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Influence of soil surface features and vegetation on runoff and erosion in the Western Sierra Madre (Durango, Northwest Mexico)

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Abstract

In mountainous areas, runoff and soil erosion are closely linked to soil surface features, particularly stoniness. Depending on the size of rock fragments (gravel, pebbles, stones and/or blocks) and especially the way they are integrated into the soil matrix, they may facilitate or hinder infiltration and promote soil losses. The present study examines the role of different soil surface features and their influence on runoff formation and on soil erosion in an area seriously affected by overgrazing.

Based on measurements made on hillslopes for 2 years at the plot scale, the results show that grass cover, pebbles and sand content increase runoff and erosion. Inversely, slope value, tree cover percentage, structural stability and organic matter content are negatively correlated with runoff and soil losses.

It is shown that the correlations can be explained by the major role played by the surface features on hydrologic behaviour of the hillslopes. Two main surface features were identified and hydraulically characterised, namely: (i) crusted surfaces with embedded gravel widespread on gentle slopes which induce high runoff and erosion rates; and (ii) stony surfaces, where free

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pebbles and blocks protect the top soil against raindrops and overland flow kinetic energy and lead to reduce runoff and soil losses.

Keywords: Runoff; Soil losses; Western Sierra Madre; Overgrazing; Crusted soils; Hydraulic properties

1. Introduction

In mountain zones, overland flows are influenced by surface features, slope value and vegetation. In particular, the presence of gravel or stones affects runoff and erosion. According to Yair and Lavee (1974), on scree slopes in the Sinai desert, the presence of large boulders increases runoff while small stones decrease it. Their effects vary with the position of the gravel which can be either free or embedded into the soil surface as observed by Poesen et al. (1990). Casenave and Valentin (1989), Valentin and Casenave (1992) and Valentin (1994) observed the same difference in West Africa, where infiltration was found to be significantly increased by the presence of "gravel mulch". In the same region, Chevallier et al. (1990) have put an emphasis on the role played by the roughness of topsoil. In South Arizona, Abrahams and Parsons (1991) showed a negative correlation between infiltration rate and stone cover in the intershrub, and a positive one under the shrubs. Poesen and Lavee (1994) and Poesen et al. (1994), in their reviews, observed that the protective effect of gravel is scale dependent. Under Mediterranean climate, Ingelmo et al. (1994) concluded on the "increase of surface runoff with an increase of volumetric rock fragment contents of the soil". Moreover, this protective effect is related to the position of the gravel which can be either embedded into the soil surface or simply placed on it. Descroix (1994a,b) showed that in the southern Alps, a 4-m^2 plot covered with 30% free stones experienced approximately 30% less denudation than a control plot without stones. Derouiche et al. (1997) made a similar observation in Spain. The authors pointed out that the stony cover resulted from selective sheet erosion and that this process was self-limiting since it produced an increasingly higher proportion of protective surface stones. In a study carried out in Portugal, Figueiredo (1996) showed that surface stoniness reduced both runoff and erosion and improved infiltration. In a study conducted in a climatic zone similar to that of northern Mexico (southeast Arizona), Simanton et al. (1994) used the Revised Universal Soil Loss Equation (RUSLE) approach to show that erosion decreased with increasing pavement. The role of vegetation and slope is also a controversial subject. Most works refer to cultivated areas rather than to natural vegetation. Masson (1971), for Mediterranean mountains, and Roose (1977, 1996) for tropical areas, showed that erosion was an increasing function of slope value. In the case of steep slope, landforms must be taken into account, and an increase in slope is often associated with an increase in surface stoniness. For a toposequence in the southern Chihuahua desert (Mexico), Viramontes (1993) showed that erosion and runoff were negatively correlated with slope and stoniness (themselves strongly correlated), and with vegetation. In the western Sierra Madre (Mexico), Descroix and Poulenard (1995) observed that erosion increased with slope only below a certain threshold (27%). Summarising several studies performed on the Réal Collobrier basin (southeast of France), Grésillon (1994) showed that vegetation plays a primary role in producing runoff (bare soils producing more rapid and more abundant runoff) but that increasing slopes did not lead to higher runoff coefficients. In southern Turkey, Böhm and Gerold (1995) confirmed the essential role of vegetation (slope and soil texture having little effect) on reducing runoff and erosion. Similarly, Thébé (1987) found no influence of vegetation cover on runoff for densities of 35–40% in the Sahelian Northern Cameroon. Snelder and Bryan (1995), in Kenya, determined a critical threshold of 55% vegetation cover below which erosion increased very rapidly. In southern China, Woo et al. (1997) have shown the protective role of vegetation, while Solé-Benet et al. (1997) in southeast Spain also found a positive correlation between slope and runoff.

These variables (stoniness, slope and vegetation) govern the soil surface features. It is noticeable that they are interrelated. Depending on the hydrological context of the site, a given class of slope can, for example, be associated to a given stoniness or to a vegetation cover type.

Changes of land use can modify the water balance in certain mountain areas with possible negative impacts on the lowlands which support higher density of population. Forestry exploitation and overgrazing in particular are widespread in numerous mountain sectors.

The aim of the present study is twofold:

(i) to provide a better understanding of the role played by the soil surface features on the formation of runoff and erosion in the western Sierra Madre (northwest Mexico);

(ii) to show how changes in the characteristics of this mountain area can influence the hydrological processes.

2. Study area

The western Sierra Madre extends 2000 km from north to south, parallel to the North American Pacific coast. It acts as a "water tank" for numerous arid or semi-arid regions situated along the coast or in the high northern Mexican plateau. This study concerns the upper basin of the Rio Nazas in the north of Durango State. It forms the upstream part of the Hydrological Region no. 36, an endoreic catchment of 92 000 km^2 situated in the high plateau of the central northern part of the country (Fig. 1).

The Hydrological Region no. 36 encompasses three geo-climatic sub-regions, each playing a different role in terms of water balance and water consumption: (a) the main upstream sub-humid basin which covers 20% of the area and supplies 87% of the surface water bodies; (b) the intermediate semi-arid zone which meets the additional requirements (13% of the water supply for 40% of the area) and where water is made available on a local basis by different engineering devices (small reservoirs and water spreading structures); and (c) the downstream arid zone which mainly consumes water by evapotranspiration (no input for 40% of the area).

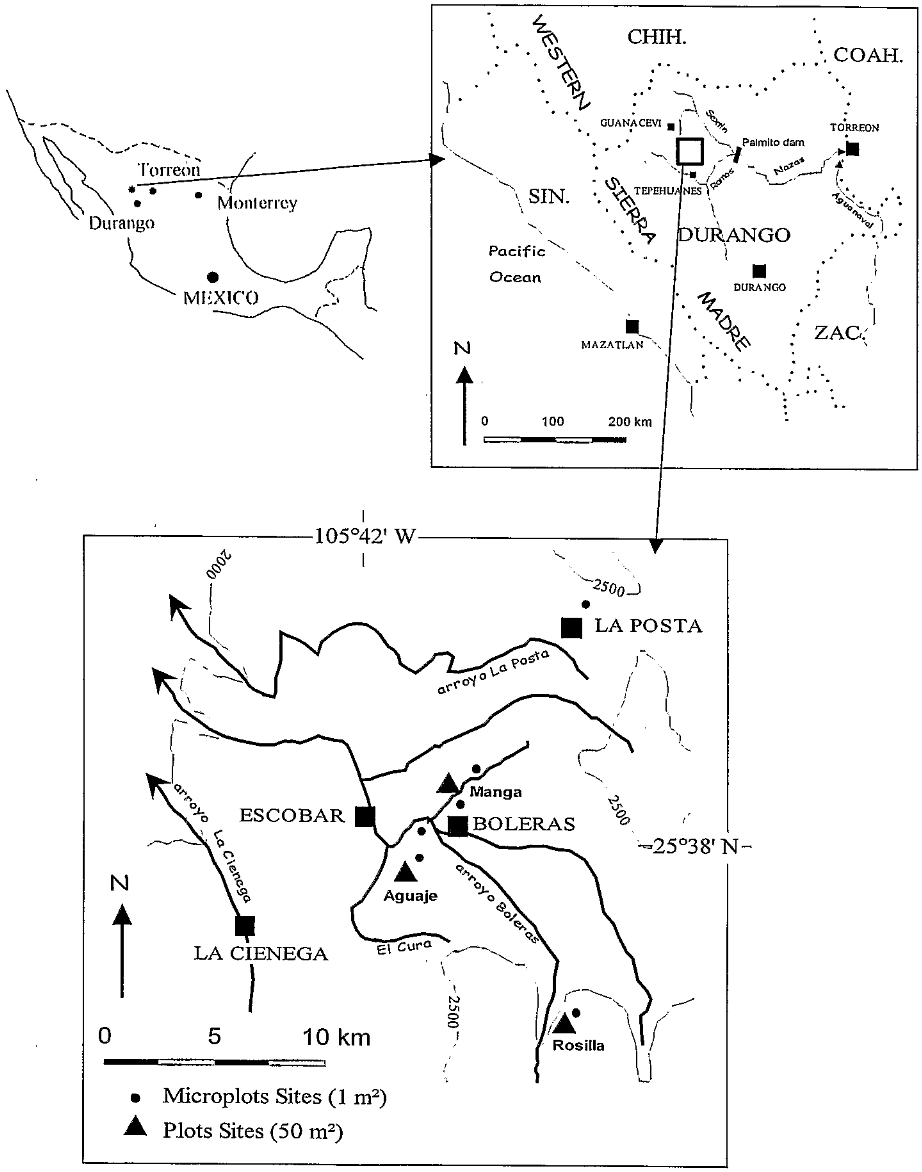

Fig. 1. Location of the Nazas basin and measuring sites.

The western Sierra Madre is a volcanic chain of medium altitude (max 3300 m). It is formed essentially with acid rocks (rhyolites, ignimbrites) dating from the end of the Tertiary and conglomerates resulting from their erosion, generally trapped in grabens.

The climate is subtropical characterised by a 4-month wet season and a long dry season from October to June with cold winters due to both the altitude and latitude (25°N) effects. The annual rainfall varies from 450 mm at 1700 m to 850 mm at 2800 m of altitude. The annual evaporation (pan class A) is 1900 mm at 2200 m and the mean temperature is 14°C with a minimum of 4°C in January and a maximum of 25°C in July.

The vegetation is adapted to the 8-month dry season. Below 2000 m, typical formations of semi-arid zones are encountered (pasture and *acacia* scrub, *prosopis*, with *cactus*). Between 2000 and 2400 m level, pastures (with a predominance of *Bouteloua hirsuta*) and oak *forests* (*Quercus grisea* and *Q. viminea*) dominate. Finally, pine forests (*Pinus cembroides* and *P. duranguensis*) are the predominant vegetation above 2400 m.

Soils are generally phaeozems, 20–60 cm deep (locally 100 cm). They are red and include a surface horizon rich in organic matter (2–6%) with accumulations of clay below. This type of soil covers approximately 85% of the area, the remaining being composed essentially of lithosols, with occasional patches of vertisols. The soil texture is sandy clay with a relatively large amount of organic matter.

In the pasture zones located below 2400 m, Viramontes (1993) observed the results of serious recent surface degradation along numerous hillslopes: on slopes steeper than 7%, the fine soil particles have mostly disappeared and there was a significantly higher proportion of gravel and stones than on gentler slopes at the top and bottom. This was attributed to overgrazing dating back some 50 years, as also attested by the presence of "terracettes" orthogonal to the slope (Poulenard et al., 1996). Trampling forms a dense network of pathways on hillslopes. This kind of "terracettes" have been also observed in the Alps and in the Andes (Serrate, 1978).

The runoff coefficient for the entire Nazas catchment basin at the El Palmito dam is 9.5% (an average value for the 1946–1996 period). Sediment accumulation at the bottom of the reservoir was measured using bathymetric techniques and applied to the entire basin. It corresponds to a soil loss of 5400 kg $ha^{-1} yr^{-1}$ from 1946 to 1971 and 5000 kg $ha^{-1} yr^{-1}$ from 1971 to 1991. These values are much lower than those reported for example in Algeria (Benchetrit, 1972), where sedimentation indicates soil losses ranging from 50 000 to 100 000 kg $ha^{-1} yr^{-1}$

Signs of recent changes can be observed in the landscapes of the high-altitude pastures and forests of the western Sierra Madre in the low density populated regions (1 to 3 inhabitants km^{-2}).

(a) The forest zones are characterised by an increasing number of clearings resulting from intensive lumbering and failure to replant trees.

(b) In certain cultivated depressions, wide and long gullies (1–5 m deep, 100–500 m long) are observed on the most gentle slopes. Some of these rills are flat at the bottom and covered with vegetation indicating that they are probably inherited and no longer functional. All the rills are visible on aerial photos taken in 1974.

(c) Much more generally, large areas of soil cover, especially in the dry part of the Sierra Madre, are degraded as the result of overgrazing. Viramontes (1995) has shown how sheet erosion resulting from the deterioration (and often the disappearance) of the grass cover has led to the appearance of many large pebbles (> 20 mm) and blocks (> 200 mm) at the soil surface. In addition, he also observed that grazing lands were increasingly invaded by pines which are unpalatable species. The tree stratum was primitively populated by oaks but their re-growth is hindered by the presence of livestock.

3. Materials and methods

Devices were installed to measure and monitor runoff and erosion in the catchment areas and plots in a sector considered as representative of the upper basin in terms of elevation, climate, landforms and soils. The selected sector is located in the southern part of the basin of the Rio Sextín, the left branch of the upper Nazas (Fig. 1).

Three measurement sites were selected (see Fig. 1): one in pine forested land (Rosilla) and two in areas of pasture and oaks (Manga and Aguaje). They were equipped with 32 plots of 1 m^2, three plots of 10 m^2 and 13 plots of 50 m^2. All plots are plane. Each site has been equipped with a mechanical or electronic rain gauge. Their main characteristics are given in Table 1.

Runoff, soil losses (total per event) and rainfall were measured after each rainy event. More than 100 events were considered including 59–83 producing runoff, depending on the site, for a minimum of 2 years of measurements: 1995 and 1996 in Rosilla site, 1996 and 1997 in two others. Annual rainfall values for the 3 years at the three sites as well as at the nearest climatologic station of Cienega de Escobar are also reported in Table 1. As it can be seen, the years 1995 and 1997 were very dry (50% and 45% below the mean, respectively) and the year 1996 was wet (19% above the mean value calculated at the Cienega de Escobar station).

To obtain a clearer idea of the factors affecting runoff and soil losses, explaining variables were divided into those related to the site which were assumed to be stable over time, and event variables related to precipitation and soil water content.

Measured runoff and soil losses were compared event by event with the rainfall characteristics, such as effective rainfall, maximum intensity and antecedent precipitation index (API). An event matrix was calculated to determine the main explaining rainfall variables of runoff and erosion. The cumulative annual runoff and soil losses were also incorporated as dependent variables into another matrix including individual plots with their specific characteristics.

Table 1
Main features of the three experimental sites

Site	Altitude (m)	Lithology	Vegetation type	% Sand	% Silt	% Clay	% OM	Annual rainfall (mm)		
								1995	1996	1997
Rosilla	2500	ignimbrites	forest	63	19	18	4.08	360	612	339
Aguaje	2200	ignimbrites	pasture	52	23	25	6.3	324	690	298
Manga	2150	conglomerates + tuffs	pasture	70	16	14	3.37	284	602	322
Cienega de Escobar	2100							490	694	460

Cienega de Escobar is the nearest climatologic station, characterised by a mean annual rainfall value of 584 mm (with a standard deviation of 141 mm) calculated for the 1965–1998 period. OM is the organic matter content.

3.1. Precipitation parameters

The following characteristics for each plot or catchment were considered:

(a) PU (from "Pluie Utile", i.e. effective rainfall) which is defined as the rainfall intensity that can actually produce runoff. It is the depth of rain precipitated at intensities higher than a threshold value (Peugeot et al., 1997). Here were considered values ranging from 2 to 20 mm h^{-1} with increments of 2 mm h^{-1} (PU2, PU4,... PU20).

(b) Maximum intensity values according to different time steps namely 1, 5, 10, 15, 20, 30, 60, 120 and 240 min ($I1$, $I5$,... $I240$).

(c) API defined by Kohler and Linsley (1951) as:

$$\mathrm{API}_n = (\mathrm{API}_{n-1} + R_{n-1})\exp - \alpha t \tag{1}$$

where n is the serial number of the rain events, α is a soil moisture decrease parameter and t the time (in day or fraction of day) elapsed between the end of the previous rain event R_{n-1} and the beginning of the current event n. In the following, only rainfall events above 1 mm were considered. API_n (in mm) represents the theoretical soil water content and α (day^{-1}) is the inverse of the characteristic time of soil moisture depletion.

3.2. Soil surface characteristics

The following variables were considered:

- Textural composition (sand, silt and clay) of topsoil (sampling depth from 0 to 20 cm), as well as the amount of gravel (smaller than 20 mm: GEL), pebbles and blocks (larger than 20 mm: PBK) expressed per unit area.
- Dry bulk density (g cm^{-3}) measured on clods of earth and with a density cylinder as well.
- Organic matter content (%) determined by the Walkey Black's method (Plenecassagne et al., 1997).
- Slope (in %) estimated from a levelling survey.
- Percentage of tree cover, grass cover and bare soil.
- Presence or absence of livestock in the current year and of overgrazing, both obtained by visual inspection.

Occasionally, the following parameters have been considered in addition:

(a) Structural instability based on the percentage of water-stable aggregates ranging between 0.2 and 2 mm with and without pretreatment, and the tendency of the parent material to disperse. It is defined by the following index (Hénin, 1977):

$$\mathrm{IS} = \Sigma\mathrm{AG}/3(C + S - (\mathrm{CS}\,0.9)) \tag{2}$$

where ΣAG is the sum of aggregates expressed as a percentage; CS, C and S are the percentage of coarse sand, clay and silt, respectively. The higher the value of IS, the lower the stability is.

(b) The presence of vesicular porosity defined by visual examination if vesicular pores exceeded 30%.

(c) For pasture zones: lithology.

(d) For forest zones: presence and thickness of litter and presence of trees on the site.

All these characteristics were determined for each plot on the basis of three samples taken at the beginning, in the middle and at the end of the rainy season.

In addition, soil surface hydraulic conductivity was determined for each plot by two methods:

(i) the tension disc infiltrometer (Vandervaere et al., 1997) for values close to saturation;
(ii) the Beerkan method (Haverkamp et al., 1997) for saturated conditions.

4. Results and interpretation

In the following, the results dealing with the influence of both site characteristics and rainfall parameters on runoff and erosion are presented and discussed.

To offset the interannual variability of rainfall (see Table 1), measured runoff was, when necessary, expressed in terms of runoff coefficient (Cr) defined as the ratio between runoff and rainfall amounts both in millimeters of water.

As shown by Fig. 2, high linear correlations were found between erosion rates and runoff coefficients for the three sites. Furthermore, very significant differences can be observed between forest (Rosilla) and pasture (Aguaje and Manga) zones where for the latter one soil losses were about 20 times more important.

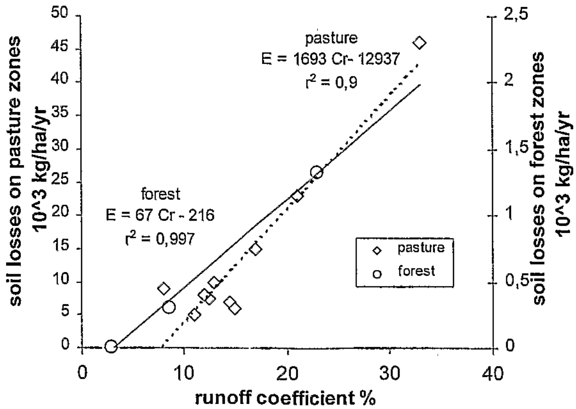

Fig. 2. Relationship between measured soil losses (E) and calculated runoff coefficient (Cr) on plots of 50 m^2 located on pasture (p) and forest (f) zones. Straight lines correspond to fitted linear regression. r^2 = Coefficient of determination.

4.1. Influence of site variables on runoff and erosion

The main results are summarised in Tables 2 and 3 for forest and pasture, respectively. They suggest the following comments:

(i) In forested zones (Table 2), runoff and erosion are drastically reduced by the presence of trees, whatever the plot sizes are. To a lesser extent, the leaf litter also acts as protection of the soil. Oak trees were found to better protect the soil than pines, because their fallen leaves provide a thicker litter inducing more efficient interception of raindrops and higher dissipation of kinetic energy.

(ii) In pasture zones (Table 3), again the protective role of trees can be observed. However, the lowest values of runoff and erosion were obtained on the fenced plots. This is not due to the presence of grass stalks but rather to the fact that the soil is not subject to trampling by livestock which modifies its structure by increasing its bulk density and by reducing its apparent porosity as well as the infiltrability.

(iii) In both forest and pasture zones, slope was not a significant controlling factor of runoff and erosion. Runoff and soil losses values were smaller on 27% slope plots than on 12% slope ones in pasture; and they are smaller on 57% slope plots than on 33% slope ones in forest. This confirms that runoff and soil losses increase with slope value only below a certain threshold, as observed by Descroix and Poulenard (1995). **Above this value, there is a negative correlation between slope on one hand and erosion and runoff on the other hand.**

In addition, it should be mentioned that factor analysis revealed that trampling by livestock explained 88% of the variance for runoff and 55% for soil losses. This method was used because the variable could not be expressed as a number but simply in terms of "presence" or "absence". Vesicular porosity was found to be poorly positively correlated with runoff and erosion ($r^2 = 0.35$ and 0.20, respectively).

Table 4 presents the correlation coefficients site by site as well as for the case where the three sites are pooled together. The following comments can be made:

Table 2
Influence of different environmental factors on the annual runoff and soil losses in forest zones (average over 1995 and 1996)

Explaining variables	Runoff coefficient	Soil loss (g m^{-2})
Presence or absence of trees (plots of 50 m^2)		
No tree	0.23	133
No tree but with litter	0.085	30
With tree	0.028	1.1
Type of trees (plots of 1 m^2)		
Pines	0.09	74
Oaks	0.03	45
Slope (plots of 1 m^2)		
12%	0.06	30
33%	0.09	110
57%	0.05	53

Table 3
Influence of different environmental factors on the annual runoff and soil losses in pasture zones (average over 1996 and 1997) on plots of 50 m^2

Explaining variables	Runoff coefficient	Soil loss ($g\ m^{-2}$)	Dry bulk density ($g\ cm^{-3}$)[a]	Time to infiltrate 250 cm^3 of water (s)[a]
Presence or absence of trees				
No tree	0.34	45		
No tree but fenced	0.19	12		
With tree	0.19	26		
Slope				
12%	0.31	42		
27%	0.21	29		
Vesicular porosity				
With	0.35	70		
Without	0.07	7		
Livestock trampling				
With	0.43	90	1.38 ± 0.08	1800 ± 165
Without	0.08	7	1.31 ± 0.09	750 ± 367

[a]Based on seven replicates.

(a) Runoff coefficient (Cr) and erosion rate (E) are negatively correlated with slope (SLO) for the pooled data (considering the 48 equipped plots); however, that is not so obvious for each site (and it has been showed previously that there is a threshold effect). That is not common, and it is due to the role played by surface features: steeper hillslopes have less grass and higher stone cover (see below).

Table 4
Coefficients of correlation between runoff coefficient (Cr), erosion rate (E) and different site variables, by measurement site, and in pooled data; all the 1, 10 and 50 m^2 plots are taken into account

Site	Variable	SLO	GSS	SAND	SILT	CLAY	IS	OM	TREE	GEL	PBK
Rosilla	Cr	−0.13		0.1	−0.45	0.23	0.76	−0.55		0.87	
	E	0.08		0.35	−0.45	−0.08	0.76	−0.48		0.97	
Aguaje	Cr	−0.41	0.63	0.85	−0.54	−0.42	0.25	−0.78	−0.83	0.26	−0.59
	E	−0.53	0.77	0.79	−0.6	−0.25	0.26	−0.73	−0.72	0.52	−0.65
Manga	Cr	−0.03	0.76	0.42	−0.68	−0.68	0.6	−0.55	−0.45	0.61	0.1
	E	0.13	0.53	0.42	−0.69	−0.92	0.49	−0.48	−0.64	0.35	0.26
Pooled data	Cr	−0.45	0.76	0.51	−0.38	−0.29	0.26	−0.67	−0.77	0.5	0.02
	E	−0.45	0.76	0.34	−0.31	−0.12	0.07	−0.31	−0.52	0.31	−0.13

Cr = Runoff coefficient; E = soil losses in $g\ m^{-2}\ yr^{-1}$; SLO = slope in %; GSS = % of grass cover; CLAY, SILT, SAND = % of clay, silt and sand respectively; IS = soil structural instability index; OM = % of organic matter; TREE = % of tree cover; GEL = % of gravel smaller than 20 mm; PBK = % of pebbles and blocks bigger than 20 mm.

(b) Cr and E are always highly positively correlated with grass cover percentage (GSS). This result is thought to be original and illustrates the role played by the soil surface features. As a matter of fact the presence of a gravely crust lying between the tufts at spots where grass is the most abundant impedes water to infiltrate and consequently enhances runoff and erosion.

(c) At all the sites Cr and E are correlated positively with percentage of sand (SAND), and negatively with SILT and CLAY. A high soil sand content corresponds with soils which have had a previous erosion stage.

(d) More in accordance with conventional findings, E and Cr rates decrease in parts where soil structural stability and organic matter content (OM) are higher (IS being structural instability, that fit with lower values of IS).

(e) Whatever the lithology, erosion and runoff are negatively correlated with the percentage of tree cover (TREE). This can be explained by the interception of the rainfall by the foliage and the dissipation of kinetic energy.

(f) The proportion of both GEL and PBK plays a different role according to lithology:

(i) on ignimbrites (Aguaje site), Cr and E are better correlated (negatively) with the proportion of big rock fragments (PBK) than with GEL;
(ii) on conglomerates (Manga site) which are in fact a stacking of conglomerates and tuffs, there is a better positive correlation of Cr and E with GEL than with PBK;
(iii) In forest zones (Rosilla site), Cr and E are also highly positively correlated with GEL.

The results of the two last cases can be explained by the presence of a gravely crust easily observable by eye, gravel being embedded into the soil.

These results were confirmed by an Empirical Orthogonal Functions (EOF) analysis (Descroix and Nouvelot, 1997).

4.2. *Influence of rainfall variables on runoff and erosion*

4.2.1. *In forest zones*

After a series of trial and error tests, the main explaining rainfall parameter of erosion (E) and runoff (Cr) was found to be the maximum intensity in 20 min ($I20$). As it can be seen in Table 5, it explains from 35% to 70% of the variance of E and from 30% to

Table 5
Coefficients of linear regression between either erosion (E) or runoff coefficient (Cr) and maximum rain intensity in 20 min ($I20$) for three plots of 50 m^2 located in forest environment. r^2 = Coefficient of determination

Plot number	$E = a(I20) + b$			$Cr = a(I20) + b$		
	a	b	r^2	a	b	r^2
30 (no tree, no litter)	0.51	−1.68	0.59	0.39	−0.61	0.53
31 (no tree but with litter)	0.18	−1.01	0.70	0.23	−1.00	0.61
32 (completely wooded)	0.005	−0.02	0.35	0.078	−0.41	0.30

61% of Cr, depending on the plot cover. It should be mentioned that small values of r^2 for plot 32 (completely covered with pine trees and a thick layer of litter) may be explained by the small number of events producing runoff (10 in 2 years as compared with 40 events for plots 30 and 31).

It can also be pointed out that runoff and erosion values decreased between plots 30 (deforested for many years and without anymore litter), 31 (recently deforested with still presence of litter), and 32 (wooded with litter). These results have been confirmed by other data collected on the 18 plots of 1 m^2 located in the forest zone.

4.2.2. *In pasture zones*

The data analysis showed that a clear distinction should be made between plots located either on ignimbrites or on conglomerates and tuffs.

On ignimbrites, effective rainfall amount with an intensity higher than 8 mm h^{-1} (RU8) has been found to explain, only for rainfall above 5 mm, from 66% to 73% of the variance of soil losses. Adding for each plot the maximum 30-min intensity ($I30$) as a second variable in the multiple regression equation led to improve significantly the percentage of the explained variance (from 84% to 93%).

For runoff, the amount of rainfall (R) was always found to be the main explaining variable with coefficients of determination varying between 0.68 and 0.82. With the introduction of the API with $\alpha = 0.1$ day^{-1}, in Eq. (1) (Descroix and Nouvelot, 1997), as a second possible explaining variable, in such a way that the percentage of the explained variance of runoff was slightly increased to reach values ranging from 72% to 88%. As an example, Fig. 3 presents, for plot 22 which produced the highest yield, the comparison between observed and calculated values of runoff depths, the latter ones being obtained by considering either R alone, or both R and API values.

On conglomerates and tuffs, the correlations were not as high as those for ignimbrites. Rainfall with intensities above 18 mm h^{-1} (PU18) was found to be the main

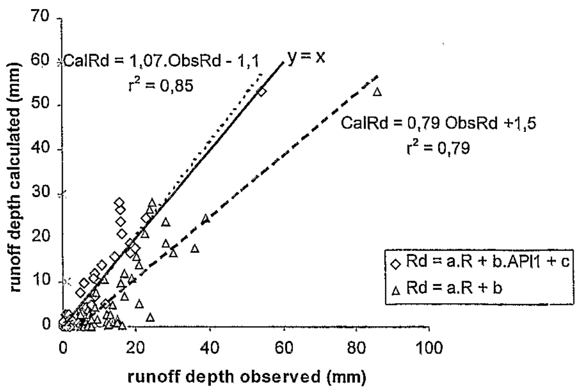

Fig. 3. Comparison between calculated (CalRd) and observed (ObsRd) runoff depth, for plot 22 (1996 and 1997), using the regression $\mathrm{Lr} = aR + b\mathrm{API1} + c$ and a simple regression $\mathrm{Lr} = aR + b$. R = Rainfall amount (mm). r^2 = Coefficient of determination.

Table 6
Impact of wet or dry year on cumulative values of erosion and runoff (plots of 50 m^2)

Pasture (10 plots)	1996	1997	1996/1997
R during the rainy season (mm)	480	224	2.15
Cr	0.25	0.06	4.2
E (kg ha^{-1})	26000	900	29
Forest (3 plots)	1995	1996	1996/1995
R during the rainy season (mm)	300	570	1.9
Cr	0.06	0.18	3
E (kg ha^{-1})	450	650	1.44

variable controlling both soil losses (26–68% of the explained variance depending on the plots) and runoff (57–69%).

Because conglomerates and tuffs are known for having higher values of hydraulic conductivity than igneous bedrock's soils, higher rainfall intensities are required to reduce both runoff and erosion. That explain why different values of effective rainfall (PU18 and PU8, respectively) have been found to be the main explaining variables.

In addition, we have found marked differences between plots without trees located either on gentle slopes with gravel, or on steep and stony slopes.

So, at the plot scale, it appears that the hydrologic behaviour of soils differs according to lithology. At the catchment or basin scale, this was also verified though the rain intensity thresholds were different. As an example, PU2 for ignimbrites and PU6 for conglomerates were the main explaining variables of the runoff coefficient with about 80% of the explained variance (Descroix and Nouvelot, 1997).

It should be pointed out that vegetation types influence the hydrological response of hillslopes. Table 6 gives for pasture and forest zones the values of the runoff coefficients and erosion losses measured during the rainy seasons of the years 1995, 1996 and 1997. It can be seen that the impact of a dry year is more important on pastured areas (which are strongly deteriorated by overgrazing) than on forested areas.

5. Discussion: the importance of soil surface features

Some of the results obtained in the study have been found to be in agreement with classical expected observations on soil surface hydrological behaviour:

- The protective role of trees and organic matter. It was observed that protection by small trees was much more efficient than that afforded by annual plants and grasses.
- Antecedent erosion stages enhanced surface stoniness on steeper slopes, leading to reduce runoff and erosion processes because of the dissipation of kinetic energy.
- The importance of the position of gravel: Cr and E can be enhanced or reduced depending on the size and the position of gravel, respectively embedded or free on the soil matrix.

On the other hand, other results appear to be different from conventional findings.

- The higher Cr and E values are observed on gentler slopes.
- The importance of soil structure and texture themselves linked: here a higher silt content of the soil results in a good structural stability and both leading to reduced erosion and runoff.
- Small values of runoff and soil losses correspond with high values of grass cover and/or soil sand content.

These controversial results can be explained by soil surface features. In the western Sierra Madre, three main types of surface features have been clearly identified.

The first one was found both in parts of the forest zones not protected by trees or litter and on pastured land (below 2400 m). It is characterised by a crusted soil, with an abundance of embedded gravel (< 20 mm). The crusts were between 1 and 5 mm thick. Under dry conditions, they were easily detachable from the soil because of their strong inner cohesion. They are referred to as "GC" (as "Gravel Crust") for convenience in Figs. 4–6. Splash disturbs the fine particles which then seal the pores of the soil and fix the gravel into the matrix. This type of GC was found on the gentler slopes ($< 20\%$), where the highest runoff coefficients and soil losses were recorded. In pasture environment, the percentage of grass cover was positively correlated with erosion and runoff. This was due to the GC which develop in the large spaces between the grass tufts, caused by overgrazing and the short rainy season. These zones are highly exposed to splash, poor in clay and organic matter. It seems similar to the pavement crust of Valentin and Casenave, 1992, also called GC. As it has also been observed by Poesen et al. (1990), the embedding of gravel into a crust explains the high values of Cr.

The second surface feature was mainly found in pasture but also locally in forest environments. It is characterised by a high percentage of stones and blocks (> 20 mm) free (nonembedded) into the matrix. This type of surface feature called FPB in Figs. 4–6 is encountered only on slopes steeper than 20%. Above values higher than 25%,

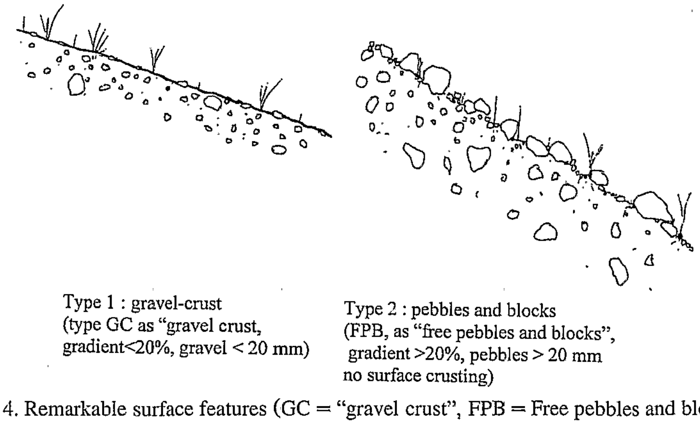

Fig. 4. Remarkable surface features (GC = "gravel crust", FPB = Free pebbles and blocks).

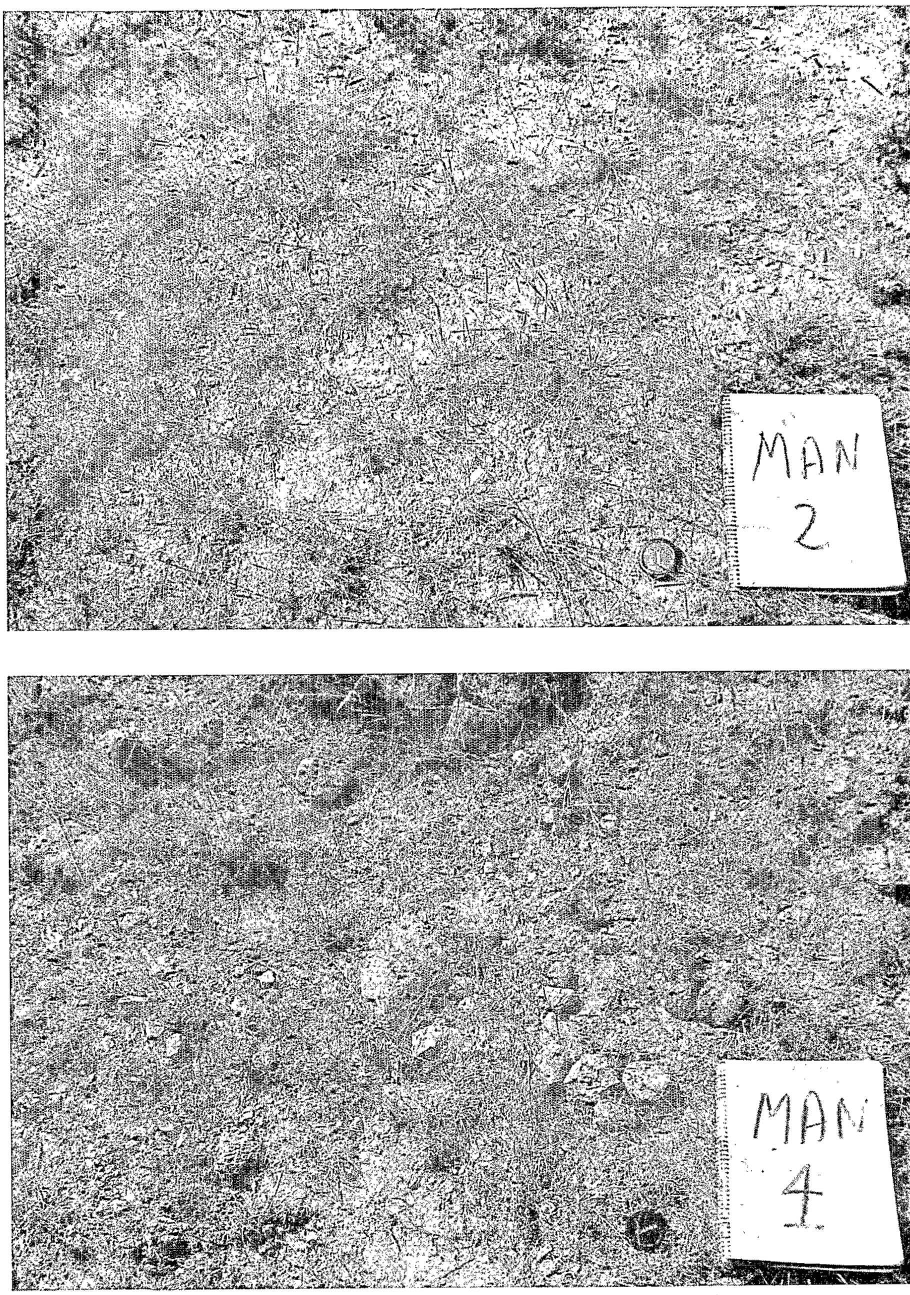

Fig. 5. The two dominant types of surface feature: GC (top); FPB (bottom).

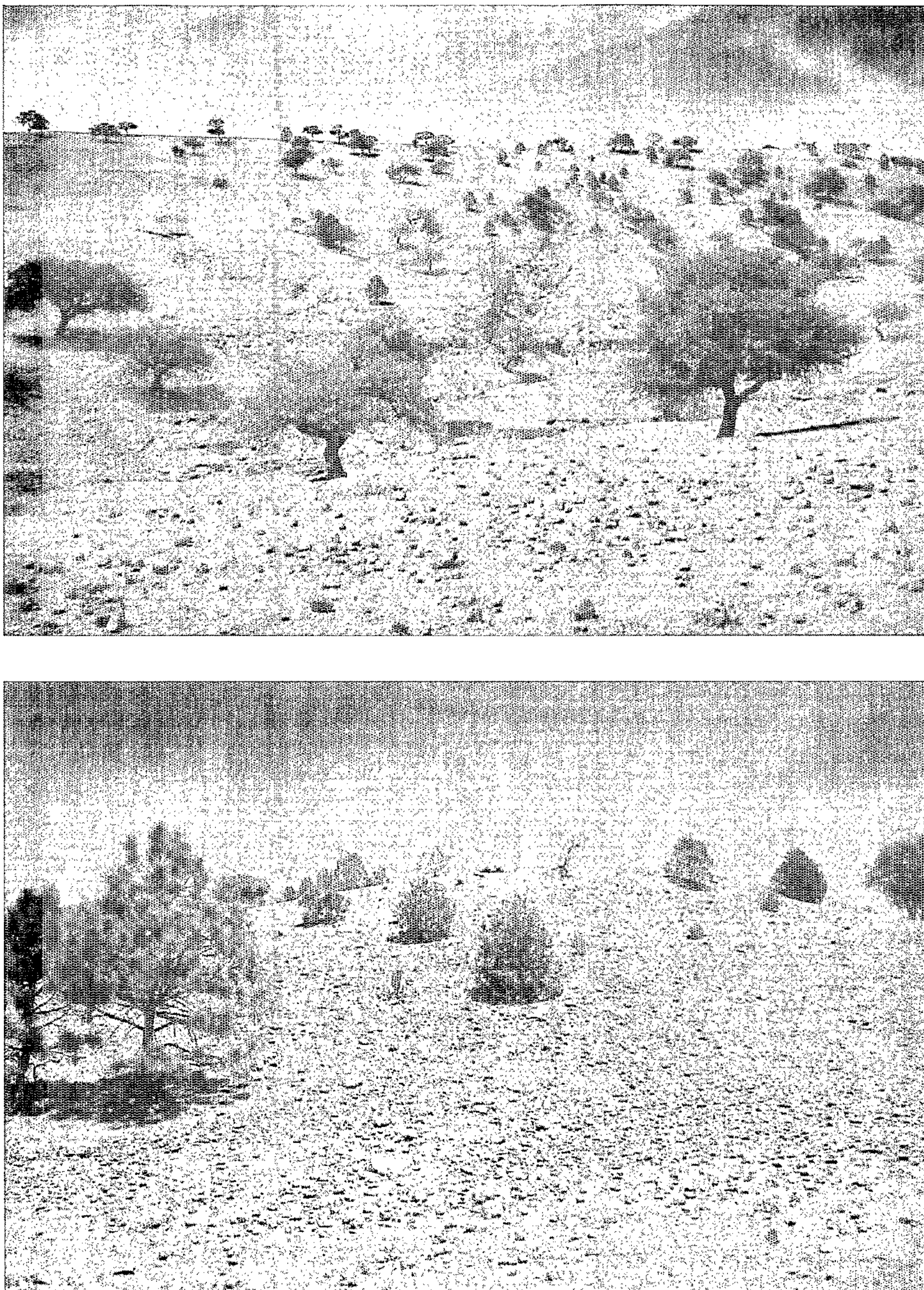

Fig. 6. The two dominant types of surface feature in the landscape: GC (top); FPB (bottom). In the first one, gullying occurs frequently because crusting enhances runoff; but gullies become deep (2–5 m) only in the bottom of grabens or valleys, where soils are thick and bedrock erodible (Descroix et al., 2000).

overgrazing can result in the formation of "terracettes" on hillslopes caused by cattle trampling.

The high stone cover may be explained by a previous erosion stage. Trampling induces a weakening of grass cover such that the fine soil particles are detached by splash and taken away by overland flow. Then, after years, stones appear and cover increasing proportions of the soil surface. These pebbles and stones are free because of the slope value and the continuous trampling. This type of stoniness enhances roughness and reduces therefore runoff and soil losses. It absorbs kinetic energy of raindrops and dissipates the overland flow one. This type of differentiation has already been observed by Valentin and Bresson (1992) and Poesen and Lavee (1994). It should be mentioned that because grass tufts existing on both GC and FPB surfaces are generally few centimetres above the surrounding bare soil, they become preferential infiltration zones only under a significant sheet water flow (Planchon and Janeau, 1990).

The third remarkable surface feature was observed in all the environments, on gentle slope (below 10%), and consequently, generally in the interfluve or at the bottom of hillslopes, on grazed areas. It is characterised by an indurated soil surface layer (20–40 cm thick) in red phaeozems. Soils are severely compacted due to their high clay content and the recurring cattle trampling. This surface feature will be referred to as indurated topsoil (INT). In more tropical areas, this kind of soil could constitute an iron pan. However, because this type of surface condition represented a very small area, it was not fully considered in the study.

The first two surface types have different hydrological behaviour. Fig. 7 compares values of runoff and soil losses measured on two plots: one crusted (GC type) and one uncrusted (FPB type). It clearly appears that runoff and erosion are, respectively, three and eight times more important on the GC plot than on the FPB one. This may be

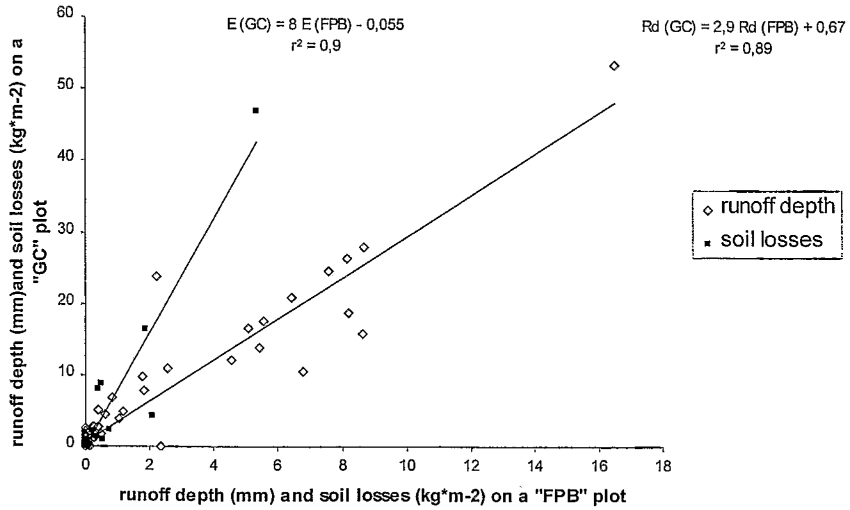

Fig. 7. Comparison of runoff depth and soil losses measured on two plots of different surface feature: GC vs. FPB. Mean values of 1996 and 1997.

Table 7
Mean and standard deviation values of hydraulic conductivity (mm s^{-1}) of different soils surface types: GC, FPB, INT

Methods	Surface features		
	GC	FPB	INT
Disc infiltrometer (suc. 10 mm)	**0.0041** ± 0.0037	**0.008** ± 0.0052	**0.0031** ± 0.0028
N	54	34	26

N is the number of measurements.

explained by the values of soil surface hydraulic conductivity (see Table 7) which show that the uncrusted soils (FPB type) are twice more permeable than crusted (GC type) or indurated (INT type) ones.

The highest runoff coefficients and soil losses rates on the gentlest slopes may also be explained by the surface features. For the "GC" type (widespread on slopes below 15%), gravel (generally smaller than 20 mm) are embedded into the topsoil, and stoniness increases runoff and soil losses. For the "FPB" type (developed on slopes steeper than 20%), gravel and pebbles are not embedded and stoniness facilitates infiltration in these rough soil surfaces. Similar observations have been made (but only with small stones), in Sinai by Yair and Lavee (1974) and in Arizona by Simanton et al., (1994).

The fact that runoff and soil losses were higher in the better vegetation covered slopes is in the opposite of classical observations made elsewhere by Wischmeier and Smith (1960), Roose (1977), Böhm and Gerold (1995), Snelder and Bryan (1995), or more recently, by Woo et al. (1997) and Solé-Benet et al. (1997). This is due to the development of the GC-type surface on gentle slopes where grass cover, although overgrazed, is high. On the contrary, the role played by roughness and stoniness explains why runoff and soil losses have lower values on the FPB-type surface where gravel cover is smaller than on the GC one.

The initial soil moisture content was introduced through the API. Here again, the role of the soil and vegetation reservoir was found to vary according to the environment as well as to the general abundance of the rainfall. Consequently, the soil moisture decrease parameter α of API varied according to the total annual rainfall (Descroix et al., submitted).

6. Conclusions

The main explaining variables of runoff and soil losses in the western Sierra Madre have been classified in two categories. The first one includes the presence of embedded gravel, the soil sand content and the percentage of grass cover. All these factors contribute to enhance erosion and runoff. The second category comprises the presence of free pebbles and blocks, the percentage of tree cover and litter at the surface, the slope value, the silt, clay and organic matter contents of the soil, as well as its structural stability. These variables have been found to reduce runoff and erosion.

It has been shown that slope and vegetation cover alone were not able to fully explain the runoff and soil losses which are mainly controlled by the surface features and more specifically by the presence of a crust at the soil surface. So, there is a need to have detailed descriptions and hydrodynamic characterisations of these features which could be achieved properly at low cost by extensive use of rainfall simulators (Esteves et al., 2000), coupled with tension disc infiltrometry (Vandervaere et al., 1997).

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