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Effects of soil and vegetation on runoff along a catena in semi-arid Spain

J.M. Nicolau, A. Solé-Benet *, J. Puigdefábregas, L. Gutiérrez

Estación Experimental de Zonas Aridas, CSIC, General Segura 1, 04001-Almería, Spain

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Abstract

Runoff and infiltration were investigated on abandoned fields of patchy vegetation in semi-arid Spain during 15 months of natural rainfall and by rainfall simulations. The aim was to ascertain sources and sinks of runoff and the effects of soils and plant cover. Soils of the catena developed from mica schists of the upper hillslopes, fan deposits of the lower hillslopes, and an alluvial terrace at the bottom. Runoff from natural events were from three sets of three pairs each of 10×2 m runoff plots. The pairs of each set had different densities of plant cover; the sets were vegetated with tussock grass, *Stipa tenacissima*, a shrub, *Anthyllis cytisoides*, and a bush, *Retama sphaerocarpa*. Nineteen natural rainfall events of intensities up to 18 mm/h produced 400 mm of rain during the study period. Because the rainfall threshold for runoff production was about 20 mm, only eight events produced runoff. The rainfall simulations used a sprinkler that produced 50 mm/h of rain for 30 minutes; runoff was recorded each minute in 0.24 m^2 bounded plots.

The depth and structure of the soil mantle provide the main controls on runoff rates, which are lowest on the lower fan deposits and highest on the thin upslope soils. The river-bank terrace, with a surface covered by crusts and mosses, also yields relatively high runoff. In general, vegetation density varies inversely with runoff. Nevertheless, shrub and bush litter favor runoff, as does a particular spatial distribution of individual plants on the hillslope. Settling of the upper few centimeters of soils of the alluvial fan following cessation of cultivation 15 to 40 years ago has produced a near-surface compacted layer favoring shallow subsurface runoff. Apparently contradictory results between runoff plots and rainfall simulations are the result of differing processes.

1. Introduction

In semi-arid mountain areas slopes are often rocky and poorly covered with shallow soils whereas at the base of the slopes extensive sediment fills develop that are cut by ephemeral-drainage systems. An understanding of: (a) the flood-forming conditions, (b) the spatial distribution of overland flow, and (c) potential sites for ground-water storage, requires accurate information about the importance and localization of runoff sources and sinks, and about the factors controlling these functions.

That upper parts of semi-arid slopes constitute the sources for runoff and the bottom sediments are the sinks for runoff is a poor generalization. The physical properties of slopes that determine the hydrological responses are highly variable in both landscape units (Pilgrim et al., 1988); for example, soils of the lower slopes often have the coarser particle sizes. Data concerning runoff from marl or limestone areas are relatively abundant (Scoging, 1982; Yair et al., 1982; Romero-Díaz et al., 1988; Benito et al., 1992), but runoff conditions of metamorphic areas are much less

* Corresponding author.

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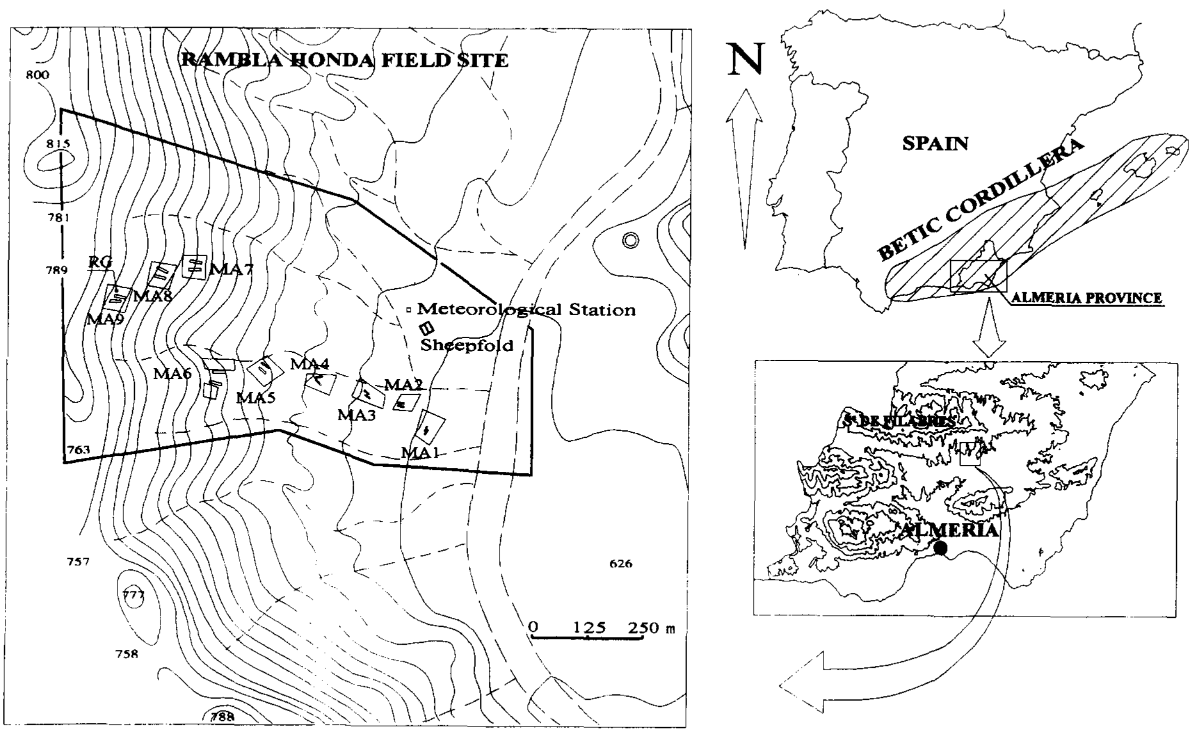

Fig. 1. Maps of the Rambla Honda field site, southeast Spain. Measurement sites (MA) 1, 2, and 3 are dominated by *Retama sphaerocarpa*, 4, 5, and 6 by *Anthyllis cytisoides*, and 7, 8, and 9 by *Stipa tenacissima*.

documented. In particular, characteristics of runoff from mica schists, with high lithologic and structural variability, is poorly known (Gilman and Thornes, 1985).

In the eastern part of the Betic Cordillera, in the Almeria province of Spain (Fig. 1), metamorphic reliefs and marl depressions alternate in the landscape, the latter being partly formed of pediment and alluvial-fan systems produced by the former. Such areas were extensively cultivated up to the 1960s and have been abandoned thereafter. Previous research reported that the disruption of cultivation increases the infiltration capacity of soils and decreases overland flow as plant cover and biomass increase (Greenland, 1977). Nevertheless, after ploughing, soils tend to compact and to develop surface crusts that favor runoff (McIntyre, 1958). The interaction between the two phenomena is not well documented. In the scope of the problems just stated, this paper utilizes information from a broad study on a mica-schist slope of the southern versant of the Sierra de los Filabres (Almeria, Spain), under the MEDALUS Project (see Acknowledgements section). This research assesses the relative importance of mica-schist slopes and alluvial fans as runoff sources or sinks. In addition, the research will provide field information about the hydrologic response of the alluvial-fan system after cessation of cultivation, and about the effects of plant cover on runoff.

The study reported here is on-going. Field data, available for a one-year period of 1993, were collected in bounded plots at a rainfall-event resolution time. Therefore, insufficient information is available to provide conclusions about the control of rainfall characteristics on runoff because the number of events is too small and no data are available on the runoff hydrographs. The results presented in this paper are specific for restricted areas in different slope situations; they cannot necessarily be extrapolated to the drainage-system scale.

2. Materials and methods

2.1. Location and climate

The study area is in the Rambla Honda Basin (Fig. 2), an ephemeral river, or rambla, in the lower

Fig. 2. Photograph of Rambla Honda experimental watershed, which is underlain by mica-schist bedrock in the upper part, alluvial-fan deposits in the middle part, and stream alluvium in the lower part.

part of the southern slopes of the Filabres Range (Fig. 1). Nine measurement areas of the study are designated MA 1 through MA 9 (Fig. 1). The sloping area consists of a catena of soils and vegetation characterized by: (1) soils derived from mica-schist bedrock (MA 7, 8, and 9) and colluvium (MA 6) with *Stipa*

Fig. 3. Photograph showing tussocks of *Stipa tenacissima* growing on slopes of mica schist.

Fig. 4. Photograph showing shrubs of *Anthyllis cytisoides* growing on the upper part of the alluvial-fan area of the watershed.

tenacissima tussocks on the uppermost slopes (Fig. 3), (2) soils derived from alluvium and covered with shrubs of *Anthyllis cytisoides* in upper parts of the alluvial fan (MA 4 and 5) (Fig. 4), and (3) alluvial soils with *Retama sphaerocarpa* on the lower alluvial fan (MA 2 and 3) and bottomlands (MA 1) (Fig. 5).

The climate is semi-arid with long, hot summers. Geographical interpolations among nearby weather sta-

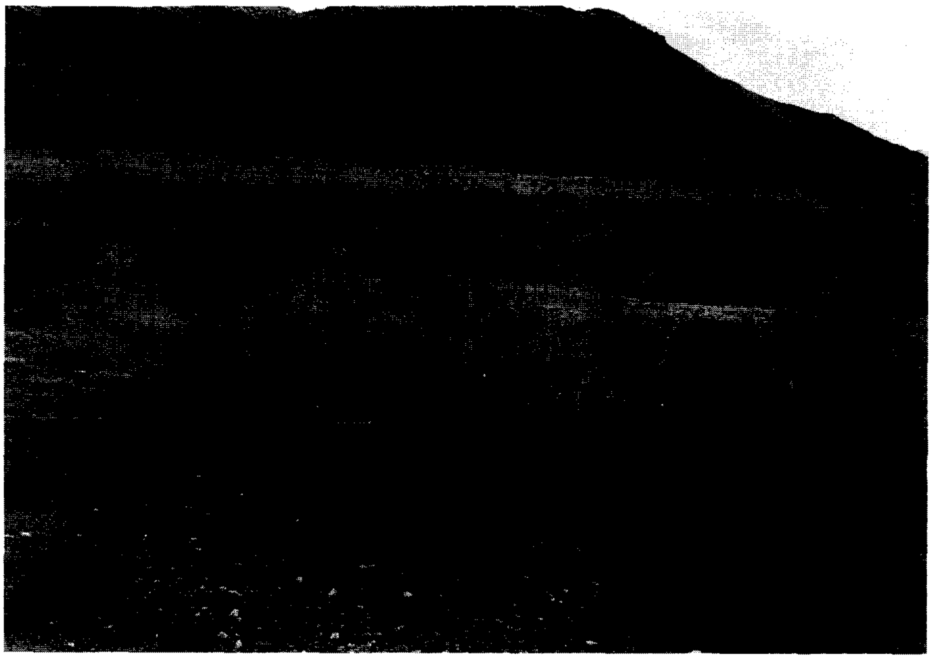

Fig. 5. Photograph showing bushes of *Retama sphaerocarpa* growing on a terrace surface of the lowest part of the watershed.

Table 1
Characteristics of Rambla Honda soils

MA	Depth cm	Percent of sample, by size (mm)					O.M. %	Da kg/l	V total %
		> 2 mm	2–0.2	0.2–0.02	0.02–0.002	< 0.002			
1	0–4	12.75	21.29	53.13	9.51	3.32	1.57	1.76	33.57
	11–42	31.46	34.88	27.35	4.73	1.64	0.77	–	–
2	0–3	22.71	32.46	34.78	7.42	2.71	1.38	1.87	29.61
	3–34	38.64	29.76	24.91	5.09	1.66	0.68	–	–
3	0–6	40.68	31.97	20.35	5.22	1.84	1.38	1.88	28.91
	21–38	29.39	35.80	28.24	5.15	1.41	0.71	–	–
4	0–4	40.06	24.33	25.29	7.19	3.06	1.83	1.98	25.32
	20–50	45.31	17.34	24.28	9.30	3.77	0.92	–	–
5	0–3	40.63	18.82	31.83	6.06	2.67	2.57	2.03	23.41
	20–60	44.70	18.64	25.55	8.79	2.27	1.08	–	–
6	0–5	60.12	15.32	17.11	5.78	1.71	1.82	1.85	30.03
	> 16	62.01	8.13	14.66	11.81	3.38	1.42	–	–
7	0–5	55.83	13.25	20.63	7.02	3.31	5.20	1.69	36.21
	5–30	58.47	12.38	17.90	7.77	3.53	1.91	–	–
8	0–3	47.05	14.08	26.37	8.42	4.08	4.80	1.85	30.04
	> 15	54.06	11.99	15.44	13.74	4.78	2.54	–	–
9	0–6	55.19	16.58	20.12	6.86	1.25	3.82	1.76	33.55
	6–60	28.56	15.43	32.29	19.00	4.72	1.67	–	–

MA = measurement area (Fig. 1); O.M. = organic matter; Da = bulk density; V total = total porosity.

tions with long records (Lazaro and Rey, 1991), along with data from a meteorological station installed in the study area, provide estimates of 300 mm average annual rainfall, occurring mainly in the cold season, and a mean temperature of 16°C.

2.2. *Soil features*

The soils of the Rambla Honda field site developed mostly from alluvial and colluvial deposits. Soils of the upper slopes developed from bedrock and thin deposits veneering the bedrock. The parent material is a fine-grained, dark-grey, Devonian–Carboniferous mica-schist containing graphite and garnets; it has numerous quartz veins that have contributed abundant rock fragments to all parts of the catena. In general, soils of the slopes show a moderate chemical evolution, but physical processes appear to be strongly dominant. The soils of the alluvial fan and rambla terraces, the surfaces of which are presently subject to periodic flooding, also show little development of pedogenic horizons and exhibit a clear stratification and an irregular distribution of organic matter along the profile. Except for the rambla terraces, where soils are mainly very-fine sandy loams, soil stoniness is a prominent feature of all geomorphic surfaces (bedrock slopes and alluvial fan). Coarse particle sizes, > 2.0 mm, account for about 13% to as much of 62% of the soil mass (Table 1).

An important morphological feature of most of the alluvial-fan soils is micro-layering of surface horizons, which has developed since the abandonment of ploughing activities 15 to 40 years ago. This layering (Fig. 6)

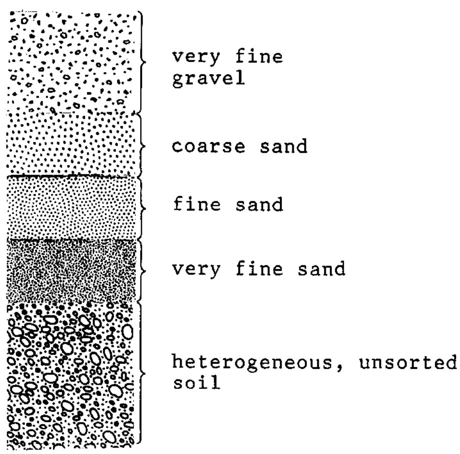

Fig. 6. Diagram of micro-layering observed in upper 3 cm of soil profiles.

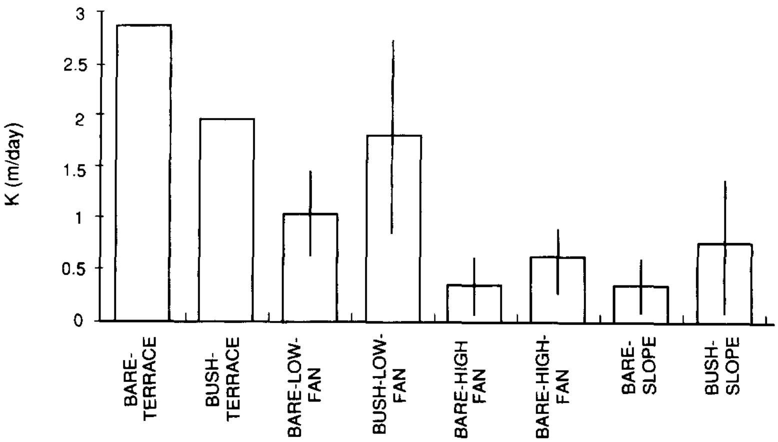

Fig. 7. Average saturated hydraulic conductivity of the first 50 cm of representative soils of the low terrace, lower and upper parts of the alluvial fan, and upper slopes under vegetated (under bushes, shrubs, or tussocks) and bare conditions.

typically exhibits a 1- to 10-mm thick surface layer, exclusively formed by very-fine gravel, that is underlain by coarse, well-sorted sand. Beneath these surficial horizons is an "illuvial" horizon of well compacted very-fine sand 2- to 5-mm thick; this layer is broken by vertical to sub-vertical cracks (observed in hardened, polished blocks and in thin sections). Underlying these horizons is soil of less delineated layering, with lenses of different textures, and soil mass that is heterogeneous and unsorted. Soil structure, fine to medium crumby, is poorly developed and occurs only around and among roots.

The organic matter of the uppermost soil horizons, mostly the top 6 cm, is largely dependent on vegetation type and cover. In measurement areas (MA 1 through MA 9), the near-surface organic content of those dominated by *Retama sphaerocarpa* ranged from 1.38 to 1.57 percent; in areas of *Anthyllis cytisoides* the range was 1.82 to 2.57; and in areas of *Stipa tenacissima* the range was 3.82 to 5.2 (Tables 1 and 2). The organic contents in lower horizons, as deep as 60 cm (Table 1), are representative of soils of an alluvial–colluvial origin.

Hydraulic conductivity is also an important soil property. The highest values are in alluvial soils dominated by *Retama sphaerocarpa* (MA 1, 2, 3), and the lowest hydraulic conductivities occur in the uppermost areas of the alluvial fan (MA 5, 6) (Fig. 1); hydraulic conductivity shows a gradient between the two extremes. In all cases except for the terrace, hydraulic conductivity is slightly higher in soils under or close to bushes than it is under bare soil (Fig. 7).

2.3. Vegetation

Shrub cover in each runoff plot was measured by means of photographs of the soil surface taken from a height of 2.5 m. Examples of shrub-cover pattern from RP 5A and RP 5B are represented in Fig. 8. Litter was sampled in November, 1991, from 15 quadrats, 50 cm

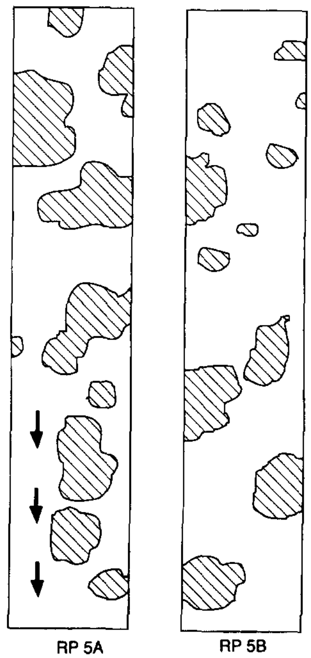

Fig. 8. Diagram of shrub-cover patterns in dense (RP 5A) and sparse (RP 5B) vegetation runoff plots, MA5; The alinement of shrubs in RP 5A may be the cause of greater runoff than in RP 5B.

Table 2
Main characteristics of the measurements areas (MA) that include runoff plots

MA	Surface	Altitude	Dominant vegetation	Dense vegetation		Sparse vegetation	
		(m)		Slope (deg)	Plant cover (%)	Slope (deg)	Plant cover (%)
1	Terrace	628	*Retama*	2	25.54	2	0
2	Alluvial fan	632	*Retama*	4	54.77	4.5	5.85
3	Alluvial fan	637	*Retama*	4.5	43.18	5	4.36
4	Alluvial fan	648	*Anthyllis*	7	48.34	8.7	24.33
5	Alluvial fan	662	*Anthyllis*	11.7	36.45	12	21.65
6	Colluvium	681	*Anthyllis*	20	47.59	21.5	15.29
7	Mica schist	720	*Stipa*	24	40.23	23	22.71
8	Mica schist	730	*Stipa*	21	44.43	18	30.34
9	Mica schist	752	*Stipa*	21	32.2	23	28.51

on a side, within each measurement area. Annual plant biomass was measured in the maximum growth period (May, 1992) by sampling, drying, and weighing all plants from 10 representative quadrats within each measurement area.

2.4. Experimental layout

The nine measurement areas (MA) are arranged roughly in a line along the slope catena, three dominated by *Retama sphaerocarpa*, three by *Anthyllis cytisoides*, and three by *Stipa tenacissima* (Fig. 1). In each measurement area, two runoff plots (RP) were built, one with more dense (A) and another with less dense (B) perennial plant cover; a rain gauge was installed in each area. In addition, each area was provided with three types of plots for sampling soil moisture, litterfall, and vegetation. Characteristics of the measurement areas and runoff plots are shown in Table 2.

The 18 runoff plots measure 2 m by 10 m and are all equipped with two collector tanks of 200 liters. When the first tank overflows, 1/10 of the water is conveyed to the second through a slot divisor. Readings are made after each rainfall event and samples are taken for determination of coarse sediment (> 2 mm) and fine sediment (< 2 mm) bulked with total solutes by drying.

2.5. Events

Nineteen rainfall events occurred during the period October 1, 1991, through December 1, 1992, the total of which was 400 mm. Eight rainfall events resulted in runoff, four of them accounting for 65% of the total precipitation during the period. These four events followed a typical mediterranean pattern, occurring in winter (January 28 and February 20, 1992), late spring (June 14, 1992), and autumn (November 8, 1992). Rainfall intensities were moderate, 18 mm/h (November 8, 1992) and 13 mm/h (February 20, 1992) being the highest recorded.

2.6. Rainfall simulations

Rainfall-simulation experiments were conducted at the nine measurement areas using a sprinkler-type rainfall simulator like that described by Calvo et al. (1988). Simulated rainfall was applied over circular plots of 0.24 m^2 at a constant intensity of 50 mm/h during 30 minutes. Runoff was measured at one minute intervals during each simulation.

3. Results

3.1. Runoff plots

(1) Runoff measurements during the period of study indicate that the mica-schist (RP 7, 8, and 9) and upper alluvial-fan (RP 4, 5, and 6) slopes and the rambla terraces (RP 1) mainly contribute to the highest water output. Seldomly does the lower alluvial fan (RP 2 and 3) contribute runoff (Fig. 9).

(2) When plotting precipitation depths against runoff rates for the eight rain events (Fig. 10), the following points appear clearly: (a) high variability occurs in the response of runoff plots to the eight rain events;

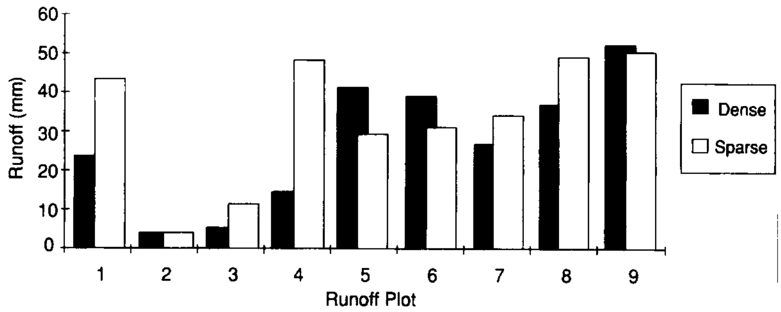

Fig. 9. Graph showing total runoff from plots during the study period.

(b) points relating runoff to rainfall for plots on the mica-schist slope (dots, Fig. 10) largely define the upper boundary, or line of relation; (c) the threshold of rain necessary to generate runoff is roughly 10 mm; and (d) the relation between depth of precipitation and the generated runoff, also in mm of depth, can be expressed as:

$$\text{runoff} = m \times (\text{rainfall} - k)$$

where m is the slope of the relation line and k is the rainfall depth required to yield runoff (Fig. 11). Data conform well to the equation for all plots excluding those from MA 1 on the rambla terraces. The values of m increase from the lower part (MA 2, 3) to the higher part (MA 4, 5, 6) of the alluvial fan and are highest on the mica-schist slope (MA 7, 8, 9), where the most runoff results from rainfall (Fig. 11).

Values of k, the threshold depth of rainfall required to yield runoff (Fig. 12), are lowest in the upper alluvial fan (MA 4, 5, 6). As examples of the variation that occurs in the rainfall/runoff relation, data from precipitation events are given for September 6, 1991, and for November 7 and 8, 1992 (Fig. 13A). The first event was a short but intense low-volume rainfall (14 mm) that generated the most runoff from the upper part of the alluvial fan (RP 4, 5; Fig. 13B). The second storm was an important and long rainfall (50 mm), for which plots on the mica-schist slope (RP 7, 8, 9; Fig. 13C) generally showed the greatest runoff.

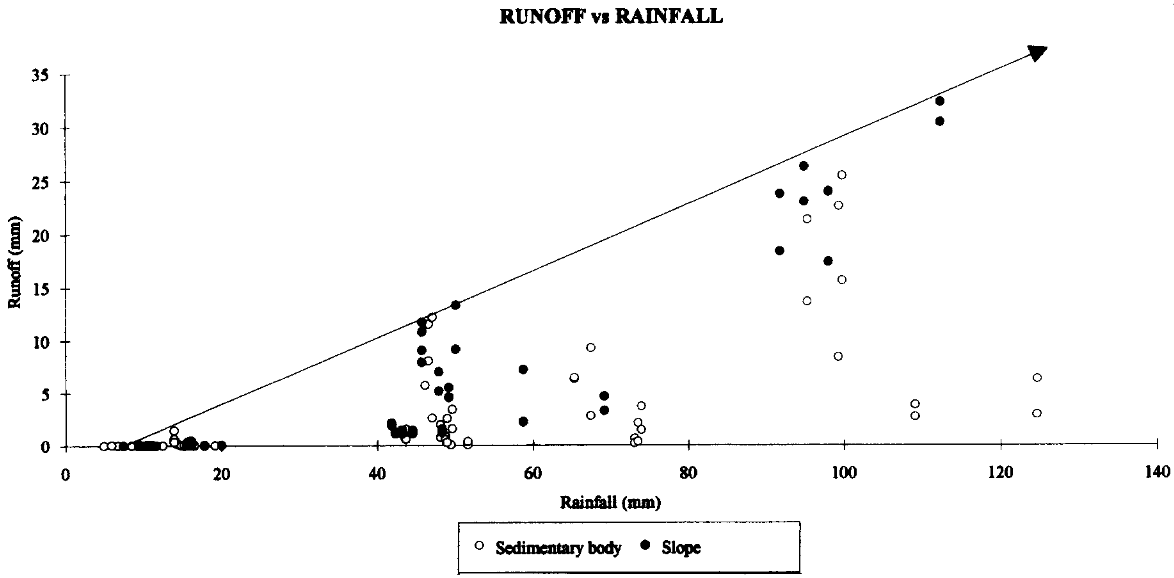

Fig. 10. Graph showing ranfall–runoff relations for the study period.

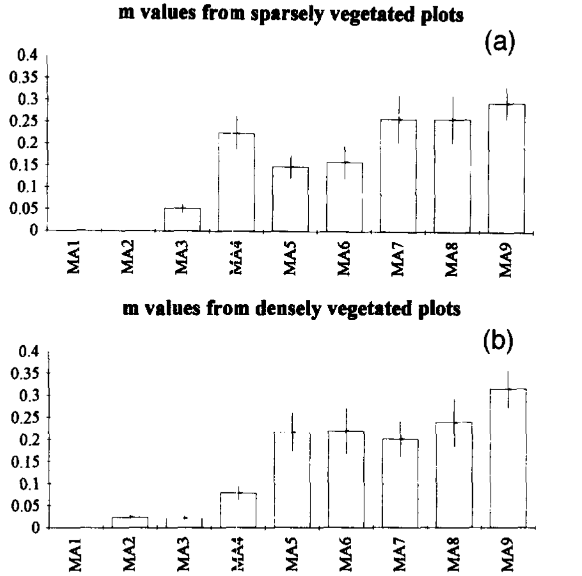

Fig. 11. Graphs showing values of m for sparsely vegetated plots (a), and densely vegetated plots (b).

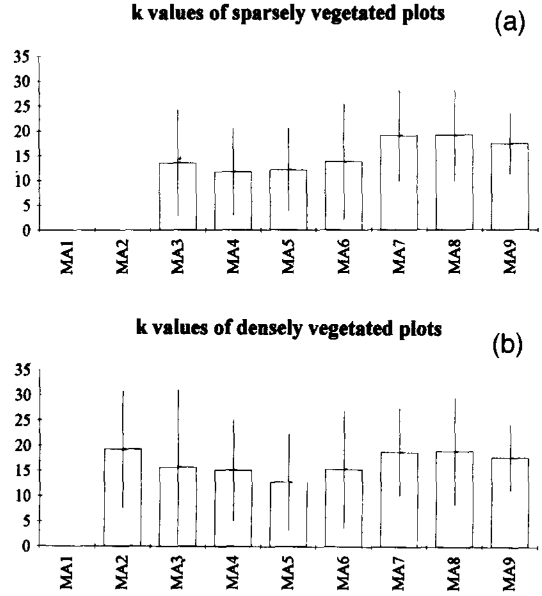

Fig. 12. Graphs showing values of k for sparsely vegetated plots (a), and densely vegetated plots (b).

3.2. Rainfall simulations

Results of rainfall-simulation tests conducted on dry and wet soil surfaces are summarized in Table 3. The runoff coefficients, m (the percent of rainfall resulting in runoff), generally are greatest for the mica-schist slope and least for the lower-fan and rambla-terrace surfaces. Values of the rain to runoff threshold, k, from the soil surfaces are an order of magnitude lower than those estimated from the runoff plots owing to the smaller size of the plots. There is, however, a coincidence in the spatial trend of the rain to runoff thresholds in both series along the catena, besides the mica-schist slope, which responds later in the runoff plots.

Runoff coefficients for bare patches and bushes generally are similar and, in some cases, are higher for the

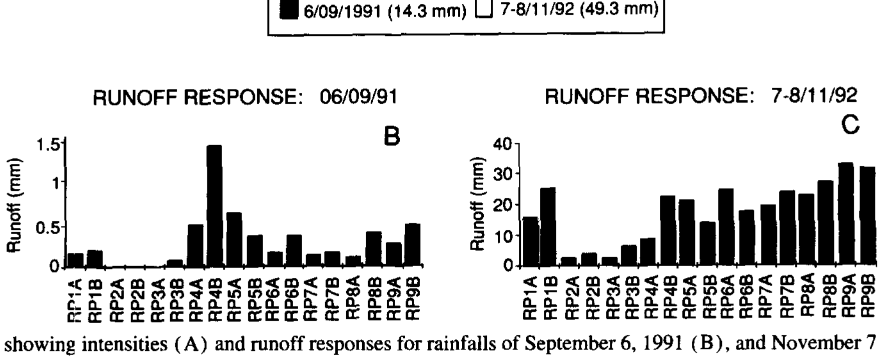

Fig. 13. Graphs showing intensities (A) and runoff responses for rainfalls of September 6, 1991 (B), and November 7 to 8, 1992 (C).

Table 3
Data obtained from rainfall simulations performed over bushes (ma) and bare soil (cl) in the nine measurement areas

MA		Dry soil					Wet soil				
		Infiltr. front (mm)	Rain to runoff (mm)	Runoff coef. (%)	Runoff coef. last 25%	Steady runoff (mm/h)	Infiltr. front (mm)	Rain to runoff (mm)	Runoff coef. (%)	Runoff coef. last 25%	Steady runoff (mm/h)
1	ma	4	1.31	0.85	0.98	45	15	2.16	0.67	0.83	37
	cl	120	8.21	0.28	0.53	–	160	3.38	0.44	0.56	25
2	ma	5	1.84	0.43	0.51	–	30	3.57	0.35	0.29	12
	cl	90	4.61	0.16	0.19	14	150	3.98	0.31	0.41	20
3	ma	40	2.99	0.36	0.39	–	130	3.43	0.46	0.62	30
	cl	35	1.98	0.47	0.58	22	150	2.43	0.49	0.61	30
4	ma	30	4.93	0.45	0.75	26	90	2.05	0.69	0.93	35
	cl	50	3.90	0.44	0.65	29	110	1.87	0.67	0.78	35
5	ma	50	2.10	0.31	0.44	–	90	1.75	1.00	1.00	42
	cl	30	1.96	0.65	0.77	39	130	1.67	0.76	0.86	40
6	ma	10	3.12	0.89	0.98	46	40	3.20	0.95	1.00	48
	cl	45	1.38	0.84	0.92	50	60	1.33	0.86	0.95	44
7	ma	10	1.36	0.72	0.88	37	40	1.16	0.70	0.76	39
	cl	30	2.71	0.62	0.73	37	100	1.59	0.69	0.78	33
8	ma	90	1.55	0.89	0.95	50	110	1.33	0.87	0.96	49
	cl	40	1.34	0.84	0.95	36	80	1.50	0.83	0.96	38
9	ma	45	1.87	0.63	0.83	30	130	1.49	0.66	0.78	35
	cl	10	1.16	0.78	0.90	40	40	0.81	0.74	0.82	42

MA = measurement area; ma = vegetated; cl = bare soil.

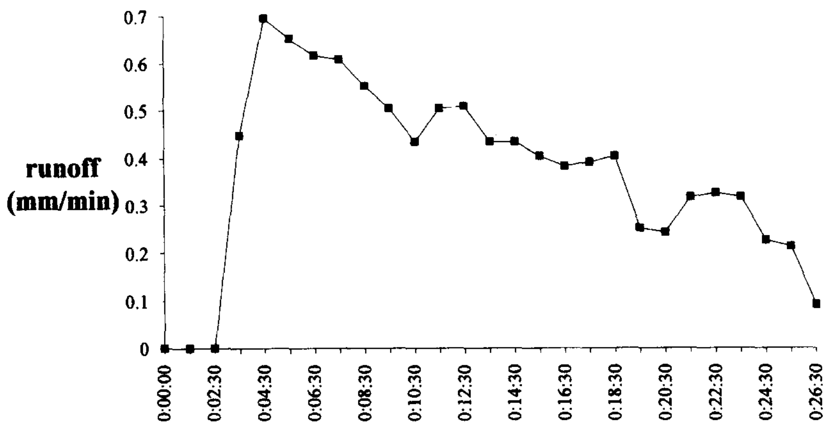

Fig. 14. Hydrograph of rainfall simulation over a bush; runoff reduction with time, following an early rise, may be due to initial hydrophobicity of the dry litter.

bush-covered areas. Nevertheless, in a few cases of bush areas, runoff hydrographs show a trend of which runoff decreases during the rainfall-simulation test (Fig. 14). The cause of the decreasing runoff is inferred to be hydrophobicity of the organic litter.

4. Discussion

The high runoff rates from the rambla terrace, both in runoff plots and rainfall simulations, indicate a limited infiltration capacity of the soil. Indeed, the percent of surface occupied by crusts and mosses on the terrace is much higher than on the alluvial fan (Fig. 15). More

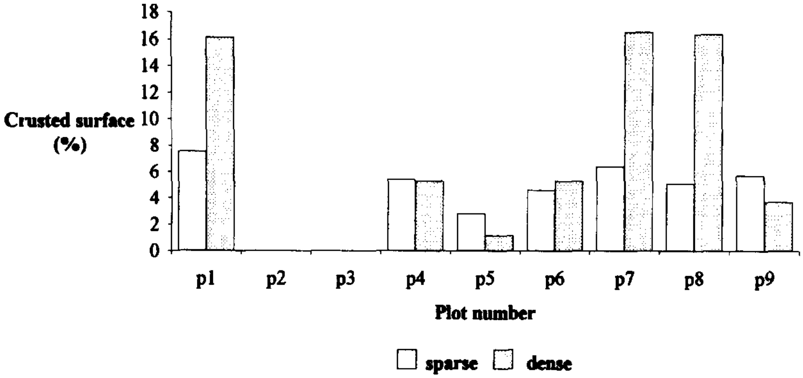

Fig. 15. Graph showing percentages of soil surface occupied by sparsely and densely crusted parts of runoff plots.

over, the occurrence of pavement stones on the rambla terrace, as indicated by particle sizes > 2 mm (MA 1, Table 1) is low, whereas the soil content of very fine sand with a platy morphology is high.

The tendency for greater runoff from the upper parts of the alluvial fan is interpreted to have resulted from the rearrangement of surface-horizon structure after the agricultural abandonment, and to variations in soil characteristics. For example, the thickness of the stone pavement and the proportion of coarse sand both are lower in upper parts of the alluvial fan than in the lower parts; increasing hydraulic conductivity with distance down the fan (Fig. 7) is consistent with these variations. The differences in runoff with position on the alluvial fan also may be caused by the ability of vegetation to increase macroporosity and, thus, infiltration capacity. Annual plants, as measured by biomass (Fig. 16), appear to increase soil permeability of the lower fan areas, thereby reducing runoff relative to less-vegetated areas higher on the fan.

The role of the bush cover on runoff dynamics is quite complex. Rainfall-simulation trials showed no clear difference between bare patches and patches with bushes, although hydraulic conductivity of soil is generally higher below bushes than in bare areas. It is presumed that the hydrophobic properties of organic matter (litter pool) may be an important variable of runoff, as stated in the above section. Nevertheless, in the runoff plots, the general trend for runoff is that sparse vegetated plots give higher values than dense vegetated plots.

The apparently contradictory results between the runoff plots and the rainfall simulations may be explained by the observation that distinctly different processes occur in the two situations. Indeed, infiltration of runoff in the runoff plots is associated with surface roughness and is an important and known phenomenon. Runoff infiltrates more readily in runoff plots with higher vegetation cover, and, consequently, with higher surface roughness. This effect is slightly modi-

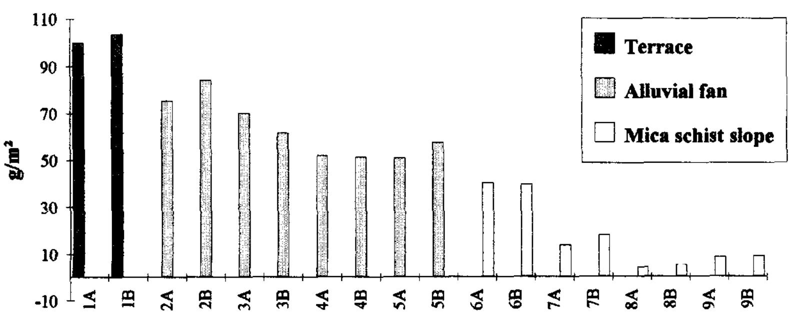

Fig. 16. Graph showing plant biomass, in grams per square meter, of annuals in runoff plots.

fied by the spatial distribution of bushes, as in the runoff plots RP 5A and 5B (Fig. 8). In these particular cases, the densely vegetated runoff plot, RP 5A, exhibits a particular pattern of shrubs lineated along the slope and favoring runoff concentration. In the sparsely vegetated plot, RP 5B, shrubs are unevenly distributed, following a zig-zag pattern that favors infiltration.

On the alluvial fan, the contrast between the two types of plots increases toward the top, except for the upper-fan runoff plots of MA 5. The spatial heterogeneity and roughness caused by *Retama sphaerocarpa* in the lower fan areas is much less than that of *Anthyllis cytisoides* higher on the fan, resulting in greater runoff variations on the lower fan.

The influence of antecedent soil moisture on runoff generation in this particular semi-arid environment was found to be low. An explanation is that quite low (1 to 2%) and consistent soil-moisture values prevailed before most rainfall events, a result of the high evapotranspiration that occurs during the long dry periods that commonly separate rainfall events. Only soil moisture was found to be related to runoff during moist winters, such as the event of February, 1992. Soil-moisture storage during rainfall events, however, is an important process in runoff generation.

5. Conclusions

Rocky slopes formed on mica schist show greater runoff than do alluvial-fan surfaces at the slope base. This tendency is particularly true in the case of large rainfalls. Local variations in runoff from mica-schist slopes show no trend along the slope, whereas, on the fan a trend of decreasing runoff is apparent from the apex to the base. The lowest portion of the sedimentary body, the rambla terrace, exhibits very large runoff responses to large rainfall events. These observations indicate that the main sources for storm runoff are on the rocky slopes and on terraces along the river.

After the abandonment of cultivation, a vertical rearrangement of the material occurred in the uppermost layer of the alluvial fan. Particle sizes smaller than medium sand were washed down and filled the previous pore volume. This phenomenon caused a vertical differentiation with coarser materials upon the finer ones. In this manner, a compacted subsurface layer was created that favors runoff within the upper layer of gravels.

This process of soil evolution has increased runoff from the upper part of the fan following typical or normal precipitation events. Thus, the upper fan is less supplied with water than is the lower sector of the fan, which is fed by lateral runoff. Differences in runoff between patches of vegetated and bare soil surfaces are least on the lower part of the fan (Fig. 9), whereas plant density, as indicated by biomass, generally increases downfan (Fig. 16) because of increases in soil moisture.

Below mica-schist slopes of this semi-arid area, where moisture conditions do not allow dense plant cover, the abandonment of agriculture may lead to an increase of runoff from the fan systems by vertical reorganization of grain sizes in the upper soil horizons (Fig. 9). On the other hand, the large runoff volumes generated from fields along river beds may increase flood discharges as traditional human structures for managing water from one field to another are destroyed.

A change in the factors controlling runoff occurs from the patch level (rain-simulation plot) to the small-slope sector (runoff plot). In the former, runoff generation in vegetated patches is determined by properties of the organic matter (hydrophobicity?), and this situation often yields more runoff than do the bare patches. At the runoff-plot scale, runoff is more dependent on other factors, including the spatial distribution of vegetated and bare patches, that may create spatial heterogeneity, preferential routes for overland flow, and more permeable mounds of sediment on the upslope side of the shrubs.

At the slope scale, factors that promote runoff in sparsely vegetated areas may override the effect of factors that increase runoff at the vegetated-patch level. These features provide an example of complex response of a heterogeneous dynamic system organized in a hierarchical structure.

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References

Benito, G., Gutiérrez, M. and Sancho, C., 1992. Erosion rates in badland areas of the central Ebro basin (NE Spain). Catena, 19: 269–286.

Calvo, A., Gisbert, J.M., Palau, E. and Romero, M., 1988. Un simulador de lluvia portátil de fácil construcción. In: Sala and Gallart (Editors), Métodos y técnicas para la medición en el campo de procesos geomorfológicos, Monografía no. 1, pp. 6–15, Sociedad Española de Geomorfología, Zaragoza.

Gilman, A. and Thornes, J.B., 1985. Land-use and prehistory in Southeast Spain. The London Research Series in Geography, 8. George Allen and Unwin, London, 217 p.

Greenland, D.J., 1977. Soil damage by intensive arable cultivation: temporary or permanent? Philos. Trans. R. Soc. Lond., 281: 193–208.

Lazaro, R. and Rey, J.M., 1991. Sobre el clima de la provincia de Almeria (SE iberico): Primer ensayo de cartografía automatica de medias anuales de temperatura y precipitacion. Suelo y planta, 1(1): 61–68.

McIntyre, D.S., 1958. Permeability measurements of soil crusts formed by raindrop impacts. Soil Sci., 85: 185–189.

Pilgrim, D.H., Chapman, T.G. and Doran, D.G., 1988. Problems of rainfall–runoff modelling in arid and semi-arid regions. Hydr. Sci. J., 33(4): 379–400.

Romero-Díaz, M.A., López-Bermúdez, F., Thornes, J.B., Francis, C.F. and Fisher, G.C., 1988. Variability of overland flow erosion rates in a semi-arid Mediterranean environment under matorral cover (Murcia, Spain). Catena Suppl., 13: 1–11.

Scoging, H.M., 1982. Spatial variations in infiltration, runoff and erosion on hillslopes in semi-arid Spain. In: Bryan and A. Yair (Editors), Badland Geomorphology and Piping. Geo Books, Norwich, pp. 89–112.

Yair, A., Goldberg, P. and Brimer, B., 1982. Long-term denudation rates in the Zin-Havarim badlands, northern Negev, Israel. In: Bryan and A. Yair (Editors), Badland Geomorphology and Piping, Geo Books, Norwich, pp. 279–291.