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# An experimental analysis of hydrodynamic behaviour on soils and hillslopes in a subtropical mountainous environment (Western Sierra Madre, Mexico)

L. Descroix[a,*], J.L. Gonzalez Barrios[b], J.P. Vandervaere[c], D. Viramontes[d], A. Bollery[e]

[a]*IRD-LTHE, Domaine Universitaire, BP 53, 38041 Grenoble Cedex 9, France*
[b]*Cenid-Raspa-INIFAP, AP 225-3, 35 071 Gomez Palacio, Dgo, Mexico*
[c]*UJF-LTHE, BP 53, 38041 Grenoble Cedex 9, France*
[d]*IMTA, CTH, CP 8532, 62560 Juitepec, Mor, Mexico*
[e]*UJF-IGA, BP 53, 38041 Grenoble Cedex 9, France*

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**Abstract**

Many soils parameters and features play a role in explaining the hydrodynamic behaviour of a watershed. Textural data are relatively easy to obtain and to spatialise, due to their low spatial variability. Inversely, structural features usually exhibit great spatial variability and thus, are difficult to interpolate and to integrate in the framework of a hydrologic model. However, structural characteristics of the soils seem to have a greater influence on catchment hydrological balance than the textural ones.

The objectives of this study were to identify which parameters control the soil surface hydrological behaviour and quantify the magnitude of their spatial variability.

Measurements of soils characteristics, including bulk density and hydraulic conductivity, were carried out in five watersheds in the Western Sierra Madre (Northern Mexico). It is shown in this study that on a natural grassland under subtropical mountainous climate, spatial variability of soil hydraulic conductivity is almost as high at a 1-m$^2$ scale as at a 1-km$^2$ one.

The main discriminating variables which account for the spatial variability appeared to be the lithology and overall the soil surface features, both being related. The latter seems to be a synthetic indicator of basin hydrodynamic behaviour, and to be easier than others to spatialise. © 2002 Published by Elsevier Science B.V.

*Keywords:* Spatial variability; Hydraulic conductivity; Western Sierra Madre; Surface features; Hortonian runoff

## 1. Introduction

Runoff and sub-surface flows modelling at plot- or basin scale, requests the input of soils physical characteristics that could explain its hydrological response to a rainfall event.

Soil texture is perceived as spatially stable, as it has been observed in the study area (Descroix et al., 2001) and in other regions (Casenave and Valentin, 1992). Texture seems to have a lower influence on the infiltrability than the structure (Clothier and White, 1981; Hussen and Warrick, 1993; Logsdon and Jaynes, 1993); grain size distribution is less influent

* Corresponding author. Fax: +33-476-825286.

*E-mail addresses:* descroix@hmg.inpg.fr (L. Descroix), glzbjl@raspa.inifap.conacyt.mx (J.L. Gonzalez Barrios), vanderva@hmg.inpg.fr (J.P. Vandervaere), davidv@tlaloc.imta.mx (D. Viramontes).

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than the arrangement of grains and pores. Soil structure has a great spatial and temporal variability and should be an important factor to estimate the hydrodynamic behaviour of a plot or a catchment, but it is uneasy to characterise it as a simple factor, because difficulties are often associated with collecting soil lumps necessary to determine its structural stability and having them back at the laboratory in good conditions. Finally, the other variables are not directly connected with soil structure to characterise it (bulk density, porosity, infiltrability, penetrometry, etc.).

The spatial variability of infiltration measured or estimated is always quite high. For a grassland catchment in Oklahoma, Sharma et al. (1980) have measured coefficients of variation (CV) of infiltration depth ranging from 0.1 to 0.4 depending on the type of soils. Berndtsson and Larson (1987) determined for an area in northern Tunisia that the spatial variability of infiltration depends on the topography, particularly the position on the slope or near the wadi. In a review of field measurements, Corradini et al. (1998) showed 'considerable spatial heterogeneity of soil hydraulic properties and particularly of the saturated hydraulic conductivity'. They considered that the coefficient of variation of $K_s$ ranges from 0.3 to 1 under real conditions. In the Vosges mountains (France), Ambroise and Viville (1986) showed that soil saturated hydraulic conductivity, $K_s$, measured with a constant-head permeameter, had a great local dispersion; its coefficient of variation was close to 1 for a data set of 400 measurement points on a 36 ha catchment (with high values of $K_s$, ranging from 100 to 1000 mm/h). In an agricultural area under temperate climate in Iowa, Mohanty et al. (1994) emphasised the influence of farming practices and porosity (particularly the presence of macropores, often clogged by tractors) and used disc infiltrometers to measure the hydraulic conductivity and evaluate its spatial variability; they found CV of $K_s$ ranging from 0.7 to 1.3 in corn fields. Elsenbeer et al. (1992) showed that the variability of $K_s$ depends on the position in the slope and that it decreases sharply with depth in a sub-andine tropical rain forest. In an experiment in Spain, Vandervaere (1995) found that the CV value was 0.2 on the bare soil and 0.32 on the irrigated corn.

It is well known that the runoff is strongly influenced by the hydrodynamic characteristics of the soil, especially in a Hortonian situation (Valentin et al., 1990; Casenave and Valentin, 1992; Mohanty et al., 1994; Vandervaere, 1995; Vandervaere et al., 1997; Corradini et al., 1998). Valentin et al. (1990) particularly determined conditions and variables which explain water infiltration at catena scale and at watershed scale in tropical Africa. Location on the hillslope, soil porosity and crusting, and more generally, surface features, pedogenesis and land use, are considered by most of the authors as the main variables accounting for the hydric behaviour of the soil. The $K_s$ spatial variability has been demonstrated by Woolhiser et al. (1996) to have a crucial importance in understanding and predicting Hortonian runoff. They concluded that the 'sensitivity of runoff models to these factors is dependent on the magnitude of the runoff event, with less sensitivity being exhibited for large events'. Corradini et al. (1998) investigated the role of a high spatial heterogeneity of $K_s$; they showed that surface water is increased by the heterogeneity of $K_s$, mainly for small rainfall events. Recently, Govindaraju et al. (2001) used the $K_s$ distribution to model the expected value of areal infiltration and its variance.

Ambroise (1998) noticed the role of soil properties spatial variability, and particularly the pattern of their distribution and their geometry, on runoff yield functions. Analysing runoff generation in arid and semi-arid areas, Yair and Lavee (1985) showed that infiltration characteristics and runoff generation are more complex in these regions as compared to humid areas.

The spatial variability of hillslope hydrodynamic behaviour in semi-arid areas is due to the conjunction of many factors: stoniness, soil surface crusting, vegetation and litter pattern. Stoniness have numerous different patterns, each one inducing an original hydrodynamic behaviour: stones and pebbles can be free or embedded (Poesen and Lavee, 1994; Valentin, 1994), included in the matrix or only on the topsoil, and their size result in very distinct infiltration rates (Yair and Lavee, 1985; Abrahams and Parsons, 1991; Descroix et al., 2001). The crusting of the topsoil plays an important hydrological role leading to a severe decrease in soil permeability, as it has been shown by Valentin (1994) and Vandervaere (1995). Vegetation density and pattern obviously influences runoff and runon in semi-arid environment, even in very flat areas (Valentin et al., 1990; Valentin and Casenave, 1992); the tiger bush pattern is particularly efficient to increase surface water infiltration as it has been demonstrated in Mexico (Janeau et al., 1999) where 'biological activity, litter and roots favour a better infiltration capacity' as well as in Sahel (Galle et al., 1999). In similar environments, Tongway and Ludwig (2001) defined the differential infiltration on banded landscape, with low infiltration rates in the bare zone and high rates in the vegetated one. Previously, Tricker (1981) has insisted on the role played by soils characteristics, vegetation and its pattern, and overall the thickness of the litter and the slope, to explain the spatial heterogeneity of infiltration rates. According to Yair and Lavee (1985), surficial structures are responsible 'for great spatial variations in the area's response to rainfall in arid and semi-arid areas'; and 'infiltration capacities vary tremendously over distances of a few centimetres'.

The aims of this paper are to identify which parameters control the soil surface hydrological behaviour in a subtropical mountainous environment and quantify the magnitude of their spatial variability. Another objective is to determine if this variability in soil physical properties is linked to the topographic pattern. Furthermore, we use the descriptions of soil surface features, as early proposed by Descroix et al. (2001), in order to achieve a satisfying classification of areas with homogeneous hydraulic properties; these descriptions should include both soil textural and structural characteristics and allow to classify each area according to its hydrodynamic behaviour.

## 2. Study area

The Western Sierra Madre corresponds to the largest ignimbritic field in the world (Viramontes et al., 2000). Soils are mainly Leptosols, Cambisols and Phaeozems (ISSS-ISRIC-FAO, 1994), from 10 to 300 cm thick (but rarely more than 60 cm on hillslopes), with a sandy texture in surface and often with a clay horizon (10–30 cm thick), at depths of a few tens of cm, rich in Biotite caused by rock bed alteration and illuviation. Soils have a high carbon content: values range from 0.5 to 5% from bare soils to well preserved forest or grasslands areas. These types of soils extend on 95% of the total area (Viramontes, 2000), and they cover all the hillslopes, most of which are bare and then subject to intense laminar erosion. In some limited areas, Phaeozems can reach a thickness of 100 cm. Generally close to the talwegs, soils are Cambisols that can contain small water tables and play an important hydrologic role, particularly when they have vertic properties (vertic Cambisol), and thus are characterised by a strongly higher clay content. Cambisols are mostly thicker and have a different hydrological behaviour compared to the Phaeozems (Table 1).

This study has been carried out in the Rio Nazas upper basin, see Fig. 1, in Durango State (Northern Mexico). The study area has a sub-tropical climate; annual rainfall amount is ranging from 550 to 675 mm (80% of annual rainfall occurs between June and September). Mean temperature varies from 5 °C in January to 25 °C in July at 2200 m. Vegetation is representative of a mountain savannah, with acacias below 2000 m and oaks above this level; above 2400 m, the forest takes gradually over the pastures. The pastures are strongly overgrazed; in extended areas, there is no more topsoil; large amounts of boulders and blocks constitute a pavement that protects underlying horizons from further erosion (Descroix et al., 2001). In these zones, organic matter content is relatively low (below 1%).

Hillslope hydrodynamic is mainly of the Hortonian-type in the Western Sierra Madre (Descroix et al., 2001): overland flow is due to the exceeding of soil infiltrability by rainfall intensity. Large, bare soils areas, often crusted and/or trampled by livestock, weak sub-surface and river base flows indicate that runoff is caused by saturation of the thin topsoil or the surface layer. However, over short periods (a few weeks in August 1996, 3 or 4 days in August 1998 and June 1999), creeks ('arroyos') could flow continually because of the soil water storage. In such periods, runoff coefficients close to 100% were measured on 50 $m^2$-large plots. In some cases, the emergence of local water tables results in high runoff coefficients. These water tables are supplied by infiltration in steeper and stonier slopes uphill.

The experimental system is located in four catchments and one sub-catchment (see Table 2 and

Table 1
Water storage capacity of the main classes of soils in the Western Sierra Madre (according to Viramontes (2000))

| Soil | Thickness (cm) | % of the total area | Mean water storage capacity (mm) |
|---|---|---|---|
| Phaeozems | 0–20 | 40 | 32 |
| Phaeozems | 20–60 | 54 | 135 |
| Phaeozems | 60–100 | 1.5 | 365 |
| Cambisols | 60–300 | 2 | 628 |
| Vertic Cambisols | 60–100 | 0.5 | 683 |

Fig. 1) at a latitude of 25°40′N and a longitude of 105°40′W. The hydrological data were collected (Descroix et al., 2001) from 1994 to 1999, the years 1997–1999 being particularly dedicated to study of the hydrodynamic behaviour of the soil.

The locations of measurements were equally located along the catena (upper-, middle- and lower-parts of hillslopes) in order to determine the influence of the hillslope position on the hydrological behaviour of the soil.

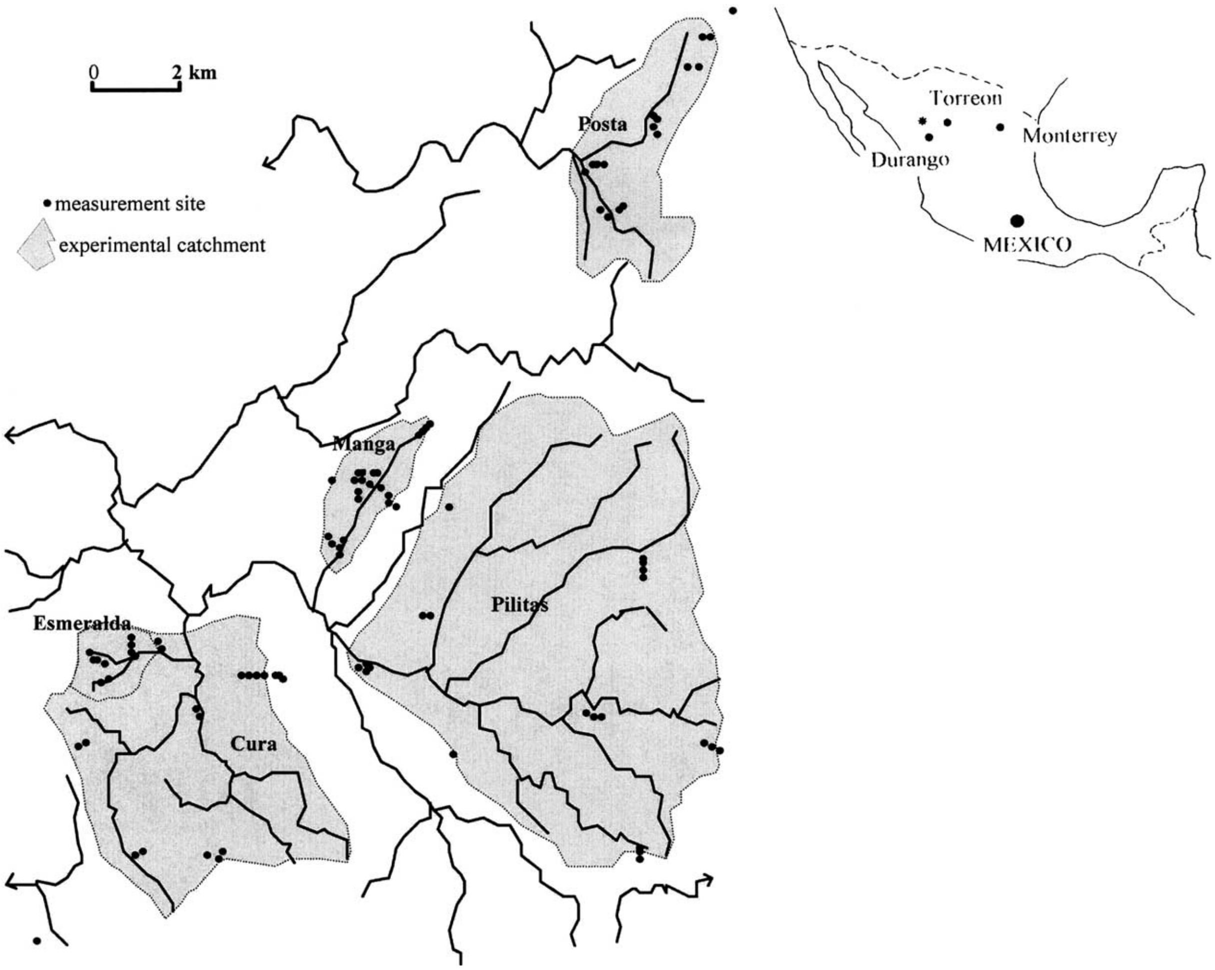


Fig. 1. Location of experimental watersheds 2nd measurement sites.

Table 2
Main characteristics of the study catchments

| Catchment | Area (km$^2$) | Runoff coefficient | Mean $K^a$ (mm/h) | Mean bulk density | $\alpha^b$ | PU (mm/h)[c] |
|---|---|---|---|---|---|---|
| Cura | 21.8 | 10.9 | 17.1 | 1.26 | 0.034 | 2 |
| Esmeralda | 1.28 | 15.1 | 13.1 | 1.44 | 0.044 | 2 |
| Manga | 3.1 | 5.1 | 29 | 1.37 | 0.39 | 6 |
| Pilitas | 50.8 | 9.8 | 25.6 | 1.2 | 0.06 | 2 |
| Posta | 8.6 | 10 | 25.1 | 1.2 | 0.1 | 2 |

[a] $K$ (−10 mm) is measured with the multi-radius method.
[b] $\alpha$ is the inverse of the characteristic time of soil moisture depletion.
[c] PU is the mean value of efficient rainfall.

## 3. The experimental system

### 3.1. Hydraulic conductivity

A field campaign was carried out to measure water infiltration in the field, using disc infiltrometers (triple ring infiltrometer at multiple suctions, TRIMS, Vandervaere, 1995); it allows the calculation of hydraulic conductivity $K$ near saturation.

These experiments were performed on 90 sites distributed on the five catchments (Fig. 1), on all types of soils, rocks and position of slopes and according to two different methodologies employed simultaneously:

- The multi-radius method (Scotter et al., 1982; Thony et al., 1991), which yields hydraulic conductivity values, $K$, in slightly unsaturated conditions (−10 mm of water). All measurements were made systematically with two discs (80- and 250-mm diameter, respectively); sorptivity values are also obtained if volumetric water content is measured before and after the test. However, this method implies that the two disc infiltrometers are set up in two different places, thus results are influenced by the variability of soil parameters.
- The multi-potential method (Reynolds and Elrick, 1991; Ankeny et al., 1991), which consists in measuring infiltration flow with disc infiltrometer at different decreasing suctions, using the Mariotte device included in the TRIMS. $K$ values obtained for different predetermined suction levels (−100 to −10 mm of water) are influenced by soil physical characteristics, particularly its grain size distribution. The infiltrometer is not removed during the measuring process, but results may be influenced by the vertical gradient of soil properties.

Basically, four TRIMS tests were performed at each of the 90 sites: two using small discs (80 mm diameter) and the two others using large discs (250 mm diameter), one of which with the multi-potential method. In this case, the last suction level imposed to the device was −10 mm, that is, the suction used in the multi-radius method. Therefore, 360 tests were realised with this device. In each case, initial and final water content were determined by manual sampling.

### 3.2. Other site variables considered

- The bulk density was measured according to the pool method: a voluminous (2–4000 cm$^3$) sample of soil is collected on the platform used for the wide infiltrometer tests (their maximum width is then 25 cm; the depth is 15 cm). The whole volume is measured within a plastic bag full of a known amount of water. This method allows to take into account gravel and stones (which can represent 5–40% of the total volume of the sample), and to determine separately the density of the stones, the density of the stone-free soil, as well as the porosity;
- Gravel and stones content, the influence of which depends on their size and whether they are embedded or free into the matrix; their proportion was measured (weight and volume) after sifting of the great size fraction (above 2 mm);

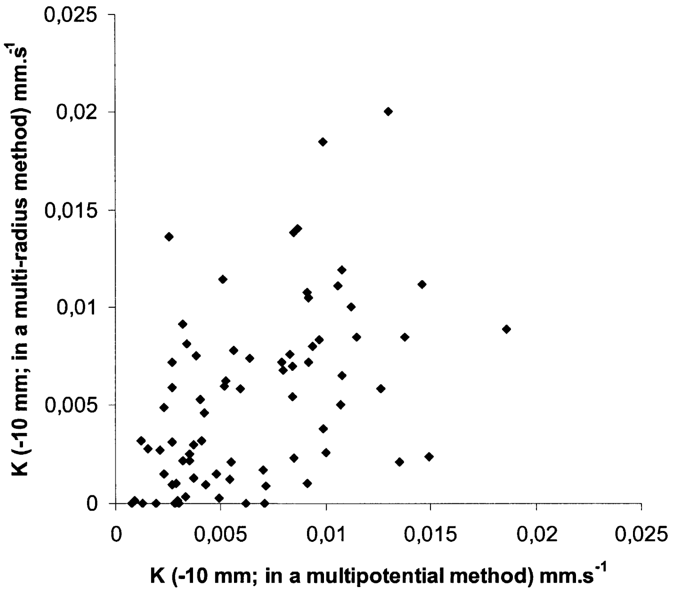


Fig. 2. Measurements of hydraulic conductivity using disc infiltrometers: comparison of values yielded by two different techniques, the multi-radius and the multi potential.

- Soil grain size distribution, determined by the Robinson pipette device;
- Poral space, measured as: $PS = (SD - BD)/(SD \times 100)$, where PS is poral space, SD and BD, respectively, the solid density and the bulk density;
- Organic matter content and total carbon by the method of Walkley and Black;
- Surface features, particularly presence of crusts and vesicular porosity; they were defined using the determination grid as that recommended by Casenave and Valentin (1992);
- Presence of litter, tree cover, grass cover, measured using graduated grids on the field.

## 4. Results

### *4.1. Comparison of methods*

Fig. 2 compares two different methods to assess the hydraulic conductivity $K$ ($-10$ mm) using disc infiltrometer: one of them using the multi-radius-technique and the other one using the multi-potential technique. Since both methods are soil destructive, it is impossible to perform the measurements at exactly the same location. Thus, locations were selected as close as possible, that is, a few tens of cm distance. Fig. 2 shows that the results seem to provide uncorrelated data; this is probably due to the high variability of soil infiltrability. Table 3 includes mean values obtained with both methods; the data are pooled according to the classes of soil surface features described further in this paper. Analysing both Fig. 2 and Table 3 shows that values of the same group are also in the same order of magnitude, regardless of the method, but the spatial variability is such that two tests made at few tens of cm yield strongly different values of $K$.

### *4.2. Variability of soils hydrodynamic behaviour*

#### *4.2.1. Correlations between hydraulic conductivity (K) and types of soils*

Phaeozems and vertic Cambisol have similar average values of $K$ ($-10$ mm; measured on the multi-radius way) even though the clay content of the latter is three times higher than that of the Phaeozems (Fig. 3). Macropores are as numerous in clayey soils as in the other types of soil; the way clays are arranged

Table 3
Hydraulic conductivity of soils classified by their surface features

| $K$ (mm/s) | | GC | FPB | INT | Others | Pooled |
|---|---|---|---|---|---|---|
| TRIMS multi-suction (−10 mm); disc radius: 25 cm | Mean | 0.0053 | 0.010 | 0.0037 | 0.0072 | 0.0067 |
| | Standard deviation | 0.0025 | 0.0053 | 0.0025 | 0.0081 | 0.0045 |
| | CV | 0.47 | 0.53 | 0.68 | 1.12 | 0.67 |
| TRIMS multi-radius (−10 mm); disc radius: 8 and 25 cm | Mean | 0.0042 | 0.0083 | 0.0038 | 0.0058 | 0.0054 |
| | Standard deviation | 0.0035 | 0.0047 | 0.0036 | 0.0066 | 0.0047 |
| | CV | 0.83 | 0.57 | 0.95 | 1.14 | 0.87 |
| Number of measurements | | 34 | 29 | 15 | 12 | 90 |

GC, FPB and INT are the main surface features determined in the study area (Descroix et al., 2001); GC type is a gravel crust; FPB type is characterised by free pebbles and blocks; INT type is an indurated topsoil with a high clay content.

in the soil is more important than the actual clay content in explaining the variability of the infiltration.

*4.2.2. Relationships between hydraulic conductivity and environments*

Figs. 4–8 show the average values of $K$, derived by the multi-potential method (disc diameter 25 cm), for different categories of sites, which are classified according to their soil and rock types, their hillslope position, the catchment they belong to and their surface features.

Fig. 4 shows that there is little difference in soil hydraulic conductivity according to soil type; Leptosols have the highest $K$ values, and inversely, vertic Cambisols and Cambisols the lowest ones.

– Soils formed on conglomerates and tuffs are more conductive than those formed on ignimbrites, but the difference is weak (Fig. 5).
– The position of the measurement site on the hillslope does not allow a clear distinction in terms of conductivity; in Fig. 6, it can be noticed that higher values of $K$ correspond to the steepest zones of hillslopes (middle-hillslope). This is probably related with their high rock fragments content; effectively, the soil erosion increased gravel exposure, leading to enhance infiltration in a negative feedback loop. The other sections of the hillslopes have similar values, except for the plateaux, which exhibit lower values.
– A classification is easier according to the

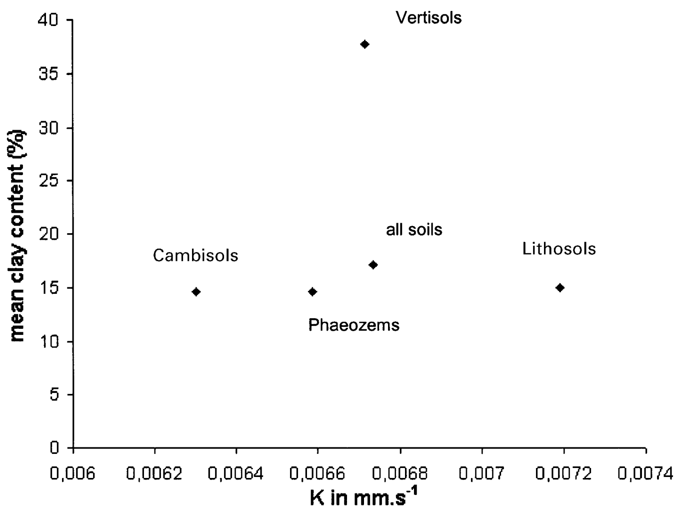


Fig. 3. Clay content vs $K$(−10 mm) for the dirrerent soil types.

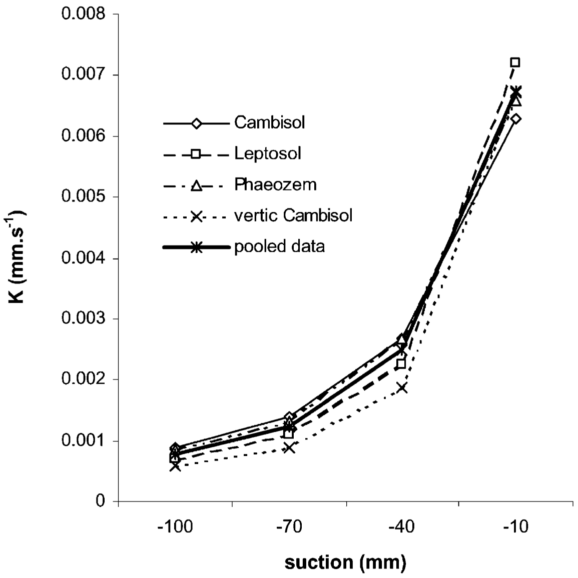


Fig. 4. Mean $K$ values at different suctions, for the different soil types.

different catchments (Fig. 7): Cura and Esmeralda have lower values than the other three ones. The two catchments mentioned are characterised by steeper slopes, thinner soils and ignimbritic bedrock, locally outcropping.

– Furthermore, it is noticeable (Fig. 8) that surface features allow a better classification of soils according to the soil hydraulic conductivity. The two types of crusted soils ('GC' = gravel crusts; and 'INT' = indurated topsoil (Descroix et al., 2001)) have strongly lower average $K$ values than the other ones. As it was observed at plot scale, stoniness is one of the factors controlling the soil permeability; thus, the presence of free pebbles and blocks surface feature (FPB) corresponds to the highest $K$ values.

The significance of all the differences between the mean values of $K$ was verified (the Student test yielded a 90% confidence level). The only parameters, which cause significant differences in hydraulic conductivity values are: lithology and surface features (all except the 'others' class). Among the catchments, Manga is the only detached class; but with a 80% confidence level in the Student test, Pilitas catchment joins the Manga one to form a group, Esmeralda and Cura constitute another one, and the Posta catchment has an intermediary behaviour, similar to the latter at high suction levels, and closer to the first group closer to saturation (Fig. 7).

### 4.2.3. Significance of K spatial variability

Table 3 showed that $K$ values and CV values slightly depend on the measurement methodology but they remain reasonably comparable.

The measurement sites are hundreds of metres to a few kilometres apart (Fig. 1) and the experimental catchments are spread over an area of 400 km$^2$. At each site, less than 2 m separate any two of the four measurement locations (two for each disc) and the whole measurement area is 4 m$^2$ large. Table 4 compares the CV of the mean $K$ values at all sites (CV1) with the mean of the CV of all the measurement points of one site (CV2): CV1 is the CV of 90 values of $K$, each one being the mean of the four measures of each site; on the line 'hillslope', all the values obtained on each slope (26 slopes were concerned) have been pooled. CV2 is the average of the 90 values of the CV (26 for the slopes), each one being obtained with four values of $K$ (10–14 for each slope).

The variability of $K$ was compared along every given hillslope (average CV = 0.74) and between all

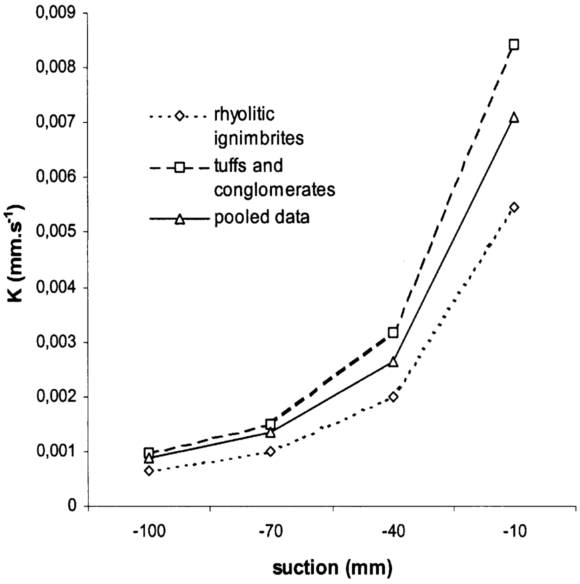


Fig. 5. Mean $K$ values at different suctions, according to the lithology.

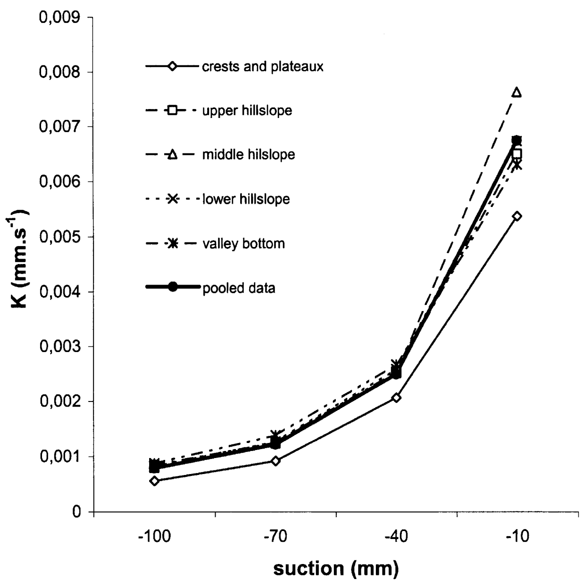


Fig. 6. Mean $K$ values at different suctions according to the position on a hillslope.

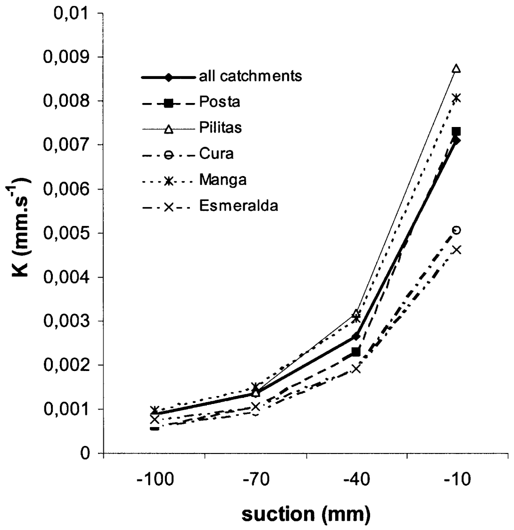


Fig. 7. Mean $K$ values at different suctions grouped by catchment.

hillslope averages (CV = 0.61); in the same way, the CV of different values of $K$ obtained at each measurement site (CV = 0.62) is similar to the CV of the mean $K$ value for all the sites (CV = 0.70).

The variogram of the soil physical properties does not yield a distance of correlation for the total area and for a maximum lag distance of 1 km.

### *4.3. Factors of the K spatial variability*

Many site parameters control soils infiltrability and hydraulic conductivity. Table 5 indicates those that have been considered and discussed later.

In order to find possible relationships between the hydraulic conductivity and other known site variables, an empirical orthogonal function (EOF) analysis was carried out. The space of variables of this analysis (Fig. 9) indicates the respective weight of each textural and structural variable; it is worth noticing that the two first axes of this analysis only explain 40% of the total variance, due to the great heterogeneity of the variables; the third axis explain 10% more of the variance.

The space of variables shows the clear positive correlation between $K$ (KMR as multi-radius; and KMP, as multi-potential) and the coarse fragments content (gravel, pebbles and stones) in volume (CEV) as well as in weight (CEW); this is consistent with previous findings about the main physical characteristic which explains water infiltration in the Sierra Madre (Descroix et al., 2001). The first axis (24% of

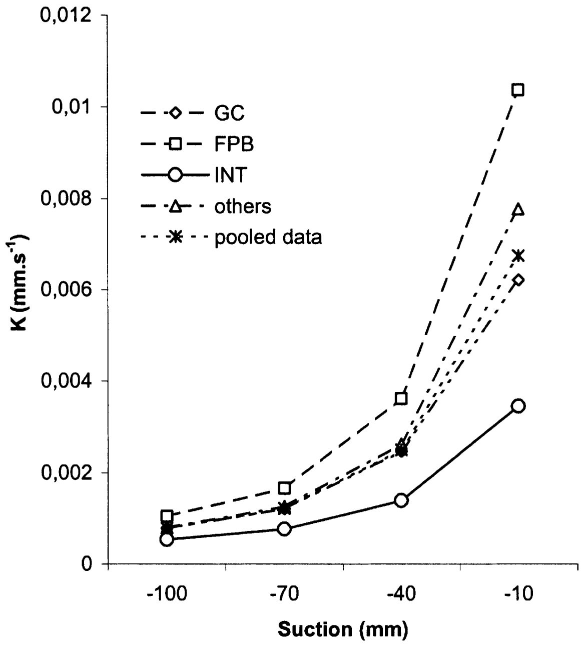


Fig. 8. Mean $K$ values at different suctions according to surface features.

Table 4
Comparison of the coefficient of variation of hydraulic conductivity at several scales

| | Inter-site | | | | Intra-site | | | | Ratio |
|---|---|---|---|---|---|---|---|---|---|
| | *N* | CV1 | *D* (km) | *A* (km$^2$) | *N* | CV2 | *D* (m) | *A* | CV1/CV2 (%) |
| All sites | 90 | 0.70 | 1 | 400 | 4 | 0.62 | 1 | 4 m$^2$ | 89 |
| Hillslopes | 26 | 0.61 | 1 | 400 | 10–14 | 0.74 | 100 | 4 ha | 121 |

Trims is the disc infiltrometer; *N* is the number of measurements; CV is the coefficient of variation; *D* is the distance class between measurement points; *A* is the area concerned.

explained variance) is also determined by porosity (POS, positive correlation) and soil matrix bulk density (BD and TBD, negative correlation); the second axis (which accounts for 16% of the variance) is characterised mainly by the clay content (CLAY), although Fig. 3 showed that the correlation between *K* and CLAY is poor, the field capacity (FCY), the wilting point (PWP), the total carbon content (CTOT) and the saturated water content (FWC), all these variables being positively correlated with *K*; solid density (SD) is negatively correlated with *K*. Finally, it is noticeable that initial water content (IWC), moistened bulb sizes (BSD and BDT), slope value (SLO), sorptivity (S), do not play a determining role in explaining *K* (Fig. 9).

## 5. An overall analysis of results

Using different methodologies (multi-radius and multi-potential) to calculate *K* leads to very different results (Fig. 2). However, Table 3 shows that the mean

Table 5
Soil physical parameters considered in the EOF analysis

| | | |
|---|---|---|
| Hydraulic conductivity: | KMR | *K* measured with TRIMS using the multi-radius test |
| | KMP | *K* measured with TRIMS using the multi-potential test |
| Soil bulk density | TBD | Global bulk density of the soil (matrix + stones) |
| | DGS | Density of gravel and stones |
| | SD | Solid density |
| | BD | Bulk density of the matrix |
| Porosity | POS | Poral space |
| Slope value | SLO | Slope value |
| *Dimension of the moistened bulb at the end of the infiltration test* | | |
| | BDT | Total depth of moistened bulb |
| | BSD | Bulb superficial diameter |
| | BD5 | Bulb diameter at 5 cm depth |
| | BD10 | Bulb diameter at 10 cm depth |
| | BD15 | Bulb diameter at 15 cm depth |
| | BD20 | Bulb diameter at 20 cm depth |
| Texture | CLAY | % of clay |
| | SILT | % of silt |
| | SAND | % of sand |
| Coarse element | CEV | % of soil coarse element (in volume) |
| | CEW | % of soil coarse element (in weight) |
| Sorptivity | S | sorptivity |
| Soil water content | IWC | Initial water content |
| | FWC | Final water content |
| Soil properties | FCY | Field capacity |
| | PWP | Permanent wilting point |
| | CTOT | % of total carbon content |

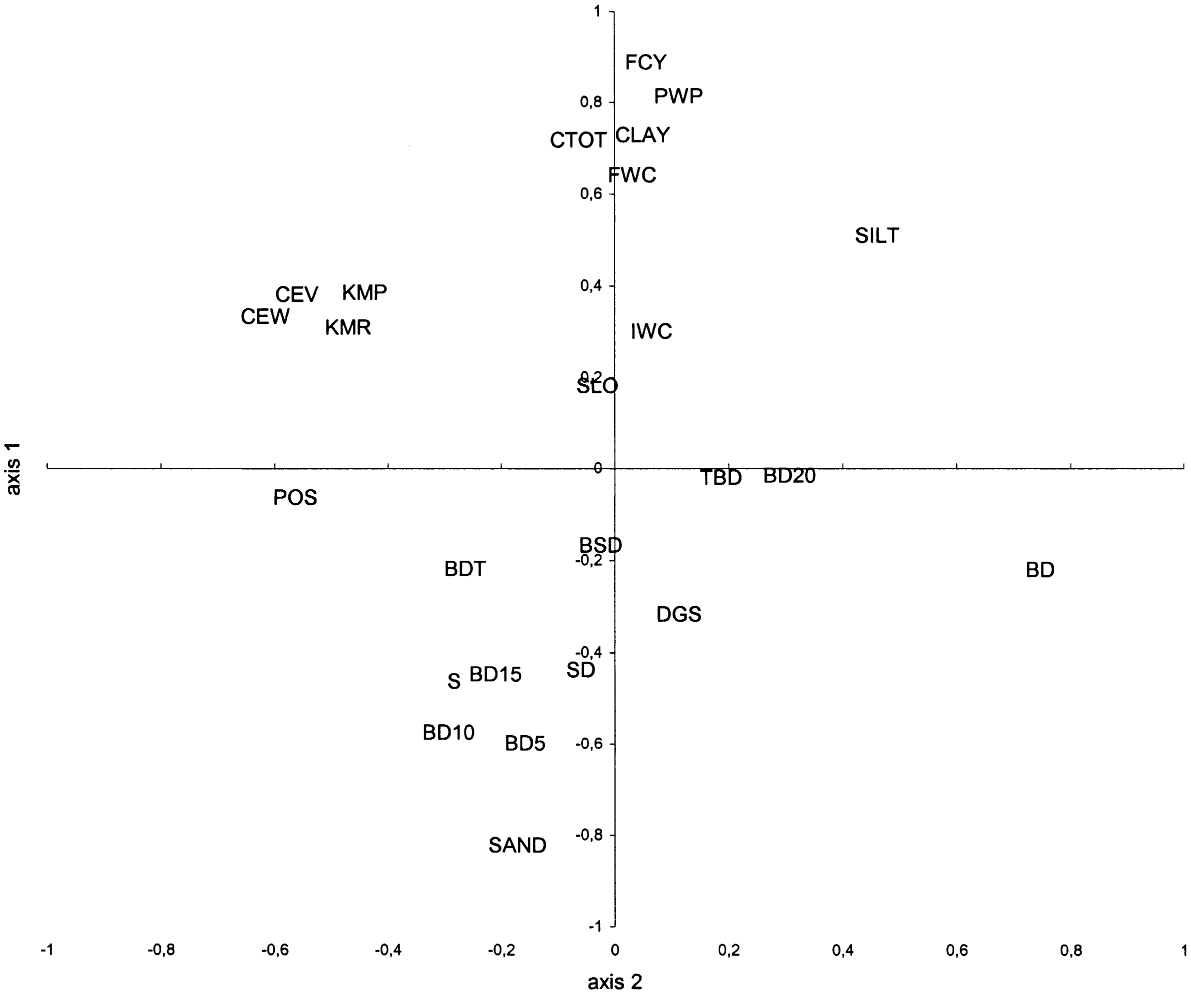


Fig. 9. Space of variables of the EOF analysis of soil characteristics and conductivity.

values obtained using both methods are very close. Average $K$ values grouped by type of soil surface features are reasonably similar, the difference ranges from 2 to 20%. Nevertheless, standard deviation is always very high, as shown by the dispersion of the points in Fig. 2, due to the strong spatial variability of soil physical properties.

Table 2 allows to separate the Manga basin from the other ones. It is the only watershed wholly located in tuffs and conglomerates, and it has the lowest runoff coefficient, the highest $K$ values and efficient rainfall (which is the rainfall which has caused runoff due to an intensity exceeding the soil infiltration capacity), the highest $\alpha$ coefficient ($\alpha$ is an empiric soil moisture decrease parameter in the antecedent precipitation index (API)). Following the definition of the API (Kohler and Linsley, 1951; Chevallier, 1983), $API_n$ is calculated as:

$$API_n = (API_{n-1} + P_{n-1})\exp(-\alpha\Delta t) \qquad (1)$$

where $\Delta t = t_n - t_{n-1}$ is the time (day and/or fraction of day) elapsed between the end of the previous rain event $P_{n-1}$ and the beginning of the current one ($P_n$).

All these factors are inter-related and rely on the fact that conglomerates are more permeable than ignimbrites. Thus, under the conditions of a Hortonian functioning, the Manga catchment needs higher intensity rainfall to exceed its infiltrability and to produce flowing. The $\alpha$ parameter is high where water retention capacity of the soil is low; in this case, the 'memory' of previous events is not preserved for a long time in the soil. High soil $K$ values allow a rapid drainage on the conglomerates of the Manga catchment. The Esmeralda catchment, on ignimbritic bedrock, has exactly the opposite characteristics.

At the event scale, it is necessary to distinguish two types of behaviour according to bedrock composition and environment (Descroix et al., 2001):

- on ignimbrites: the intensity of the efficient rainfall is 2 mm/h at catchment scale, and 14 mm/h at plot scale; efficient rainfall being soil moisture dependent, these values are mean values;
- on tuffs and conglomerates, the intensity values of the efficient rainfall are 6 and 18 mm/h at catchment and plot scale, respectively.

Moreover, it is shown (Fig. 8) that surface features are the best parameter to classify soils according to their hydrodynamic behaviour. Mean values of $K$ are very different depending on the type of surface features (Table 3); three main types were particularly noticed here. The first one is crusted (GC as gravel-crust), the second one has a 30 cm-thick indurated topsoil (INT); both have $K$ values roughly twice lower than the third one, FPB (as free pebbles and blocks). FPB is characterised by a high roughness as result of a previous erosional stage, which has removed fine particles from the soil and exposed the coarse fragments (Descroix et al., 2001). FPB is characteristic of slopes steeper than 20%.

On the stony hillslopes, erosion is a self-limitating process. An increasing rock fragments content leads to the formation of a natural pavement. This pavement has a 2-fold impact: firstly, stoniness protects the soil from the raindrop kinetic energy; secondly, it increases soil roughness and enhances infiltration and hydraulic conductivity (Figs. 8 and 9 and Table 3). 'GC' and 'FPB' surfaces are compared in Fig. 10. However, it is important to notice that the spatial variability of $K$ and bulk density is as high in the first category as in the second. The role of rock fragments on hydrological processes has been described and discussed in a synthesis by Poesen and Lavee (1994). They showed "that rock fragment cover at the soil surface has an ambivalent effect on infiltration rate and on overland flow generation". Processes depend on whether rocks are embedded or free. Valentin and Casenave (1992) indicated that infiltration rate increased with increasing free coarse fragments cover while mean diameter of fragments is less than 29 mm. For greater pebbles, infiltration decreased with increasing gravel cover rates. Inversely, Brakensiek and Rawls (1994) concluded that "surface rock sizes have been shown to be directly related to the infiltration, i.e. smaller rocks decrease and larger surface rocks increase infiltration". In a semi-arid hillslope closer to Mexico, Abrahams and Parsons (1991) obtained a negative correlation between infiltration and stone cover. In the area concerned here, Descroix et al. (2001) showed that $K$ values were higher on steep slopes, due to their correlated high pebbles and stones content; in this case, rock fragments are free.

This explains the great variability of hydrological behaviour of hillslopes. Furthermore, this type of results is in agreement with those obtained in tropical areas (Casenave and Valentin, 1992; Vandervaere, 1995) for crusted soils, as well as in temperate countries by Ambroise and Viville (1986) for mountainous areas, and by Mohanty et al. (1994) on a plain.

More generally, our results confirm the conclusions of Corradini et al. (1998): the $K$ heterogeneity mainly plays a major role in the generation of overland flow. As it is known that subtropical mountains are mainly characterised by a Hortonian-type runoff, the possible occurrence of runon processes could be important for the catchment water balance at storm scale.

## 6. Conclusion

The spatial variability of soil physical properties is very high, complicating the spatial characterisation of watershed hydrodynamic behaviour. The comparison of soil morphological and hydraulic properties leads to the conclusion that, in the Western Sierra Madre, there is no correlation between hydraulic conductivity and the structural and textural soil data.

Fig. 10. Profile of two different major soil surface features: "GC" at left and "FPB" at right.

All the results showed that 70% of the total variability calculated within a 400 $km^2$ area can be observed within a 4 $m^2$ one. The presence of crusts, gravel content, grass and tree cover, clay content and clay arrangement in soils, erosion of topsoil, are all subject to a great spatial variability. Consequently, it is of great interest to group them in more synthetic indicators, such as 'surface features', the hydrodynamic behaviour of which is determined at plot- and catchment-scale.

The hydrological behaviour of crusted soils cannot be explained by other physical parameters, such as bulk density, clay content or the location on the catena; the Hortonian overland flow is generated in the thin surface crust, whatever the structure and texture of the soil are.

Runoff site factors are numerous and each one (except for the soil texture) has a great spatial variability. This contributes to explain the extreme heterogeneity of hydraulic conductivity and runoff yield conditions, even within a unique context of Hortonian overland flow.

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