraded slopes are probably linked to spatial variations in soil infiltration capacity, governed by the presence of cracks or macropores on the soil surface and differences in soil physical properties. These spatial variations could provide some opportunities for the infiltration of runoff in areas with unsatisfied infiltration demand, especially as the spatial scale of the slope increases. In contrast, for those precipitation categories that are the most important sources of runoff (active Atlantic front events and convective storms), scale dependency was observed only at the most vegetated slope (slope 5). In fact, higher vegetation cover and soil roughness both contributed to reduce the spatial connectivity of runoff produced by these more intense events between the different scales monitored (Table 4). Similarly, other studies have highlighted a prevailing role of vegetation cover and surface roughness, which actively increase the residence time of runoff on the slope, for the reductions in unit area runoff with increasing scale under long and/or intense rainfalls [*van de Giesen et al.*, 2000, 2005]. The degraded slopes showed a remarkable inability to store and delay runoff when convective thunderstorms produced large amounts of overland flow. Under these high-intensity precipitation events, rill networks were the dominant modifiers of the effects of scale, increasing the spatial connectivity of runoff at large scales (Table 4).

4.2. Erosion

[33] The effects of scale (plot length) on erosion varied dramatically with degradation level (Figure 2b). For the highly degraded slopes (slopes 1 and 2), annual sediment yield increased noticeably with plot length, showing an in-

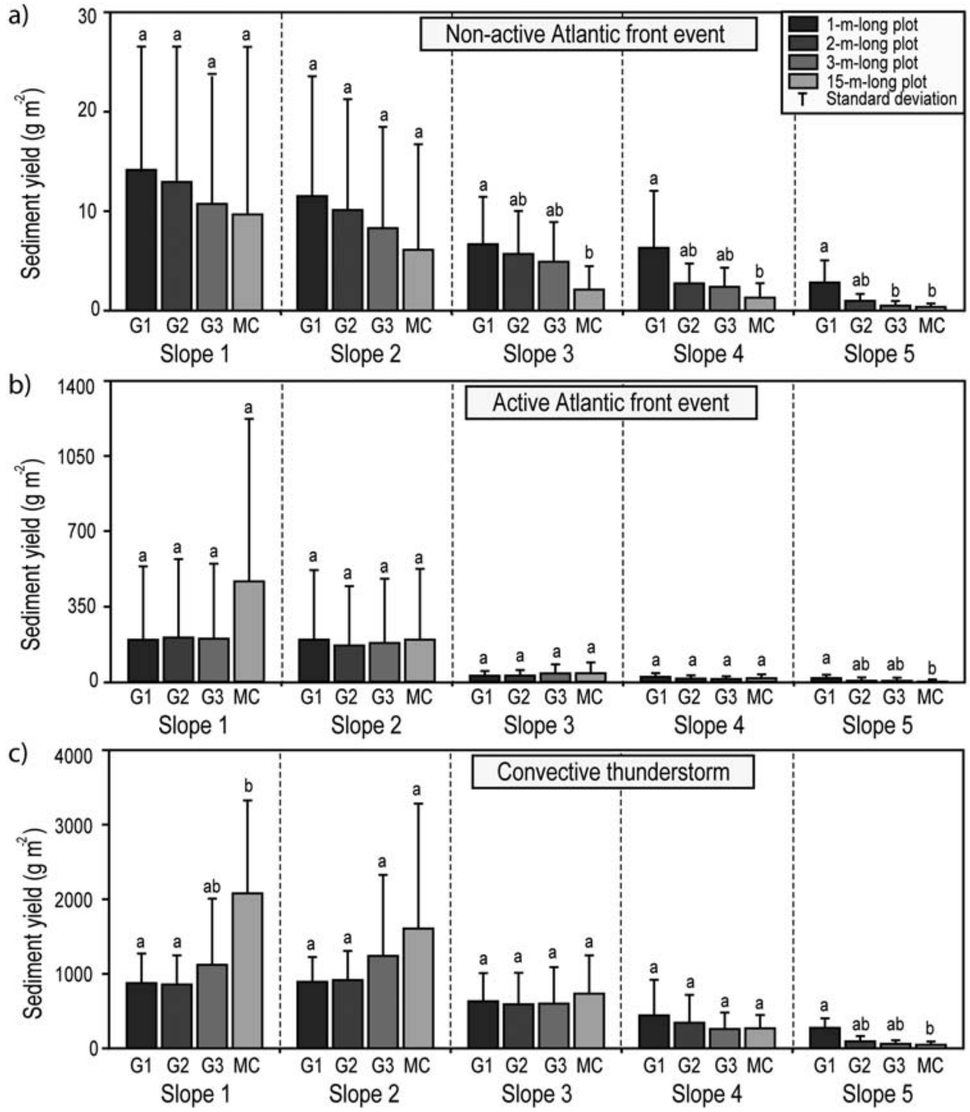

Figure 4. Mean sediment yield generated from the different plots by runoff-producing events of the various precipitation categories: (a) nonactive Atlantic front, 11 events; (b) active Atlantic front, 8 events; and (c) convective thunderstorm, 4 events. Bars with the same letters (a or b) within slopes do not differ significantly at $\alpha = 0.05$. Sediment yield was analyzed using nonparametric Kruskal-Wallis and post hoc Mann-Whitney U tests. Detailed information on the three most typical runoff events for each precipitation category is available in the auxiliary material.

crease of 130% from the 15 m long plot (MC) compared with the 1 m long plot (G1) in the most severe case. These increases were due mainly to erosion caused by concentration of runoff in rill networks. Conversely, for the most vegetated slopes (4 and 5), sediment yield decreased with plot length. The main process involved in sediment delivery along these vegetated slopes was sheet erosion, as there were no rills (slope 5) or only poorly developed and discontinuous rills (slope 4), allowing sediments to be retained within the slope.

[34] Such positive effects of scale on erosion rates have generally been attributed to rill erosion processes [*Foster et al.*, 1977; *Loch*, 1996; *Parsons et al.*, 2004]. In the absence of rill erosion, sediment yield frequently shows no scale dependency; occasionally, it may even show a decrease with increasing scale [*Parsons et al.*, 1993; *Wilcox et al.*, 2003; *Parsons et al.*, 2006]. This kind of scale-dependent sediment redistribution process has been commonly observed in low gradient (usually < 12°) undisturbed hillslopes, where the loss of overland flow by downslope runoff reinfiltration limits the entrainment and travel distances of eroded particles. Our results provide empirical evidence that such scale-dependent sediment and runoff redistribution processes can also be quite active on steeper slopes (20° gradient) under sheet flow conditions.

[35] Precipitation category dramatically affected the scale relationships of erosion as well. For all five slopes the relationships observed between annual cumulative sediment yield and plot length reflected, in general, the pattern observed for the most intense precipitation events, especially the summer thunderstorms. Nevertheless, in the case of the most degraded slope (slope 1), the observed trend under these

high-intensity storms (a general increase of soil erosion rates with plot length) disappeared under the low-intensity nonactive Atlantic front events. In addition, the trend found for nonactive Atlantic events in slope 3 (a general decrease of erosion rates with increasing plot length) disappeared under more intense precipitations. These trends are coherent with previous evidences which suggested that the influence of plot length on erosion rates could depend on rainfall characteristics [*Kinnell*, 2009].

[36] The variable scaling behavior of the most degraded slopes under different precipitation categories can be explained by a transition from interrill to rill dominated processes with increasing rainfall intensity. In fact, rills strongly ruled the routing of overland flow by increasing the spatial connectivity of water runoff under high-intensity convective precipitations. Flow concentration in these situations led to an enhanced contribution and spatial continuity of sediment yield at large scales (Table 4), and consequently, to higher erosion rates with increasing plot length (Figure 4c). Conversely, the negative influence of vegetation and surface roughness on runoff connectivity under high-intensity precipitations (Table 4), inhibited flow concentration and the resulting transition from sheet flow conditions to rill dominated processes in the most vegetated slope (slope 5). This allowed the preservation of active sediment redistribution processes (i.e., a reduction in sediment yield with increasing plot length) in this slope even under high-intensity storm conditions (Figure 4c). *Liu et al.* [2000] reported that the relative contribution of rill processes to total erosion is highly dependent on rainfall intensity, with important consequences in scaling outcomes; which also supports our finding that the influence of plot length on soil erosion varies greatly with precipitation characteristics.

4.3. Overall Influence of Degradation

[37] The overall results of this study are consistent with the conclusions reached by *Wilcox et al.* [2003] regarding the influence of degradation on the scale dependency of runoff and erosion processes. Indeed, under degraded conditions surface runoff reinfiltration in the downslope direction was severely constrained. The effect of plot scale on unit area runoff was particularly limited when the amount of surface runoff generated was large (produced by active Atlantic events and convective storms, Figure 3). At the same time, soil erosion rates under degraded conditions tended to increase with increasing plot scale under degraded conditions (Figure 4), as a consequence of rill erosion processes being initiated by high-intensity convective storms (these events produced over 70% of annual cumulative soil erosion). These trends were particularly marked in highly degraded slopes (slopes 1 and 2), where hydrological responses were conditioned by dense rill networks (rill density > 0.60 m m^{-2}).

[38] On the whole, degraded conditions led to a substantial loss of resources (water and soil) from the slope system. These results contribute to our understanding of degradation processes in drylands, as similar mechanisms may operate in disturbed, water-restricted hillslope systems. In fact, there is now ample evidence that the drastic alteration of vegetation cover and distribution prompted by severe disturbance (e.g., overgrazing, fire, extreme drought) is associated with the loss of soil and water resources from hillslope systems, owing to a decrease in the efficiency of surface runoff reinfiltration and the active contribution of rill and gully erosion [*Wilcox et al.*, 1996; *Puigdefábregas*, 1998]. These losses (specifically, the net loss of water resources from hillslope systems) could play an important role in ecosystem function, reinforcing the degradation process through feedback mechanisms with vegetation [*Davenport et al.*, 1998; *Sarah*, 2004; *Turnbull et al.*, 2008]. Indeed, water losses caused by the degradation of vegetation and the acceleration of soil erosion processes could greatly reduce water availability for plant growth, lowering plant production and cover further and thereby increasing overland flow runoff and erosion [*Wilcox et al.*, 2003; *Zehe and Sivapalan*, 2009; *Espigares et al.*, 2010].

5. Conclusions

[39] Through this study, we have obtained empirical evidence supporting the hypothesis of *Wilcox et al.* [2003], that effects of scale on hillslope runoff and erosion are substantially altered by degradation processes. In fact, we found that the efficiency of surface runoff reinfiltration in the downslope direction decreases as degradation increases, leading to more continuous flows along the hillslope. Similarly, the effects of scale on erosion (sediment yield), are considerably modified by degradation processes: for highly degraded (densely rilled) slopes, the tendency of erosion decreasing with plot length is reversed (unit area sediment yield actually increases with plot length). In addition, this reversal of scale effects for the most degraded slopes is especially pronounced under high-intensity precipitation conditions. Active rilling processes that result from large amounts of runoff on poorly vegetated slopes impede the ability of the slopes to slow, retain, and store water and sediments. The overall effect of degradation processes on relationships between scale and runoff and erosion is a substantial loss of water and soil resources from the slope. The results of this study contribute to our understanding of degradation processes in water-restricted environments, showing that the loss of water resources due to degradation of vegetation (both extent and distribution of coverage) could have important repercussions on ecosystem function, probably even reinforcing the degradation process.

[40] **Acknowledgments.** The authors would like to thank Núria Sau and Carlos Ontiveros for field assistance and the Utrillas Council for logistic cooperation. An earlier version of this manuscript benefited from the helpful comments of Graham Sander and three anonymous referees. This research was supported by CICYT projects REAM (CGL2004-00355/BOS) and INTERBOS03 (CGL2008-04503-C03-03/BOS) from the Spanish government, as well as the REMEDINAL research network.

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