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Saturated Hydraulic Conductivity and Land Use Change, New Insights to the Payments for Ecosystem Services Programs: a Case Study from a Tropical Montane Cloud Forest Watershed in Eastern Central Mexico

Alberto Gómez-Tagle (Jr.) Ch.[1], Daniel Geissert[2], Octavio M. Perez-Maqueo[2], Beatriz E. Marin-Castro[2] and M. Beatriz Rendon-Lopez[1]

[1]*INIRENA, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán,*
[2]*Instituto de Ecología, A.C., Xalapa, Veracruz,*
Mexico

1. Introduction

Water infiltration into soil is a complex process that in field conditions varies for every precipitation event (Wit, 2001) due mainly to its dependence of antecedent soil moisture (Cerdà, 1995; Lassen & Lull, 1951). Some authors use saturated hydraulic conductivity (K_s) as a descriptor of the infiltration process (Wit, 2001; Ziegler, et al., 2004). This hydrophysical variable allows field based comparison between sites with different initial moisture contents and soil characteristics. Several researches report differences in infiltration and K_s, associated to vegetation patches (Cerdà & Doerr, 2005), land use change patterns (Buytaert, et al., 2005; Tobón, et al., 2004; Ziegler, et al., 2004) and vegetation recovery (Li & Shao, 2006; Zimmermann & Elsenbeer, 2008). This trend has been reported in many different ecosystems and vegetation types ranging from tropical rain forests (Zimmermann & Elsenbeer, 2008) to semiarid and Mediterranean shrublands (Cerdà & Doerr, 2005; Li & Shao, 2006). Differences can be marginal or up to several orders of magnitude (Li & Shao, 2006). This allowed the possibility of using land use and plant cover as an indicative variable of the infiltration process.

Payment for ecosystem services (PES) schemes include in most cases a "consumer" that pays the "provider" for maintaining the ecosystem functions that generate the ecosystem services in question. Perhaps, two of the most common examples of payment for ecosystem services are the carbon sequestration programs (Ordoñez, et al., 2008) and the hydrologic service initiatives (Naranjo & Murgueitio, 2006).

In Mexico, the Federal Government has recently developed a strategy of payment for ecosystem services (PES) which encompass biodiversity, carbon sequestration and hydrologic ecosystem services. The Mexican program in 2008 had the largest budget worldwide for such an initiative (60 millions US dollars) (CONAFOR, 2008). While an important step in the incorporation of economics to conservation, some authors pointed out

that the Federal government initiative is based on unverified relationships between land use/cover and water flow in the soil and hydrologic response of watersheds (Gómez-Tagle, 2009; Pérez-Maqueo, et al., 2005).

Initiatives at the local scale have also been established to compliment Federal programs. The first local PES initiative in Mexico was developed in 2003 in the municipality of Coatepec. The city of Coatepec (population 73,500) is in the state of Veracruz and receives over 98 percent of its' water from surface flow from the Gavilanes river. Therefore the PES municipal program is focused on the preservation of cloud forests in the Gavilanes watershed through monetary incentives. This program makes the assumption that mature cloud forest cover maintains year round stream water flow in the headwaters, and that this type of forest favors water infiltration into soil allowing both ground water recharge and water storage in the soil. Nevertheless, implementation of PES in the area follows a binary approach with two levels; forested, namely land with tree coverage, and unforested or land without tree coverage. By definition within the local PES initiative, the first level is considered appropriate for economic compensation while the latter is not.

Recent research (Gómez-Tagle and Geissert, unpublished) indicate that this watershed includes many different land use types/coverages, some of them are related to diminished infiltration and hydraulic conductivity (Karlsen, 2010; Marín-Castro, 2010), thus infiltration capacity may vary significantly from one to another.

In this chapter we examine the relationships between land use/cover and key hydrophysical variables in order to strengthen and aid policy making related to PES initiatives in the area. Specifically, the analysis addresses the following questions: 1) What is the relationship between land use/cover and saturated hydraulic conductivity? and 2) Which transitional/successional stages are linked to higher infiltration rates and are prone to be included in PES initiatives?

2. Methods

2.1 Study area

The Río Gavilanes watershed is a 33.2 km² exoreic catchment in the headwaters of La Antigua River basin. The watershed is located between 97°06´09.46" and 96° 59´52.67" W and 19°31´46.38" and 19°27´33.2" N on the windward slope of Cofre de Perote strato-volcano in the state of Veracruz in eastern central Mexico (Figure 1). The elevation of the watershed ranges from 1180 to 2960 m above sea level. Environmental conditions result from three different climatic subtypes according to Köppen's system modified by García (2004): subtropical humid in the low portion, temperate humid in the middle, and cool temperate humid in the high portion. Mean annual temperature for the three portions is 19.3, 14.3 and 9.3 °C respectively, while total annual rainfall is 1800.4 (low), 3036.9 (middle) and 1724.4 (high) mm. The hottest month is May and the coldest is January (Figure 2). Precipitation shows a different trend; the low and high portions of the watershed receive similar amounts of rainfall during the year while the middle portion receives a significant higher amount of precipitation (Figure 2). The annual potential evapotranspiration estimated by means of the modified Thornthwaite (1948) method is 1455.0 (low), 850.3 (middle) and 588.9 (high) mm and the annual estimated water budget is 345.5 (low), 2186.7 (middle) and 1135.4 (high) mm. The low portion has seven months (November-May) of negative water budget, while
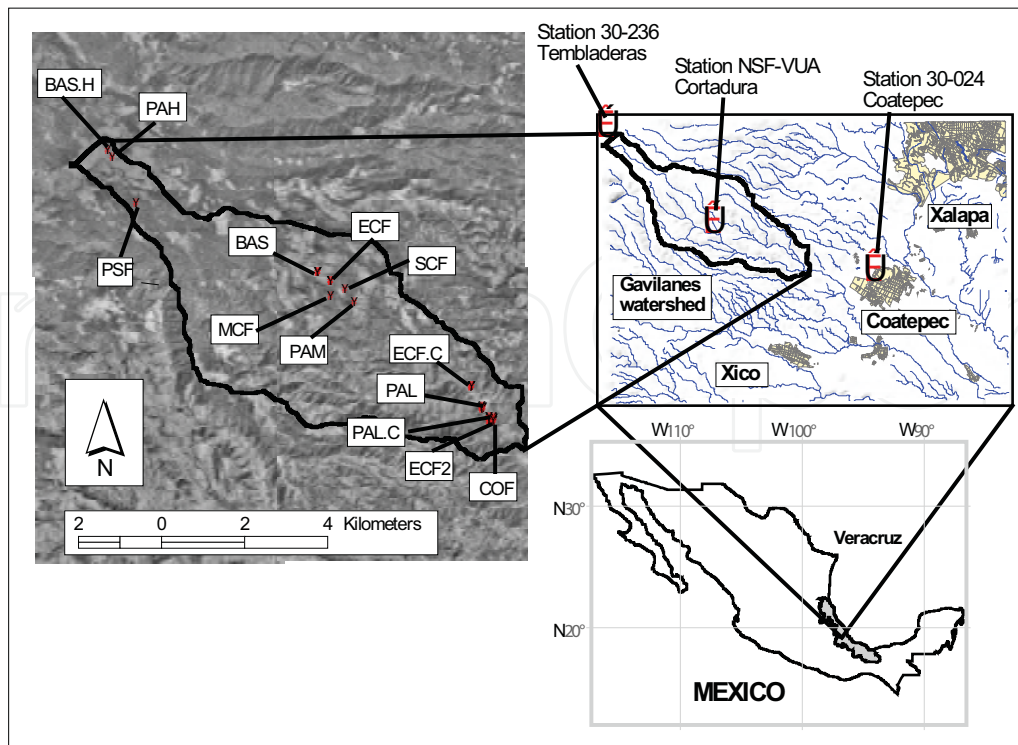
Fig. 1. Study area and sampling sites; *Bacharis-Pteridium* shrub middle (BAS), *Bacharis* shrub high (BASH), coffee plantation low (COF), early cloud forest regeneration middle (ECF), early cloud forest regeneration low (ECF2, early cloud forest regeneration from coffee plantation low (ECFC), mature cloud forest middle (MCF), pasture high (PAH), pasture low (PAL), well managed pasture low (PALC), pasture middle (PAM), pine-spruce forest (PSF), secondary cloud forest (SCF).
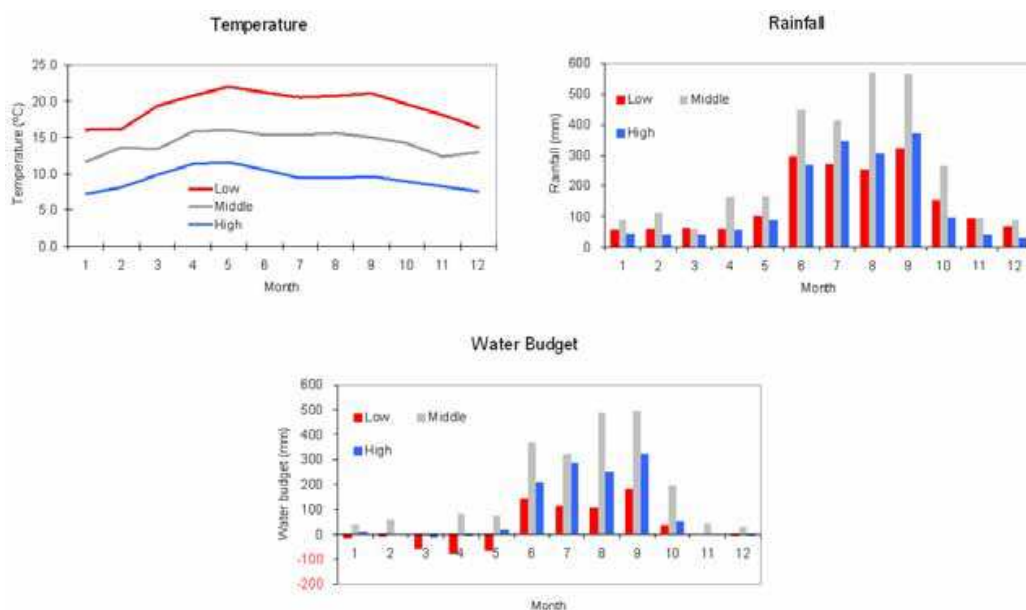

Fig. 2. Climatic variables in the study area; mean monthly temperature, mean monthly rainfall and monthly water budget. (Data from weather stations 30-236 Tembladeras and 30-024 Coatepec. The low and high portion climatic data from García, (2004). Middle portion data from NSF-UVA Cortadura station Holwerda et al. (2010).
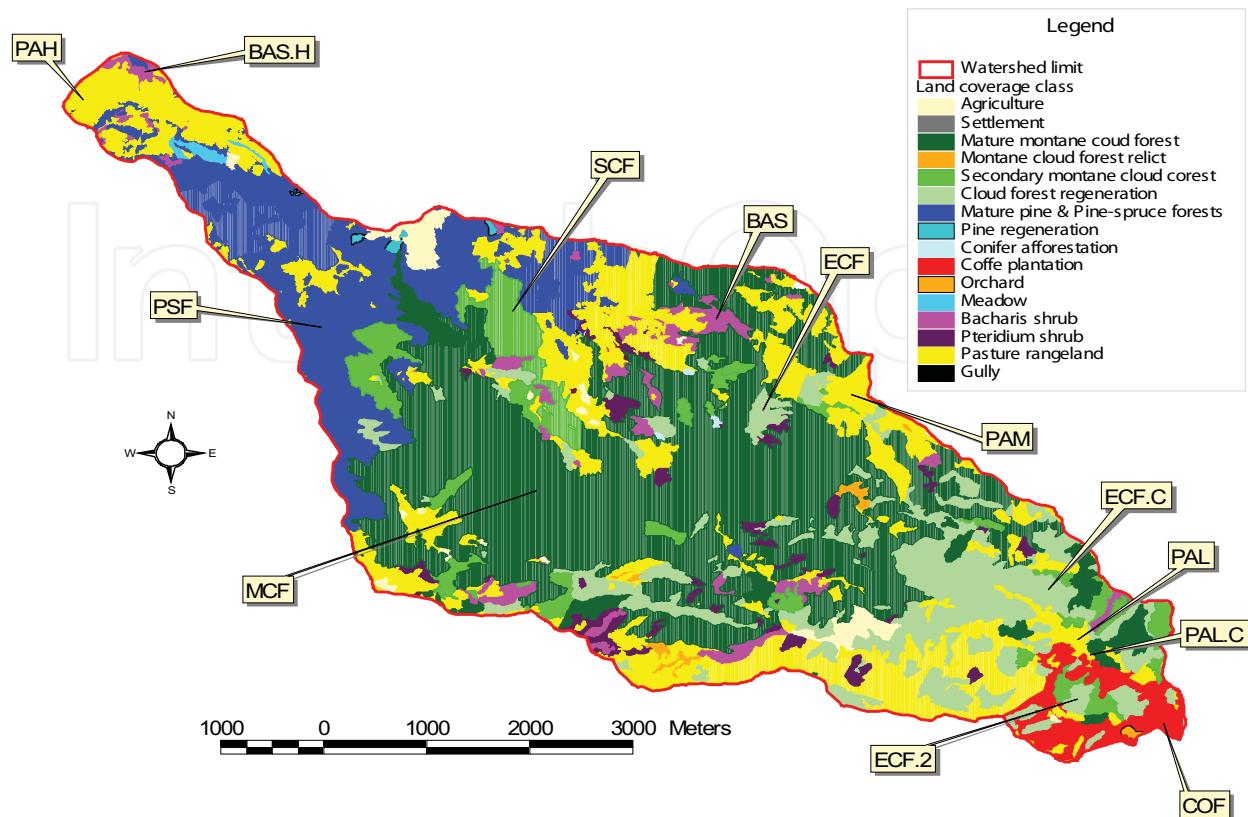
Fig. 3. Land use coverage map of Gavilanes watershed for 2009 (Gómez-Tagle and Geissert, unpublished map).

the high portion has only three (March-April and December). The budget figures for the middle portion indicate only one month of deficit (March) (Figure 2). All water budget estimates are positive indicating total annual surplus in the whole watershed.

2.2 Sampling procedures

Sampling took place between October 2008 and November 2009, following a stratified model design that included each major portion of the watershed (high, middle, low) and the land use/coverage class (Figure 1). A summary of sites and measurements is presented in Table 1.

Unsaturated infiltration measurements were conducted in the field using INDI-INECOL tension infiltrometers based on the design of Špongrová (Kechavarzi, et al., 2009; Špongrová, 2006; Špongrová, et al., 2009) with 10.0 cm diameter and an effective contact surface of 0.00785 m² (Figure 4). Commercially available grounded sand (92% sand) was used as contact material. Water height in the infiltrometers was recorded every two minutes with a Campbell Scientific CR1000 datalogger and several pre-calibrated Motorola Free-Scale MPX2010DP differential pressure transducers with 0 to 10 kPa pressure range (Motorola, 2002). Recording was carried out until unsaturated flow reached a steady state condition which usually occurred before two hours of elapsed time at a particular tension.

Land use & coverage	Watershed portion	Key	Actual Payment	Altitude (masl)	Observations	Infiltration measurements
Mature cloud forest	Middle	MCF	Yes	2100-2160	-	16
Secondary cloud forest	Middle	SCF	Yes	2090-2150	-	16
Early regeneration cloud forest	Middle	ECF	Yes	2200-2240	-	30
	Low	ECF2		1360-1420	-	30
	Low	ECF.C		2140-2180	From coffee plantation	30
Coffee plantation	Low	COF	No	1350-1400	Shade coffee plantation	30
Shrub	Middle	BAS	No	2280-2300	*Bacharis spp.* y *Pteridium sp.* Shrub	30
	High	BAS.H	No	2940-2950	*Bacharis spp.- Muhlembergia sp.* Shrub	12
Pasture	Middle	PAM	No	2050-2120	Degraded pasture	17
	Low	PAL	No	1370-1420	Degraded pasture	30
	Low	PAL.C	No	1360-1390	Well managed pasture	10
	High	PAH	No	2930-2940	Well managed pasture	18
Pine-spruce forest	High	PSF	Yes	2870-2890	Pine-spruce (pine-*Abies religiosa*) forest	34

Table 1. Unsaturated infiltration sampling measurements for each land use/coverage class and watershed portion.

The exponential Gardner equation (Equation 1) describes the relationship between tension and hydraulic conductivity, $K(h)$ is the unsaturated conductivity, K_s is the saturated conductivity, a is the inverse of capillary length in the soil and h corresponds to tension (Gardner, 1958). Using this model it is possible to estimate K_s using tension infiltrometer data.

The Logsdon and Jaynes (1993) non-linear simultaneous solution (Equation 2) allows the estimation of K_s and a parameter using the infiltrometer radius r, the π constant (3.1416), $q(h)$ or steady state infiltration flow for the applied tension h. This approach requires the
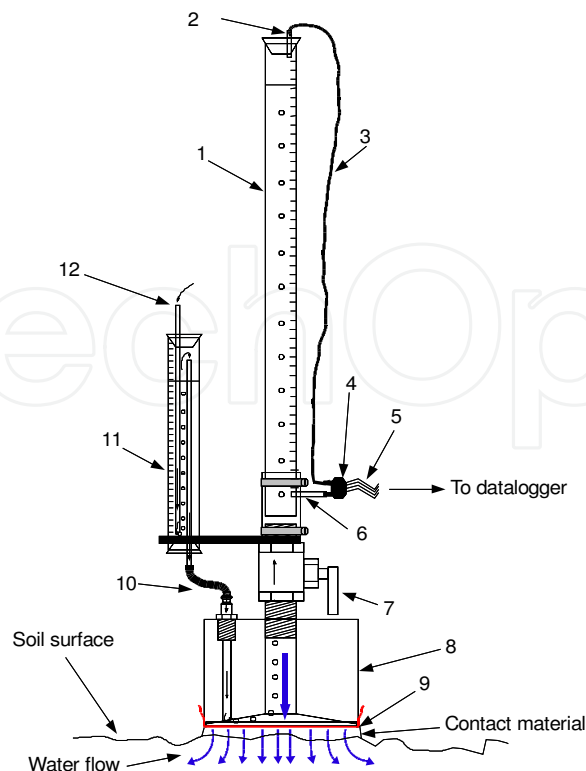
Fig. 4. Schematics of the INDI-INECOL tension infiltrometer used in this study. Main reservoir (1), top rubber lid with tubing connection (2), pressure transducer tubing to air chamber in main reservoir (3), MPX2010DP differential pressure transducer (4), four line cable to datalogger (5), reservoir to transducer tubing connection (6), two way valve (7), machined aluminum base (8), 15 μm nylon mesh (9), mariotte to base flexible connection (10), mariotte reservoir (11), air inlet (12). Arrows depict air and water flow in and out the infiltrometer.

measurement of steady state flow rates at two or more tensions (*h*). In our case we used three tensions applied in a decreasing order (-0.882, -0.343 and -0.049 kPa).

$$K(h) = K_s \cdot e^{\alpha h} \tag{1}$$

$$q(h) = [1 + (4 / \pi r \cdot \alpha)] \cdot K_s e^{\alpha h} \tag{2}$$

The method proposed by Watson and Luxmoore (1986) allows the estimation of number of pores of the effective conductive porosity, this is the interconnected porosity that actually conducts water at certain tension. Number of pores, percentage of pore space and proportion of infiltration flow was estimated for three apparent diameter intervals of effective pores ≥ 1.0 mm (-0.0145 kPa), between 0.3 and 1.0 mm (-0.049 to -0.0145 kPa), and between 0.01 and 0.3 mm (-1.47 to -0.049 kPa). The largest apparent diameter interval corresponds to macropores while the other size classes represent mesopores. In order to compare pore size contribution to total infiltration flow, proportion of infiltration flow in percentage was determined from *K(h)* defined by the Gardner equation (Equation 1) (Gardner, 1958), and applying Equation 3, where FP_d is the flow proportion for certain diameter interval *d*, K_d is the unsaturated hydraulic conductivity for the pore diameter interval and K_s is the saturated hydraulic conductivity. The proportion of infiltration flow

was calculated for the apparent pore diameter categories listed above but also for < 0.01 mm
(> -1.47 kPa) micropores according to Watson and Luxmoore (1986).

$$FP_d = (K_d / K_s) \cdot 100 \qquad (3)$$

In addition to the unsaturated infiltration measurements in the field, soil samples were
obtained by carefully removing the contact material from the soil surface. Bulk density was
determined by the core method (cylinder 5.5 cm diameter and 4.0 cm length) (Miller &
Donahue, 1990). Particle size distribution was performed by the Bouyoucos Hydrometer
Method (Gee & Or, 2002), organic carbon by means of dry combustion on a CN Truspec
LECO analyzer and final moisture content by gravimetry. Coarse sand and fine sand
fractions were separated by sieving.

2.3 Data analysis

Data analysis included Shapiro-Wilk normality tests, Pearson´s correlation analysis between
physicochemical properties and target hydrophysical variables (K_s, α), analysis of variance
(ANOVA) and mean comparison test applying the Tukey Honest Significant Differences
(Bates, 2006).

Given the hierarchical structure of sampling in which data were collected at different spatial
scales, a mixed-effect model was conducted in order to elucidate if the current payment
scheme classes depicted statistical differences in K_s. This model was constructed as follows:
saturated conductivity was log transformed (Log K_s) and analyzed as the response variable.
A categorical variable named Payment, with two levels (yes and no) was generated and
associated with each land use type depending on the possibility that a determinate land use
was considered within the payments for hydrological ecosystem services or not. This
follows the municipality ranking for ecosystem services payment scheme, namely forested
and not forested, practically defined as the presence or absence of trees. This scheme does
not differentiate between cover classes like mature cloud forest and pine plantations which
may differ substantially in K_s and infiltration. The model was analyzed using lmer function
released by Bates (2006) and specified according to Crawley (2007). Thus random effects
were listed from largest to smallest spatial scale as follows: zone/payment/land uses/site.

All data analysis were performed using standard mathematical and statistical methods
within the R language and environment for statistical computing (R version 2.10.1)
(R_Development_Core_Team, 2004) and the packages for R *lmer4* (Bates & Maechler, 2010)
and *lattice* (Sarkar, 2008).

3. Results

3.1 Hydraulic conductivity (K_s)

Two hundred and sixty five unsaturated infiltration measurements were successfully
conducted and processed. K_s values obtained with the Logsdon and Jaynes method (1993)
ranged from 2.8×10^{-7} to 2.42×10^{-5} m s^{-1}, while the α parameter was between 0.1 and 7.96 m^{-1}.
The overall K_s data set did not exhibit a normal distribution either directly or through log-
transformation. However, Shapiro-Wilk test of normality on original K_s and log-transformed
K_s of watershed portions confirmed the log-normal distribution at this scale (Table 2). At the
individual land use/cover scale the log-normal distribution was confirmed for eleven out of
thirteen classes (Table 3). This concurs with earlier published results concerning the
probabilistic distribution of K_s and other flow related soil properties (Esteves, et al., 2005;
McIntyre & Tanner, 1959; Rogowski, 1972; Russo & Bresler, 1981; Soil Survey Staff, 1993).

Original K_s data (m·s⁻¹)							
Watershed Zone	min	median	mean	max	sd	W	p Value	Normality
High	2.49E-06	7.24E-06	7.84E-06	1.87E-05	3.42E-06	0.916	0.001	No
Low	2.80E-07	4.49E-06	5.40E-06	2.42E-05	4.68E-06	0.842	<0.001	No
Middle	8.33E-07	3.11E-06	3.98E-06	1.68E-05	2.61E-06	0.846	<0.001	No
Log transformed K_s (ln m·s⁻¹)							
Watershed Zone	min	median	mean	max	sd	W	p Value	Normality
High	-1.29E+01	-1.18E+01	-1.18E+01	-1.09E+01	3.42E-06	0.991	0.939	Yes
Low	-1.51E+01	-1.23E+01	-1.25E+01	-1.06E+01	4.68E-06	0.982	0.124	Yes
Middle	-1.40E+01	-1.27E+01	-1.26E+01	-1.10E+01	2.61E-06	0.992	0.882	Yes

Table 2. Descriptive statistics and normality (Shapiro-Wilk) analysis for K_s of different watershed portions (α=0.95).

The Tukey HSD test revealed the existence of five groups for natural log- transformed hydraulic conductivity values according to land use/cover classes (a to e in Figure 5A) and two groups according to watershed portion (Figure 5B). In Figure 5A the low case letters indicate membership to the groups. Because of the in-class dispersion many land use/cover classes belong to different groups, except for four classes that belong only to group d. Red lines indicate K_s threshold values that separate low, intermediate and high K_s values within the data set, while blue dashed lines indicate Soil Survey Staff (1993) class limits; low (1 x 10⁻⁷ m·s⁻¹), moderately low (1 x 10⁻⁶ m·s⁻¹) and moderately high (1 x 10⁻⁵ m·s⁻¹).
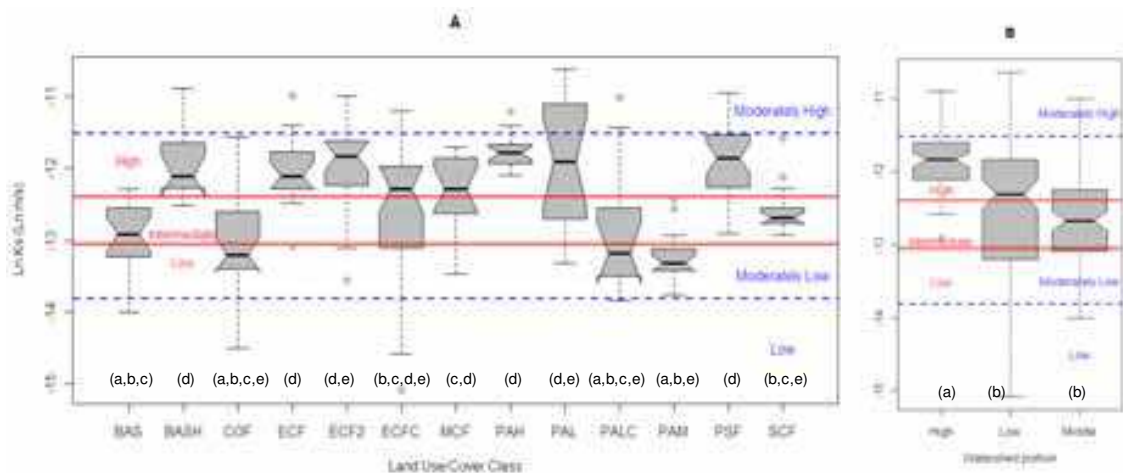

Fig. 5. Boxplots of log transformed K_s for all land use/coverage classes (A) and watershed portions (B). Land use/coverage classes and watershed portions with same letters are no different from each other, different letters indicate significant difference α=0.95 (TukeyHSD test). Red lines represent the threshold values for K_s values for different land uses/cover within the dataset, blue dashed lines correspond to K_s class thresholds according to Soil Survey Staff (1993). Bacharis-Pteridium shrub middle (BAS), Bacharis shrub high (BASH), coffee plantation low (COF), early cloud forest regeneration middle (ECF), early cloud forest regeneration low (ECF2), early cloud forest regeneration from coffee plantation low (ECFC), mature cloud forest middle (MCF), pasture high (PAH), pasture low (PAL), well managed pasture low (PALC), pasture middle (PAM), pine-spruce forest (PSF), secondary cloud forest (SCF).

Land use/cover	Original K_s data (m·s⁻¹)							
	min	median	mean	max	sd	W	p Value	Normality
BAS	8.3E-07	2.5E-06	2.7E-06	4.6E-06	1.2E-06	0.944	0.2797	Yes
BASH	3.7E-06	5.5E-06	7.4E-06	1.9E-05	4.3E-06	0.777	0.0052	No
COF	5.0E-07	1.9E-06	2.7E-06	9.5E-06	2.2E-06	0.795	0.00007	No
ECF	2.1E-06	5.5E-06	6.5E-06	1.7E-05	3.2E-06	0.852	0.0057	No
ECF2	1.3E-06	7.2E-06	7.7E-06	1.7E-05	4.0E-06	0.942	0.1151	Yes
ECFC	2.8E-07	4.6E-06	4.7E-06	1.4E-05	3.1E-06	0.94	0.1124	Yes
MCF	1.4E-06	4.7E-06	5.0E-06	8.2E-06	2.1E-06	0.942	0.3699	Yes
PAH	5.5E-06	7.6E-06	8.0E-06	1.4E-05	2.0E-06	0.889	0.03694	No
PAL	1.6E-06	6.7E-06	9.1E-06	2.4E-05	7.2E-06	0.878	0.01594	No
PALC	9.8E-07	1.9E-06	3.9E-06	1.7E-05	4.7E-06	0.582	0.00003	No
PAM	1.1E-06	1.6E-06	1.9E-06	4.0E-06	7.8E-07	0.795	0.00176	No
PSF	2.5E-06	7.1E-06	7.9E-06	1.8E-05	3.8E-06	0.934	0.06263	Yes
SCF	2.4E-06	3.1E-06	3.6E-06	9.4E-06	1.7E-06	0.614	0.00002	No

Land use/cover	Log transformed K_s (ln m·s⁻¹)							
	min	median	mean	max	sd	W	p Value	Normality
BAS	-14.0	-12.9	-12.9	-12.3	0.489	0.952	0.3899	Yes
BASH	-12.5	-12.1	-11.9	-10.9	0.470	0.911	0.2201	Yes
COF	-14.5	-13.2	-13.1	-11.6	0.721	0.964	0.4153	Yes
ECF	-13.1	-12.1	-12.0	-11.0	0.453	0.974	0.8385	Yes
ECF2	-13.6	-11.8	-11.9	-11.0	0.602	0.963	0.3873	Yes
ECFC	-15.1	-12.3	-12.6	-11.2	0.894	0.926	0.0488	No
MCF	-13.5	-12.3	-12.3	-11.7	0.497	0.929	0.2351	Yes
PAH	-12.1	-11.8	-11.8	-11.2	0.231	0.953	0.4752	Yes
PAL	-13.3	-11.9	-11.9	-10.6	0.845	0.952	0.4032	Yes
PALC	-13.8	-13.2	-12.9	-11.0	0.897	0.85	0.0573	Yes
PAM	-13.8	-13.3	-13.2	-12.4	0.346	0.92	0.1468	Yes
PSF	-12.9	-11.9	-11.9	-11.0	0.487	0.98	0.8347	Yes
SCF	-12.9	-12.7	-12.6	-11.6	0.3	0.753	0.0006	No

Table 3. K_s descriptive statistics and normality analysis; *Bacharis-Pteridium* shrub middle
(BAS), *Bacharis* shrub high (BASH), coffee plantation low (COF), early cloud forest
regeneration middle (ECF), early cloud forest regeneration low (ECF2), early cloud forest
regeneration (ECF), coffee plantation low (ECFC), mature cloud forest middle (MCF),
pasture high (PAH), pasture low (PAL), well managed pasture low (PALC), pasture middle
(PAM), pine-spruce forest (PSF), secondary cloud forest (SCF), (α=0.95).

According to this land uses/coverages COF, PALC and PAM have low K_s, while BAS, ECFC
and SCF have intermediate K_s and BASH, ECF, ECF2, MCF, PAH, PAL and PSF have high
K_s.

In the case of watershed portion, Figure 5B shows a larger variation in K_s in the low portion
of the watershed than in the two other portions. The K_s in the high portion of the watershed
is statistically different to the middle and lower portions, which are not statistically different
from each other.

3.2 Effective porosity and infiltration flow proportions

Total porosity ranged from 54.5 to 91.9 %, descriptive overall statistics for total porosity and
effective pore numbers are shown in Table 4. The span between maximum and minimum

was two orders of magnitude ($\geq$ 1.0 mm apparent pore diameter) and three orders of magnitude for the other two classes. Total porosity did not correlate with the number of effective pores for any of the three diameter classes analyzed.

Total porosity	Percentage				
	min	median	mean	max	sd
	54.47	74.09	74.47	91.91	9.50
Apparent pore diameter (mm)	Number of effective pores per m²				
$\geq$ 1.0	1.28E+00	7.39E+01	1.26E+02	6.83E+02	1.82E+02
0.3 - 1.0	1.58E+02	9.12E+03	1.55E+04	8.43E+04	2.24E+04
0.01 - 0.3	1.28E+04	7.39E+05	1.26E+06	6.83E+06	1.82E+06

Table 4. Overall total porosity statistics and number of effective pores for three apparent diameter classes.

Test for normality (Shapiro-Wilk) revealed that for the three apparent diameter pore size intervals nine out of thirteen land use/cover classes had log-normal distribution.

Flow proportion results indicated that, in general, macropores ($\geq$ 1.0 mm apparent diameter) contributed about 3% (0.15 - 11%) to total infiltration flow (Table 5). Large mesopores (0.3 - 1.0 mm apparent diameter) contributed nearly in 7% (0.3 - 21%) of flow, while small size mesopores (0.01 – 0.3 mm apparent diameter) accounted for nearly 74% (13 - 86%) of total infiltration flow. Micropore (< 0.01 mm apparent diameter) contribution was extremely variable and ranged between being insignificant (0.003%) and contributing almost to all of the infiltration flow (99.27%) in specific cases, while on average, micropores contribute up to 40% of the total infiltration flow. These results contrasted with those of Watson and Luxmoore (1986) in forested soils where macropore flow accounted nearly 73% of the infiltration flow. In this specific setting texture and soil particle distribution related mesoporosity have a major role in infiltration than structure related macropores, this will be discussed and analyzed further in the text.

Apparent pore diameter (mm)	Flow proportion (%)				
	min	median	mean	max	sd
$\geq$ 1.0	0.147	2.656	3.093	11.050	2.051
0.3 - 1.0	0.342	5.921	6.689	21.250	4.167
0.01 - 0.3	13.190	81.490	74.940	85.980	15.311
< 0.01	0.003	25.840	39.570	99.270	36.042

Table 5. Infiltration flow proportion statistics of four apparent pore diameter sizes.

Flow proportions in all three watershed portions were highly variable. Infiltration flow contribution from macropore ($\geq$ 1.0 mm, Figure 6A) and large mesopores size (0.3 - 1.0 mm, Figure 6B) in the low portion of the watershed was significantly lower than in the Middle and High portions. The contribution of small mesopores flow contribution (0.01 - 0.3 mm, Figure 6C) is significantly higher for the middle portion of the watershed.

Figure 6 also shows that the infiltration flow through micropores, was statistically different for the three portions of the watershed even when it had very wide ranges (Figure 6D). The land use/cover level reflects the flow trends mentioned above in which the largest flow proportion occurred through small size mesopores (0.01 - 0.3 mm). For certain land
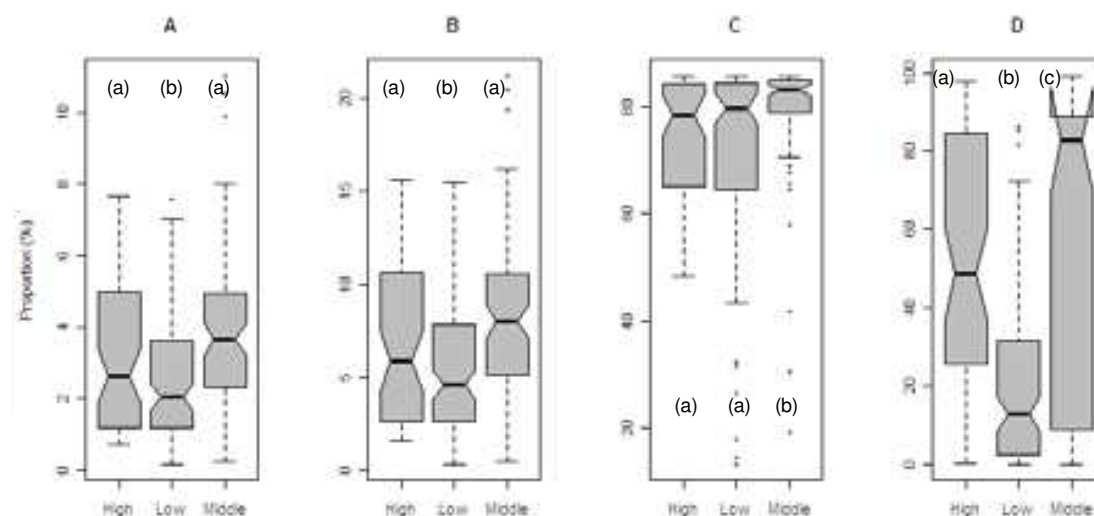
Fig. 6. Boxplots of flow proportion for four apparent pore diameter sizes at the watershed portion level; apparent pore diameter ≥ 1.0 mm (A), 0.3 - 1.0 mm (B), 0.01 - 0.3 mm (C) and < 0.01 mm (D). Different low case letters indicate Tukey HSD statistical difference (α=0.95).

use/cover classes (PAL) the infiltration flow proportion departs from the general mean (≈75%) and goes as low as 61.1% while mean micropore flow proportion increases up to 34.3%. In other land use/cover classes e.g. PSF, the 0.3 - 1.0 mm pore flow proportion increases near 10% and the micropore flow proportion decreases under 10% indicating a shift in infiltration flow to larger mesopore use and lower micropore use.

3.3 Physicochemical soil properties

Two hundred and thirty six samples were analyzed in the laboratory for nine physicochemical soil properties. Overall descriptive statistics of these soil properties are presented in Table 6.

Soil Property	min	median	mean	max	sd
Bulk density (g/cm³)	0.1	0.5	0.5	1.1	0.09
Final moisture content (% wt)	21.4	52.9	67.3	182.2	42.0
Total porosity (%)	54.47	74.09	74.47	91.91	9.50
Clay %	4.5	26.9	29.7	54.4	5.24
Silt %	12.0	36.0	36.5	71.4	7.17
Sand %	9.6	30.3	33.8	68.4	9.19
Fine Sand %	2.5	14.8	14.5	50.5	4.78
Coarse Sand%	0.4	19.9	19.3	46.4	7.30
Organic Carbon%	1.3	16.0	15.2	44.8	3.40

Table 6. Descriptive statistics for the analyzed soil properties.

Final moisture content varied from 21.4 to 182.23%; soils in the low watershed soils had overall lower final water content, while the high and middle watershed soils had larger moisture contents (not shown). Bulk density was low, concurring with previously reported values for volcanic Andisols in the area (0.2 - 1.3 g/cm³; (Meza-Pérez & Geissert-Kientz, 2006) and elsewhere (Alvarado & Forsythe, 2005; Porta, et al., 1999). The lower portion of the watershed has the highest values of bulk density, while the higher and middle portions have lower values (Figure 7A).
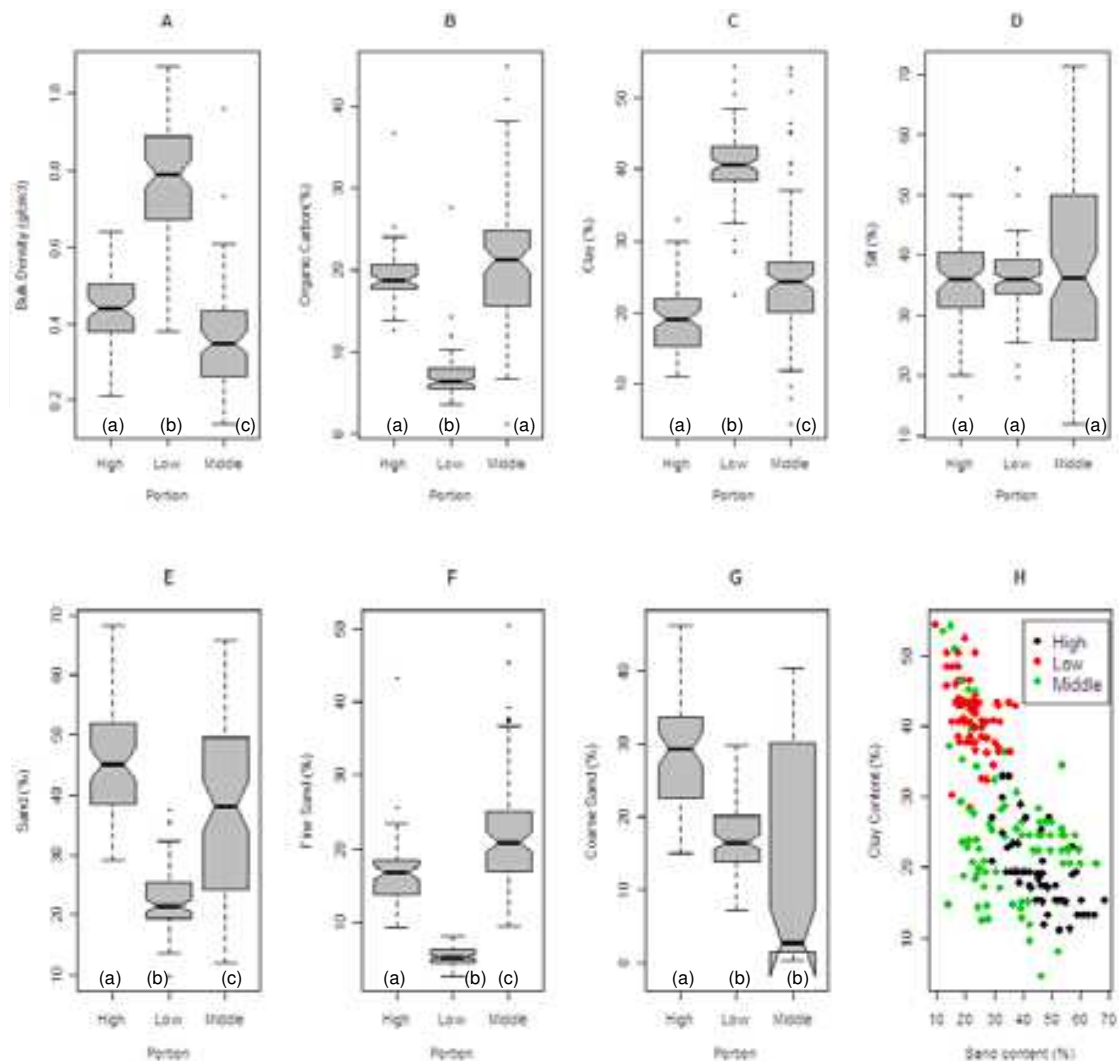
Fig. 7. Boxplot of soil properties by portion of the watershed: Bulk density (A), organic carbon (B), clay content (C), silt content (D), sand content (E), fine (F) and coarse sand content (G), overall sand *vs.* clay relationship (H). Different lower case letters indicate statistical difference between portions of the watershed (Tukey HSD), α=0.95.

Total porosity ranged between 54.5% and 94.0%. Andisols from areas nearby are reported to have porosities between 44 and 91% (Meza-Pérez & Geissert-Kientz, 2006). A wide range was found in the organic carbon content throughout the watershed (between 1.3 and 44.8%, Table 6) although a trend was found relating the carbon content with the portion of the watershed. The lower portion had significant lower values than the middle and higher portions, while the middle portion had the largest variation (Figure 7B). Meza-Pérez and Geissert-Kientz (2006) reported organic carbon contents between 0.4 and 8.0% in forested and agricultural surface soil from an area near the higher portion of the watershed, while Marín-Castro (2010) reported mean contents between 22 and 49% in forest (Mature and secondary cloud forest) and pasture land from the middle portion of the watershed.

Since silt content is mostly constant, clay and sand contents show an opposite trend (Figure 7H). The lower portion of the watershed had significantly higher clay contents and lower sand contents, while the high and middle portions resemble one another, although clay is significantly higher and sand lower in the middle than in the higher portion (Figure 7C, E). Thus for these two particle sizes every portion of the watershed was different.

There were no significant differences in silt content in the three portions of the watershed (Figure 7D). Fine sand content (Figure 7F) shows an opposite trend to that of clay (Figure 7H) and resembles the sand content (Figure 7E). These boxplots indicate that the middle portion of the watershed had the largest variation.

Nine of the 12 USDA soil texture classes (Soil Survey Staff, 1993) are present in surface soils of the study area. The most frequent classes were Clay (27.7 % of the samples), followed by Loam (26.9 %), Clay Loam (13.4 %), Sandy Clay Loam (10.1%) and Silty Loam (9.7%). The other five classes represented less than six percent each (Figure 8A). Sandy Clay was the only texture class with one sample. Sand, Loamy Sand and Silt texture classes are not present in surface soils.
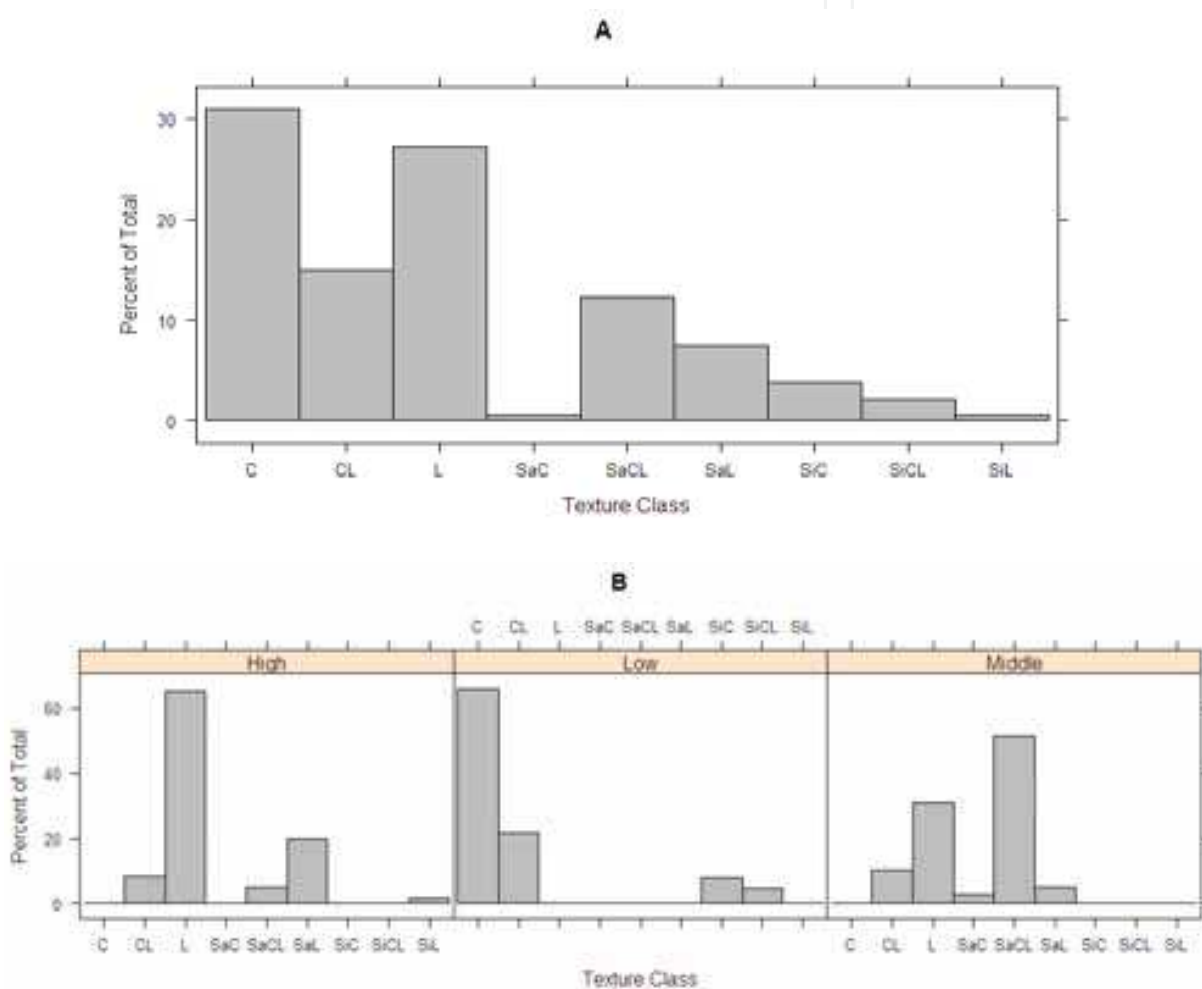
Fig. 8. Texture classes. Overall sample percentage by texture class (A), texture class by watershed portion (B), see Figure 9 for texture key.

In terms of texture class, the study area is quite diverse, because it has nine out of twelve classes. The texture differed depending on the portion of the watershed. The higher portion is dominated by Loam, while the lower is dominated by Clay and Clay Loam. The middle portion is dominated by Sand Clay Loam and Loam textures (Figure 8B). The middle portion of the watershed had the greatest number of texture classes (8 of 9) is the middle portion with eight out of the nine classes identified in the study area (Figure 8B).

Further, land use/covers are not homogeneous regarding texture. Most of the land use/cover classes include three or four texture classes (Figure 9).
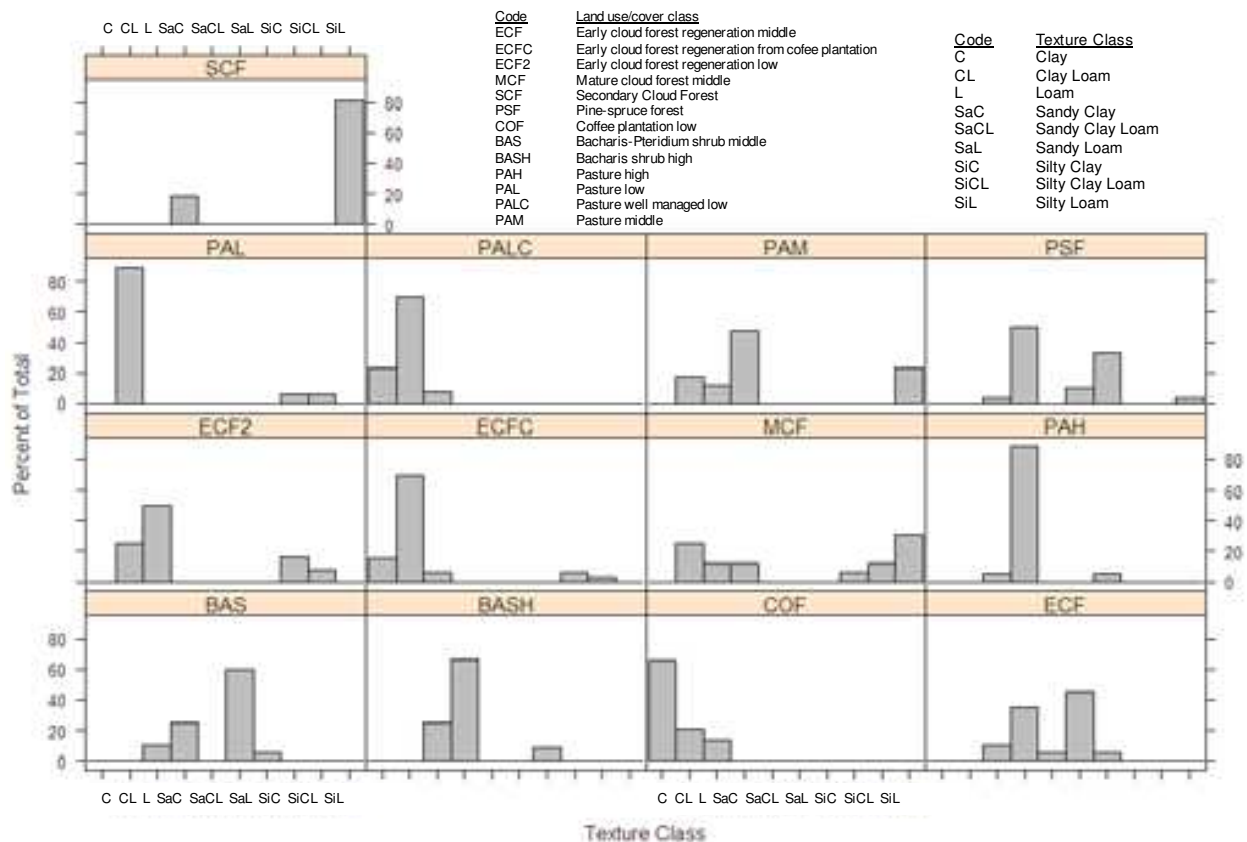

Fig. 9. Texture classes by land use/cover, texture classes follow the watershed portion relationship. There is no cause-effect relationship between land use/cover and texture.

3.4 K_s, porosity and flow proportion relationships with soil properties

At the watershed level correlation analysis with the whole dataset (Pearson´s product-moment correlation) indicated that Log K_s had a significant negative overall correlation with clay content, as well as a minor positive correlation with coarse sand fraction. The highest significant correlation score for Log K_s occurred with Clay/Silt ratio (Table 7). None of the other soil properties showed a significant correlation.

The alpha parameter (α) of the Gardner exponential model (Gardner, 1958) that expresses the inverse of the average capillary length within the soil matrix had a significantly negative relationship with bulk density (t= -5.738, p<0.001, r= -0.3513), clay content (t= -2.837, p=0.005, r= -0.1816) and coarse-sand/fine-sand ratio (t= -4.646, p<0.001, r= -0.2895). This parameter was also positively correlated with organic carbon content (t= 5.061, p<0.001, r= 0.3129), sand content (t= 2.634, p= 0.009, r= 0.1690) and fine sand content (t= 5.08, p<0.001, r= 0.3139). Increasing values in bulk density are related with surface soil compaction or heavier textures, and therefore the reduction in α.

A negative correlation was also found between α and clay and coarse-sand/fine/sand ratios. Low bulk density values are related to loose granular and microgranular structured soils with high α values.

Similar to the α parameter, the number of macropores per square meter were positively correlated with organic carbon content, sand and fine-sand content and negatively with bulk density, clay content and coarse-sand/fine-sand and clay/silt ratios. Bulk density scored highest of all tested physicochemical properties (t= -3.9034, p<0.001, r= -0.2472). The same trends were found for the number of pores in the other two diameter intervals studied. From the analyzed physicochemical properties, bulk density had always the top scores.

Flow proportions for micropores (<0.01 mm in diameter) had positive significant correlations with bulk density, clay content and coarse-sand/fine-sand ratio and negative correlations with organic carbon, sand, and fine-sand fraction.

Watershed portion	Variable	r	p-value
High	Organic carbon%	-0.293	0.023
Low	Clay %	-0.238	0.025
Low	Organic carbon%	-0.273	0.010
Low	Coarse sand%	-0.285	0.007
Low	Fine sand %	-0.290	0.006
Middle	Bulk Density (g/cm³)	-0.393	< 0.001

Table 7. Significant correlations between Log K_s and physicochemical properties at the watershed portion level.

While correlations were generally low in the whole watershed, within watershed portions correlations suggest distinct relationships between K_s and physicochemical variables (Table 7). At this scale, the tightest correlation was found for bulk density and K_s in the middle portion.

During the field work it was observed that in the middle portion, all land uses except of BAS and PAM presented high root density in the first fifteen centimeters. Compacted surface soil by cattle trampling and overgrazing was observed at PAM sites, nevetheless bulk density values for this site were rather lower than expected (mean 0.47 g/cm³) and not statistically different from those in the SCF (mean 0.45 g/cm³). However bulk density values were different from those in the MCF (mean 0.36 g/cm³).

Significant correlations between Log K_s and specific physicochemical variables at the land use/cover scale occurred only in five out of the thirteen land uses analyzed (Table 8). Bulk density correlated with Log K_s in PSF, ECFC and BASH, the first two showed positive relationships while the latter had a negative relationship. Clay percentage was negatively correlated at the ECF site. Organic carbon content was negatively correlated with Log K_s at PSF and ECFC sites. Silt percentage showed a positive correlation at the ECFC and PAM sites. At the land use/cover scale only a few land use/cover classes showed significant correlations. For the ECFC class six out of the eight analyzed physicochemical variables had significant correlations with Log K_s.

Correlations indicate different controls across scales. For some physicochemical properties certain land use/cover class may influence the relationship at the watershed portion scale, e.g. bulk density in PSF class (r= -0.498) influences the overall correlation for the high portion of the watershed (r= -0.293) (Figure 10B, C).

Land use/cover class	Watershed Portion	Variable	r	p-value
BASH	High	Bulk Density (g/cm³)	-0.838	<0.001
ECF	Middle	Clay (%)	-0.492	0.028
ECFC	Low	Bulk Density (g/cm³)	0.442	0.019
ECFC	Low	Coarse Sand%	-0.630	<0.001
ECFC	Low	Fine Sand%	-0.699	<0.001
ECFC	Low	Organic Carbon%	-0.697	<0.001
ECFC	Low	Sand %	-0.681	<0.001
ECFC	Low	Silt %	0.740	<0.001
PAM	Middle	Silt %	0.495	0.043
PSF	High	Bulk Density (g/cm³)	0.511	0.004
PSF	High	Organic Carbon%	-0.498	0.005

Table 8. Significant correlations between Log K_s and physicochemical properties at the land use/cover level. *Bacharis* shrub (BASH), early cloud forest regeneration (ECF), early cloud forest regeneration from coffee plantation (ECFC), pasture (PAM) and pine-spruce forest (PSF).
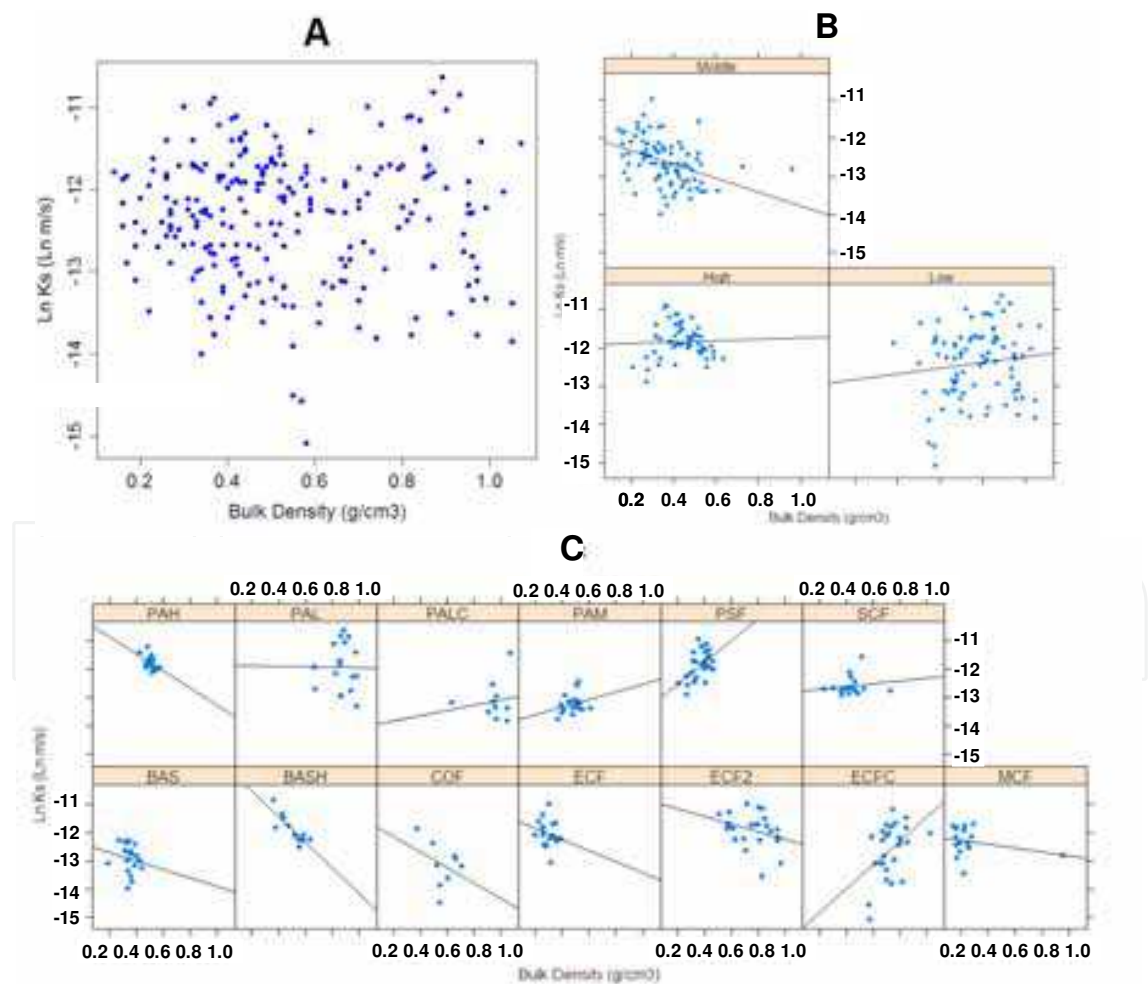
Fig. 10. Correlation between bulk density and Log K_s at three scales levels, whole watershed (A), watershed portion (B) and land use/coverage class (C).

3.5 Mixed-effect model

A large percentage of the variation of conductivity measurements was not explained by the factors tested in the mixed-effect model (residual = 40%, in Table 9). Despite the above, 19% of the variation was observed for land uses; 18 % between sites; 16%within watershed portions and only 4 % between payments (Table 9). Firstly these results indicate that there was not significant variation in conductivity values between those areas potentially considered within payments programs and those that are not; secondly, that land use did have an important effect on the overall variance in the data. According to this, Akaike's information criterion and p values showed that most of variation in K_s could be explained by land use and site (Table 10).

Groups	Name	Variance	Variance components (%)	Std.Dev.
Site:(LUC:(Payments:Portion)	(Intercept)	0.125908	18.10	0.35484
LUC:(Payments:Portion)	(Intercept)	0.138129	19.86	0.37166
Payments:Portion	(Intercept)	0.032249	4.635	0.17958
Portion	(Intercept)	0.114736	16.50	0.33873
Residual		0.284224	40.88	0.53313
Total		0.695246	100	

Table 9. Summary of random effects for the full model "A" (Log K_s ~1+(1 | Portion/Payments/LUC/Site). LUC= Land use/cover. Number of obs: 265, groups: LUC:(Payments: PortionZ), 14; Payments: Portion, 6; Portion,3: AIC= 513.4; BIC= 534.9; logLik=-250.7; deviance=500.4; REMLdev= 501.4.

Models	Df	AIC	BIC	logLik	Chisq	Chi DF	Pr(>Chisq)
modelB	5	510.61	528.51	-250.31			
modelA	6	512.13	533.61	-250.06	0.4822	1	0.4874
modelC	4	509.01	523.33	-250.51			
modelB	5	510.61	528.51	-250.31	0.3999	1	0.5271
modelD	3	520.94	531.68	-257.47			
modelC	4	509.01	523.33	-250.51	13.924	1	0.0001904 ***

Model A (full moldel) = (Log K_s b~1+(1 | Portion/Payments*/LUC/Site));
Model B = (Log K_s b~1+(1 | newzone*/LUC/Site)):
Model C= (Log K_s b~1+(1 | newpayment*/Site)) and
Model D = (Log K_s b~1+(1 | newLUC*))
*Factors were re-coded according to Crawley (2007).

Table 10. Summary of Model simplification.

4. Discussion

4.1 Hydraulic conductivity

In this study, we found an important variation in K_s within different portions of the watershed. The low and middle-elevation portions were not statistically different from each

other while the high portion had higher K_s. We found that differences in K_s and effective porosity are affected by soil properties, pedogenesis and land management.

Our research questions addressed the relationship between land use/cover and K_s. At this level, K_s values ranged between low and moderately high according to the Soil Survey Staff infiltration classes (1993). The local classification derived from this study separates the obtained values into three classes: low, intermediate and high. This classification used key threshold values at 2.15 x 10-6 m · s-1 and 4.12 x 10-6 m · s-1.An interesting result was that at this level an increase in plant cover was not related to an increase in K_s values in all cases. The increase in plant cover after anthropogenic disturbance has been reported to be related to an increase in K_s values in certain environments (Li & Shao, 2006; Ziegler, et al., 2004). In other environments, it seems to be an age threshold for plant cover recovery, under this threshold there is a clear relationship between plant cover recovery and K_s values, but over it there are no differences in K_s values between different ages of recovery and plant cover (Zimmermann, 2007; Zimmermann, et al., 2006).

The widely reported negative impact of land use change from forested to pasture lands on K_s and other hydrophysical variables (e.g. Singleton, et al., 2000; Tobón, et al., 2004; Zimmermann, et al., 2006) was not completely verified by our results. In our case the lowest K_s values corresponded to a pasture site (PAM) but there were also pasture sites with high K_s values (e.g. PAH, PALC, PAL). Moreover, the highest variation in K_s for a specific land use/cover class occurred in another pasture site (PAL) (Table 2; Figure 5A). The well-managed pasture site (PALC) had both high and low K_s values while the poorly managed pasture site (PAL) had some of the highest K_s values of the study. It seems that pasture land use/cover classes do not reflect differences in K_s or effective porosity behaviour. Some ideas about this facts are mentioned in the following lines.

Field observations helped to elucidate the pattern of K_s in different pasture sites. While the PAM, PAL and PALC sites occurred in very steep slopes (> 40º), PAH occurred in gentle slope terrain (3-8 º) in the high portion of the watershed. Also PAL, PAM and PALC sites were heavily grazed by cattle (cows), horses, donkeys and occasionally goats and sheep. In the PAH site grazing was done mainly by young animals, calves mostly. In the earlier pasture sites cattle was aimed to local dairy production and in the latter to commercial ranching of calves. This implies significant differences in management and also in cattle´s effect on hydrophysical properties as K_s. In gentle slope small and young animals have less impact than larger animals on steep slopes.

Further, soil particle distribution is also crucial in the explanation of these differences in K_s since coarser textures have larger pores and therefore higher K_s. The high portion of the watershed with higher K_s has also lower clay content (Figure 7C) and larger sand and coarse sand contents (Figure 7E, G), while the low portion of the watershed has higher clay and lower sand and fine sand contents than the other two portions (Figure 7C, E, F). The middle portion has characteristics of both the lower and higher portions e.g. (sand and clay content; Figure 7H). The difference in clay and sand proportions seems to be related to volcanic ash sources and to pedogenetic factors. First, the high portion of the watershed is close to several monogenetic cinder and scoria cones and received considerable amounts of fresh ash materials during the cone´s eruptions, while the middle and low portions received lower inputs of these materials. Second, both the middle and low portions are older reliefs in which pedogenetic processes have occurred longer than in the high portion and thus the

original volcanic materials had been already weathered into secondary clay minerals, which explains the higher clay contents in the lower portion.

The low K_s values for the coffee plantation in production (COF) may be explained by repeated traffic of plantation workers. These low K_s values grouped COF site with sites depicting the lowest K_s values in our study (ECFC, PALC and PAM). Even when coffee plantations have a dense tree cover that provides shading, there is no direct relationship between such a tree cover and high K_s values.

The formation of soils in this watershed (i.e. Andisols) are strongly controlled by climatic factors, especially temperature and rainfall. The rate of chemical weathering increases remarkably with increasing temperature and soil moisture. As the degree of weathering increases, metastable non crystalline materials are gradually consumed by transformation to more stable crystalline minerals (i. g. halloysite, kaolinite, gibbsite) (Dahlgren, et al., 2004).

Changes in temperature and rainfall induced by the elevation gradient across the watershed have important impacts on soil properties. Surface horizons of the Andisols from the upper portion, which developed under dryer and colder conditions have sand shifting textures, while the Andisols from the warmer lower portion with contrasting wet/dry conditions have higher clay content caused by more intense weathering. These transitions of Andisols in the tropics caused by changes in soil moisture regime have been documented by several authors (e.g. Dubroeucq, et al., 1998; Nizeyimana, 1997; Zehetner, et al., 2003). Since the central portion of the watershed consists of a highly dissected landscape, accelerated erosion and redeposition on steep slopes may have created unstable landscape positions where the andic topsoil materials have been locally removed creating intermixed soil patterns with a more variable texture.

4.2 Effective porosity and flow proportions

Flow proportions for different pore sizes indicate that infiltration processes in this system are controlled mainly by particle size related porosity rather than bypass structural related macropores. Our results contrast greatly with earlier data for forest soils where 73% of infiltration flow was transmitted by 0.04% of soil volume (Watson & Luxmoore, 1986) or where macropores flow constitutes 85% of ponded flow (Wilson & Luxmoore, 1988).

In our case macropore related flow (mean 3.09 %) was conducted through approximately 0.009 % of soil volume. The highest value in our study was for an early cloud forest site in the middle portion of the watershed where 11.05% of infiltration flow was conducted by only 0.04% of soil volume. This discrepancy between our results and earlier results in forested soils may be attributed to soil type related structure. Andisols are known for their granular and microgranular structure in natural conditions, and even when preferential flow has been reported in this type of soil (Eguchi & Hasegawa, 2008), our results indicate that in this particular setting most of the water flow occurs through fine mesopores and micropores of the soil matrix and not through macropores.

4.3 Hydrological PES schemes

The mixed effect model analysis indicated no significant statistical difference in K_s between land uses under the economical compensation scheme and those land uses not considered in the compensation scheme. Field observations and informal interviews with land owners allowed a larger understanding of the land use/cover – K_s relationship. Some land

use/coverages correspond to different transitional stages of a natural successional process. In some of the cases K_s figures are not statistically different from those of a mature cloud forest, which indicates that either part of the original infiltration capacity of the soil had been recovered or that it was not severely affected by land use change.

Land management practices also are a major driving force in the modification of infiltration patterns. Since Log K_s values from early regeneration of cloud forest were not statistically different from that of secondary or mature cloud forests, we conclude that the early regeneration patches may be infiltrating just as much as the mature or secondary cloud forests. This should be taken in account in the PES program since early regeneration cloud forests, if protected through monetary incentives, may evolve into secondary or mature cloud forests. However, in transformed and intensively managed environments such as pastures, land use/cover may not be a good criterion to assess hydraulic functionality of soil.

Further, agroecosystems such as the coffee plantations may not be suited for hydrological PES schemes. Perhaps they could be included in other PES schemes such as carbon sequestration or biodiversity conservation. But it is yet to be addressed if coffee plantations in the Gavilanes watershed represent adequately the coffee plantations within the region. Further research may include different coffee plantation configuration and similar agroecosystems.

5. Conclusions

The main aim of this chapter was to examine the relationships between land use/cover and key hydrophysical variables (K_s), in order to strengthen and aid policy making related to Payment for Ecosystem Services initiatives.

The relationship between land use/cover and hydraulic conductivity is very complex in the study area. Although land use/cover is a major driving force in K_s behavior, soil properties also contribute to hydraulic conductivity through the parent material differences (closeness to ejecta sources), pedogenetical processes (secondary mineral clay formation) and geomorphological processes (relief formation and erosion).

Successional stages such as early cloud forests have no statistical difference in K_s with mature forest formations indicating that the hydraulic functionality of the soil had been recovered or that it was not severely affected by land use change. Including these successional stages within the local and federal PES schemes may promote their recovery and transition into secondary or mature forest.

The high variability of K_s in pasture use is related to local cattle management strategies, thus a general pasture land use classification may not be a suficient criterion (or an efficient criterion) for spatial mapping of K_s.

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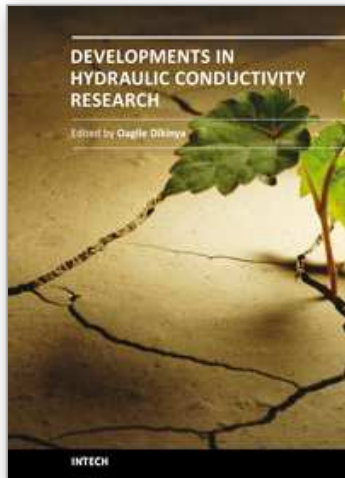
Developments in Hydraulic Conductivity Research

Edited by Dr. Oagile Dikinya

This book provides the state of the art of the investigation and the in-depth analysis of hydraulic conductivity from the theoretical to semi-empirical models perspective as well as policy development associated with management of land resources emanating from drainage-problem soils. A group of international experts contributed to the development of this book. It is envisaged that this thought provoking book will excite and appeal to academics, engineers, researchers and University students who seek to explore the breadth and in-depth knowledge about hydraulic conductivity. Investigation into hydraulic conductivity is important to the understanding of the movement of solutes and water in the terrestrial environment. Transport of these fluids has various implications on the ecology and quality of environment and subsequently sustenance of livelihoods of the increasing world population. In particular, water flow in the vadose zone is of fundamental importance to geoscientists, soil scientists, hydrogeologists and hydrologists and allied professionals.

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