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Linking hydropedology and ecosystem services: differential controls of surface field saturated hydraulic conductivity in a volcanic setting in central Mexico

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Abstract

In this study the variation of field saturated soil hydraulic conductivity (*Kfs*) as key control variable and descriptor of infiltration was examined by means of a constant head single ring infiltrometer. The study took place in five coverage types and land uses in a volcanic setting in central Mexico. The tested hypothesis was that there exist a positive relationship between plant cover and surface *Kfs* for the study area. The examined coverage types included; Second growth pine-oak forest, pasture land, fallow land, gully and *Cupresus* afforestation. Results indicate that *Kfs* did not depend exclusively of plant cover; it was related to surface horizontal expression of the unburied soil horizons and linked to land use history. Therefore the *Kfs* measured at a certain location did not depend exclusively of the actual land use, it was also influenced by soil bioturbation linked to plant succession patterns and land use management practices history. The hypothesis accounts partially the variation between sites. *Kfs* under dense plant cover at the *Cupresus* afforestation was statistically equal to that measured at the fallow land or the gully sites, while second growth pine-oak forest *Kfs* figures were over an order of magnitude higher than the rest of the coverage types. The results suggest the relevance of unburied soil horizons in the soil hydrologic response when present at the surface. Under these conditions loosing surface soil horizons due to erosion, not only fertility is lost, but environmental services generation potential. A conceptual model within the hydropedological approach is proposed. It explains the possible controls of *Kfs*, for this volcanic setting. Land use history driven erosion plays a decisive role in subsurface horizon presence at the surface and soil matrix characteristic determination, while plant succession patterns seem to be strongly linked to soil bioturbation and preferential flow channel formation.

1 Introduction

Ecosystem services can be defined as "the capacity of natural processes and components to provide goods and services that satisfy human needs, directly or indirectly", in this perspective ecosystem services are part of ecosystem structure and processes which in turn are the result of diverse and complex interactions between abiotic and biotic components of ecosystems linked trough matter and energy fluxes (De Groot, 1992). Even when 1970s' researchers addressed the importance of economic value of ecosystem functions and services, e.g. Odum and Odum (1972), it was not until recently that ecosystem services got into public and government concern worldwide. The actual environmental crisis had lead to a revaluation of the natural and transformed ecosystems as sources of ecosystem services and goods (Maass et al., 2005).

The hydropedological approach embrace a link between soil sciences and hydrologic sciences building a bridge between classical disciplines such as soil physics, pedology and hydrology studying the critical zone its functioning at different spatial and temporal scales (Lin, 2004; Lin et al., 2008, 2004; Lin and Zhou, 2008). Regulation ecosystem functions and the related ecosystem services such as water regulation and water supply are strongly dependent of the vado zone functioning, therefore the hydropedological approach may be adequate to address and study the physical processes that control this ecosystem service's performance, at least partially. The hydropedological approach can provide conceptual and methodological elements to ecosystem service quantification which in turn could improve the understanding of their functioning and dependence of the natural components and the effect of human activities on them.

Water infiltration is a key process for water regulation ecosystem functions. It is a complex process that under field conditions and natural precipitation varies for each event due to it's dependency of soil moisture content (Wit, 2001; Cerdà, 1995). Several authors have addressed the relationship between soil cover and infiltration (Zimmermann et al., 2006; Wit, 2001; Cichota et al., 2003). The importance of plant cover to infiltration has been reported in different environmental settings, from arid and semi-

arid to humid forests, and a link between plant cover and soil physical properties had been addressed (Zimmermann et al., 2006; Li and Shao, 2006). Differential effects of vegetation have been reported between vegetated and non vegetated areas (Cerdà, 1997a, b; Lyford, 1969; Álvarez-Yépiz et al., 2008). It is known that vegetation characteristics such as composition or management have a strong influence in infiltration rates, specially in areas under livestock grazing (Descroix et al., 2001; Prause and Gallardo-Lancho, 2000; Mwendera and Saleem, 1997; Singleton et al., 2000; Tobón et al., 2004).

An extensive literature review indicate that for Mexico there are few studies about hydrophysical properties in soils under non agricultural cover, and none including the hydropedological approach. The actual federal government Ecosystem Services Program (Programa de Servicios Ambientales), driven by the CONAFOR (which stands for National Forest Commission in Spanish) and claimed to be the largest worldwide (CONAFOR, 2008), establishes that payments should be done according to predefined rates (CONAFOR, 2004), in which the only evaluating criteria is vegetation type. Pérez-Maqueo et al. (2005) criticised this and mention that outlines of this federal program is based in not verified generalizations or empirical approaches regarding land use, land cover and hydrologic ecosystem services. Therefore there is a need of hard data studies relating hydrophysical properties to ecosystem services, because ecosystem service programs need to be evaluated and their intended effectiveness assessed (Cotler and Ortega-Larrocea, 2006; Perevochtchikova et al., 2005; Pérez-Maqueo et al., 2005).

On the other hand, land cover and land use change severely affects Mexico. Deforestation national rates are among the highest in the world, about 0.5% annually (Carabias, 1990; Jardel, 1990). However recent studies had demonstrated that deforestation and land use change has regional and local peculiarities. In Cuitzeo Lake basin in central Mexico López et al. (2006) found a positive relationship between farmer migration and plant cover recovery (1975–2006). The main changes occurred in abandoned marginal croplands, where shrub vegetation is recovering.

In this central part of Mexico main agricultural practices include the traditional rainfed slash-burn year-turn (roza-quema año y vez) and the burn year-turn (año y vez) of the milpa local variant. The system is similar to the highly documented Mayan milpa (Turner and Brush, 1987; Barrera-Basols and Toledo, 2005) in which forest is removed (clear-cut) then burned and after that corn (maize) is grown for a short period usually 2 to 4 years. Then the area is left to recover and revegetate for a longer period 10–30 years (Mariaca-Méndez et al., 2007). Nevertheless, in recent times due to different causes recovery times had been shortened, reducing the effective vegetation recovery (Mariaca-Méndez et al., 2007). This produced the regional and local variant of milpa, in which forest slashing is nowadays seldom used and the fields are left in fallow for 1 to 3 years. Burning is still highly used in order to eliminate weeds and pests when needed. The local system includes maize (*Zea mays* L.), beans (*Phaseolus vulgaris* L.), and different species and subspecies of Cucurbita genus, like squash and pumpkin. The crops are grown simultaneously during the rainy season (June to October) and harvest is done by hand during fall. Usually the system is maximized and during the months following the harvest, cattle is left to graze on leftover stubble. As mentioned earlier cropland abandonment and vegetation recovery had been documented in the study area as a consequence of peasant emigration (Lopez et al., 2006), abandoned land are incorporated as regular grazing areas for cattle. This activities may produce soil compaction, modify soil structure, porosity and thus hydrophysical properties (Newman et al., 1999; Singleton et al., 2000; Descroix et al., 2008).

In such a context, plant cover recovery can be described as a qualitative gradient represented by a series of sites with different level of degradation that follow different ecological recovery paths as a response of the ecosystem natural dynamic (Hilderbrand et al., 2005). Even when it is difficult to define the order and level of perturbation, plant structure suggest distinctive successional stages that may affect hydrological processes such as infiltration due to changes in soil hydraulic conductivity. The latter relationship had been reported by Li and Shao for the Loess Plateau in China (2006).

Due to infiltration dependency of antecedent soil moisture, some researchers have

recently used saturated hydraulic conductivity or field saturated hydraulic conductivity (*Kfs* from here on) as a descriptor of infiltration because it provides a homogeneous conceptual and practical framework, allowing comparison between sites with different characteristics. Besides *Kfs* is a variable particularly sensitive to soil disturbance and can be used as indicative of land use practices impact on the soil (Perkins et al., 2007; Schoenholtz et al., 2000; Berli et al., 2004).

In this study the actual postulates of the Hydrologic Environmental Services Payment Program (Programa de Pago por Servicios Ambienteles Hidrológicos of CONAFOR) part of the National Ecosystem Services Program are put to the test. And at the same time learn about the spatial variation and specific controls of field saturated hydraulic conductivity as a descriptor of the infiltration process. Thus the driving hypothesis of this work was "*Land cover type conditions the spatial patterns of variation of hydraulic conductivity such that land cover with higher plant coverage should have higher hydraulic conductivities than those with less or no plant coverage*".

2 Materials and methods

2.1 Study area

Cuitzeo basin is a closed basin with 4075 km^2 located in the central part of the Trans-Mexican Volcanic Belt (19°30′ to 20°05′ N and 100°35′ to 101°30′ W), between the states of Guanajuato and Michoacan in central Mexico, about 220 km West from Mexico City. The basin is relevant because it houses Cuitzeo Lake, the second largest natural water body in Mexico (233 km^2) while housing over 870 000 people in several towns which Morelia city, capital of Michoacan state is the largest with an estimated population of 616 948 (Lopez et al., 2006).

This study was conducted in the "Loma del Puerto del Tigre" in the southern portion of the Cuitzeo Lake basin, the area is located 18 km SE from Morelia City in Michoacan State, geographical coordinates are 101°14′24′′ W, 19°33′00′′ N (Fig. 1). This location can be considered a microcosm of the Cuitzeo basin because many of the processes addressed earlier by Lopez et al. (2006) are known to be present.

The Mexican National Institute of Statistics, Geography and Informatics (Instituto Nacional de Estadística Geografía e Informática, INEGI) which is in charge of national cartography including that of soil reports Orthic Acrisols (following the FAO 1970 nomenclature) (INEGI, 1979), nevertheless detailed studies indicate the presence of polygenetic soil profiles with sandy-loam (Chromic cambisols) with andic properties on top of clayely (Humic lixisols) soils according to FAO (2006), both from volcanic origin Gómez-Tagle (2008). Seveney and Prat (2003) mention that buried soils of this kind are common within this region of the Trans-Mexican Volcanic Belt. Lithology is extrusive basic, with ignimbritic materials (Bigioggero et al., 2004; Gómez-Tagle, 2008). The geoform corresponds to volcanic lava flow hills smoothed by volcanic ash deposits (Gómez-Tagle, 2008), slope ranges are between 0 and 20 degrees.

According to Garcia (2004), climate is temperate sub humid with rainy season during the summer and annual average temperature of 16.7°C and mean annual precipitation of 850 mm.

2.2 Land use and successional stages

The work was conducted in sites representative of five ecological succession stages, the sites were differenced mainly by plant cover, the main characteristics are mentioned further along:

Secondary Pine-Oak Forest (SPOF). Site with tree coverage >70% with average density of 97.6 trees ha^{-1}, mean diameter 46 cm, dominated by *Pinus devoniana*, *P. leiophylla*, *Quercus obtusata* and *Q. castanea*, in the overstory and *Rubus* spp., *Crataegus pubescens*, *Rhus aromatica* and *R. trilobata* and herbaceous annual plants from Poaceae and Asteraceae families in the understory.

Pasture (PA). Site where the main use is open livestock grazing, isolated shrubs are present with an average coverage of 12%, tree canopy is depleted. Shrubs are dominated by pioneer species *Baccharis heterophylla* over 1.5 m height and *Calliandra*

sp. Herbaceous vegetation is dominated by grass *Cynodon dactilon* (98%) and the rest is divided between different Asteraceae species such as *Melampodium mucronatum*, *Tagetes bippinata* and *T. lucida*. Interviews with elderly locals indicate this piece of land was earlier (30 years ago) dedicated to agriculture.

Gully (G). This site had very low plant cover (<1%) and evident sheet and gully erosive processes.

Fallow Land (FL). Site with former agricultural use that had been abandoned (±5 years); plant cover is dominated by shrub pioneer species *Baccharis heterophylla* (7% coverage) individuals under 1.0 m height, herbaceous coverage (50%) is composed by *Cynodon dactilon*, *Tagetes bippinata*, and *T. lucida* with no apparent dominance of any species. There are also young individuals of *Pinus* spp. and *Crataegus pubescens* with heights up to 1.5 m. In this site plough lines were visible in the entire surface.

Cupresus Afforestation (CuA). Site with *Cupresus lusitanica* afforestation with 35-40 years of age, mean density is 216 individuals ha^{-1}, tree canopy coverage is 84%, ground surface is covered by moss (100% coverage), there are spotted individuals of herbaceous and shrub species (<10%). This site was part of afforestation government programs during the 1960s which enforced plant cover substitution and afforestation, from annuals under the local milpa system, to tree species in marginal low productivity fields, therefore plough lines were visible in the surface.

At the study time eventual light grazing (cattle) took place in all of the sites at least once (one-two days) every two or three weeks, except for the *Cupresus* Afforestation.

2.3 Data acquisition

The sampling took place on the high portion of the geoform (summital surfaces and high hillslope), slopes were in all cases below 5°, and altitudes between 2190 and 2210 m above sea level.

2.3.1 Soil profiles description

For field soil description a pit was dug on every site. Description was done following the Soil Survey Staff outlines (Soil-Survey-Staff, 1993) and Siebe and Stahr (2006). Form each horizon soil samples were collected and analyzed. Detailed analytical results will be published elsewhere because are out of reach for the present study, at the moment can be consulted in Gómez-Tagle (2008) under request. Soil classification mentioned here follows FAO (2006) nomenclature (Gómez-Tagle, 2008; Gómez-Tagle et al., 2008).

2.3.2 Infiltration tests

At each site 49 infiltration tests were conducted. These were distributed using a regular grid of 7×7 nodes, distance between nodes was 3 m in both directions. Infiltration tests where conducted by means of a constant head top sealed single ring infiltrometer Ring diameter and height were 88.0 and 80.0 mm, respectively and insertion depth of 60.0 mm (Gómez-Tagle, 2008; Gómez-Tagle et al., 2008). This field infiltrometer is a variant of pressure infiltrometers described earlier (Elrick and Reynolds, 1992; Angulo-Jaramillo et al., 2000). These devices had been used to estimate *Kfs* (Prieksat et al., 1992; Wu et al., 1999; Matula, 2003). The device used was similar to that of Prieksat et al. (1992) but the ring is top sealed and connected to the Mariotte reservoir by a water supply tube with a two way valve. This eases the refill process of the Mariotte without affecting the ring insertion in the soil. The applied water head is monitored by means of a water head tube attached to the ring. The increase or reduction of water head height is controlled by rising or lowering bubble tube inside the Mariotte.

The applied constant water heads were between 10.0 and 40.0 mm. Water height in the Mariotte reservoir was recorded manually every five minutes until reaching a constant inflow rate indicative of steady-state infiltration phase. Constant inflow rate was recognized when 3 subsequent measurements deviate less than 10% from one another. This usually occurred after 3.0 h of elapsed time. Once the infiltration ex-

periment was finished, water was allowed to flow out from inside the ring five minutes and then the ring was removed and a final water content sample was taken (θ_2), water content was estimated using the gravimetric method (DOF, 2002).

Estimation of *Kfs* was performed following the Wu2 method (Wu et al., 1999), generated from axisymetrical scaling of Richards equation (Wu and Pan, 1997). The Wu2 method utilizes the slope of the steady-state portion of the cumulative infiltration curve (Wu et al., 1999). The Wu2 methods needs previous estimates or table values of α^*, which represents the capilar component of the hydraulic flow in the soil, α^* values were taken from Elrick and Reynolds (1992) according to the texture classes.

Besides for every infiltration measurement point, surface soil samples were taken, about 100.0 mm away of the infiltration point and processed for bulk density by the cylinder method (100 cm^3) (Miller and Donahue, 1990), initial water content (θ_1) by means of gravimetry (DOF, 2002); organic matter content by wet combustion (DOF, 2002); sand, silt and clay percentage using the Boyoucos method (DOF, 2002); texture class using the program Soil Water Characteristics version 6.02.74 (http://hydrolab.arsusda.gov/soilwater/Index.htm) (Saxton et al., 1986). Water stable aggregates with two different apparent diameter intervals; 2.0 to 4.0 mm, and 0.25 to 2.0 mm by wet sieving (Seybold and Herrick, 2001).

2.3.3 Statistical analysis

Standard statistic techniques were used to characterize *Kfs* data from different sites. Previous studies report that several air and water flow related soil properties follow Log-Normal probabilistic distribution (Russo and Bresler, 1981; McIntyre and Tanner, 1959). Therefore probabilistic distribution of *Kfs* was tested using the *W* Shapiro-Wilk test (Shapiro and Wilk, 1965). One way Analysis of Variance (ANOVA) was used to test the proposed hypothesis and therefore the existence of *Kfs* differences between sites. Tukey's Honest Significative Difference test was used to address between which sites there was statistical difference (Crawley, 2002). Multivariate statistical procedures were conducted to explore possible relationships between *Kfs* and physicochemical soil properties. Statistical analysis was done using Statistica for Windows version 6.0 (StatSoft_Inc., 1998)

Further, geostatistical techniques were applied to explore the spatial variation of *Kfs* within the studied sites. Omnidirectional and directional experimental variograms (Webster and Oliver, 2001) were computed using VarioWin version 2.2 (Pannatier, 1996).

3 Results and discussion

3.1 Soil profile characteristics

All sites are located on low slope areas (<5°). Soils were formed in situ from pyroclastic deposits. These kind of parent materials evolved to form soils with argilic horizons, the evolutionary paths had been described earlier by Sedov et al. (2003a, b) in similar areas of the Trans-Mexican Volcanic Belt. The soils can be considered as polygenetic with at least two main pedogenetic episodes, the upper horizons (A, A_{11}, A_{12}, Ap_1, Ap_2, AB) corresponds to different forms of a Cambisol with coarser sandy loam to sandy clay loam textures (Gómez-Tagle, 2008) while the subsurface horizons (2 Bt, Bt) correspond to different portions of the argilic horizons of a buried Humic Lixisol (Gómez-Tagle, 2008). The latter is truncated at the G and the CuA sites. Each one of the sites has its own characteristics. A short description is presented (Table 1). In some sites the Cambisol is not clearly recognizable due to erosion, mixing with the underlying calyley horizons by agricultural practices or forming a plough pan.

3.2 Statistics and probabilistic distributions of *Kfs*

A total of 231 infiltration measurements were performed for the five sites. Descriptive statistics are shown in Table 2. The Shapiro-Wilk test (Shapiro and Wilk, 1965), between observed and expected distribution showed that *Kfs* had a Log-Normal probability distribution behavior in all sites (Table 3). This results agree with previously

reported probabilistic functions for soil properties related to water or air flow in soil (Rogowski, 1972; Russo and Bresler, 1981; Regalado, 2005; Mallants et al., 1997). Further analysis were performed using *Kfs* transformed to *lnKfs*. The ANOVA indicated statistical difference between sites for *lnKfs* (F=35.584, p=0.0031), and Tukey SHD test (Crawley, 2002) showed a groupping pattern where sites differentiate and *Kfs* had the following trend SPOF>PA>FL=G=CuA (Table 4).

3.2.1 Relationships between *Kfs* and other soil properties

For the whole data set (five sites analyzed) *lnKfs* showed a positive relationships with the percentage of water stable aggregates for both apparent diameter intervals analyzed (2.0–4.0 and 0.25–2.0 mm), and positive relationship with sand and silt content, but negative relationships with the initial moisture content, clay percentage and bulk density. Nevertheless r values were statistically significative are considered too low to explain the relationship satisfactorily (Table 5).

The analysis of each site indicated a differential relationship between physicochemical soil properties and *lnKfs*. In SPOF three out of nine correlations were significative (water stable aggregates 2–4 mm, silt percentage and bulk density; Table 5) two positive and one negative. For CuA there were two significative correlations (silt percentage and organic carbon content; Table 5). While for PA there was only a significative correlation; organic carbon (Table 5). The rest of the sites showed no significative correlations with none of the analyzed properties. This explains partially why the whole data set correletions yielded so low (Table 6). Contrary to expected the only site where *lnKfs* correlated significatively with bulk density was SPOF (r=0.44, p=0.15). It is important to consider that the samples used to estimate bulk density were not taken exactly from the infiltration test location but from a close location (±0.1 m), therefore it is possible that the latter does not reflect the existing porosity conditions at the soil surface at the exact location of the infiltration test. At SPOF site the three properties related to *lnKfs*, suggest an important role of maropore and preferential flow paths. The profile descriptions indicate this was the only site that presented in the surface a horizon with predominance of biogenic structure, furthermore this site was statistically different to the rest of the sites (Table 4). For the Gully site (G) a relationship between sand or clay content with *lnKfs* was expected, but not detected, this site had the lowest *Kfs* values of the stuy. Upper Cambisol horizons lost due to erosion and the unburing of the Lixisol argilic horizons (2 Bt) reduce significatively the *Kfs* for the actual surface soil. The unexpected non relationship between physicochemical properties and hydraulic conductivity at this site is attribuited to macropore presence independent of the physicochemical properties analyzed.

In the FL site there were no correlations between *lnKfs* and the tested properties whereas for the CuA site some relationships were found. This indicate that silt content and soil organic carbon play an important role in *Kfs* variation control as mentioned by earlier researchers, e.g. Arya et al. (1999); Tietje and Hennings (1996). Further, silt is related to textural class and therefore to pore size and distribution (Fuentes et al., 2004), while soil organic carbon is related to aggregate stability (Porta et al., 1999). This properties had a very conspicious vertical variation pattern. In surface conditions, changes in this properties indicate the presence of subsurface horizons at the surface, due to previous erosion or soil disturbance by historical land management practices.

3.2.2 *Kfs* spatial variation

Geostatistical analysis of data did not yield good results. Even when omnidirectional and directional experimental variograms were estimated, were not able to capture the spatial variation patterns of *Kfs*. It seems that the sampling grid 3×3 m was either too coarse or too fine to capture the actual spatial variation of the variable. Other researchers using nested small scale sampling schemes had found spatial effective correlation ranges betwen 0.25 and 18.11 m (Sobieraj, 2003; Sobieraj et al., 2004; Zimmermann and Elsenbeer, 2008).

3.3 Succesional stages, subsurface horizons and *Kfs*; conceptual model

Very often literature refers to vegetation as a key promotor of infiltration due to it's effects on soil properties (Pilgrim et al., 1988; Wit, 2001; Cichota et al., 2003; Mills and Fey, 2004; Li and Shao, 2006). This study shows that even with considerably high tree cover, like CuA, low values of *Kfs* may occur, not being statisticaly different of those in very different sites like a gully (G) or a fallow land (FL). Field observations during infiltration sampling and the later data analysis allow to state that actual plant covarage is related to site's land use history. Figure 2 illustrates the conceptual model that relates land cover, *Kfs* and surface expression of soil horizons in this particular setting.

As mentioned earlier correlations between *lnKfs* and soil physicochemical properties is low (<0.5) for most of the variables, which does not allow to conclude strongly. The results presented herewith indicate a plausible differential effect of the cover and vegetation characteristics on field saturated hydraulic conductivity, in such a way that *Kfs* variation does not depend only and directly of plant cover but the unburing of certain horizons and their dominance within the surface at the site scale, as well bioturbation processes and preferential flow channel formation. *Kfs* did not depend exclusevly of plant cover and land use as hypotesized.

As mentioned before the local milpa system alternates agricultural and cattle grazing. The results of this work are similar to those of Zimmerman et al. (2006) who mention that the effects cattle grazing on *Kfs* (13 years of cattle grazing) are strong enough to be perceptible even 10 years after the grazing had stopped and an afforestation (*Tectona grandis*) had been established. Results refuse partially the idea that a dense plant cover favors infiltration or *Kfs* increase as the Mexican federal governemt Ecosystem Services Program outlines. Nonetheless the afforestation age suggests that recovery time for *Kfs* under *Cupresus* monoculture to pre-agricultural practices values, taking as reference the *Kfs* at the secondary pine-oak forest (SPOF) may be over 35–40 years in clayley soil in similar subtropical volcanic settings, or never achieved due to substantial edaphic transformation.

The excavated soil profile at the CuA site did not show evidence of bioturbation processes as the SPOF site did. Nor had the loam-clayley or sandy-loam horizons as the SPOF or the PA site soil profiles did. In a landscape perspective, physicochemical data from soil samples acquired during the infiltration tests showed that surface sand content was not statistically different between SPOF and CuA (not shown), while clay content was in deed statisticaly different, indicating the presence at the surface of 2Bt horizons. Similar results trough the whole study area suggest a textural control of *Kfs* at some level even when the statistical analysis did not reveal significant correlations. The latter agrees with the results of Elsenbeer (2001) and Lin (2004). This kind of relationship between texture class or granulometry distribution had been widely recognized and is a fundamental part of pedotransfer functions and models, e.g. Elsenbeer (2001); Pachepsky and Rawls (2003); Ferrer et al. (2004).

Direct soil profile observations and *Kfs* data indicate that bioturbation is a key process in preferential flow of water at the studied sites, and that this patterns had been related elsewhere to plant composition (Negrete-Yankelevich et al., 2008) and land use (Shakir and Dindal, 1997), but also land use history (Raty and Huhta, 2004; Callaham et al., 2006; Negrete-Yankelevich et al., 2007). It is important to consider that the soil macroinvertebrate communities are crucial because their modification of physicochemical soil properties, favoring biopores and biotunnel formation, the incorporation of organic matter into the soil matrix and the related aggregate stability (Mboukou-Kimbatsa et al., 2007). Macroinvertabretes may also alter soil stratification because they move soil material vertically and horizontally (Eisenhauer et al., 2007), favoring the macropore driven hydraulic connectivity between soil horizons (Pitkanen and Nuutinen, 1998).

Nevertheless bioturbation does not only include soil macroinvertebrates, but soil mesofauna (Wang et al., 1996; Sobieraj, 2003; Tsukamoto and Sabang, 2005; Frouz et al., 2007) vertabrate organisms (Sobieraj, 2003; Zaitlin et al., 2007) from small rodents such as gophers and mice (Matula, 2003; Zaitlin et al., 2007) to armadillos in certain tropical environments (Sobieraj, 2003), as well as root induced turbation (Chisci et al.,

2001).

Several authors had reported earlier that infiltration in the vado zone occurs mainly through preferential flow via macropores (Mohanty et al., 1997, 1988; Logsdon and Jaynes, 1993). Preferential flow occurs through macropores which has three main origins; a) biological activity (macro and mesoinvertebrates and tunnel formation due to root activity and decay), b) land use practices and c) natural phennomena such as rock fractures and tube erosion.

4 Final considerations

Even thought neither infiltration nor hydraulic conductivity are ecosystem service per se. They are linked to regulation functions of ecosystems as water regulation and water supply which in turn generate the provision of water for consumptive use as ecosystem service (De Groot et al., 2002). In Mexico's federal government programs, infiltration process is considered as an ecosystem service, and such, it is included in the economical compensation schemes. The results presented herewith support the arguments of Pérez-Maqueo et al. (2005) who criticised the evaluation criteria for the economical compensations of the Ecosystem Services Program of CONAFOR. In this program vegetation cover and type seems to be overestimated while soil role downgraded.

Despite the restricted reach of this research's results. It would be important to consider soil condition in the Ecosystem Services Program schemes, because it is the soil condition and not the vegetation that determines the infiltration. Further, the factors and relationships that define and control water flow through the pedosphere are complex. The ecosystem services approach may need to include the hydropedological perspective in order to better understand these fluxes. This new perspective may help in detailed water source areas definition and key management practices identification which allow the permanence of water sources. Hydropedology may also provide hard data foundation for ecosystem service markets design and development, and to redefine the present economical compensation schemes.

Further research is needed to unveil water flows within the pedosphere and the critical zone, therefore future studies should focus on hydropedological functioning under the ecosystem services approach. It would ease monetary resources flow into a highly specialized and yet demanded field as hydropedology.

5 Conclusions

The results does not support the conceptual framework used in the Hydrologic Environmental Services Payment Program driven by CONAFOR.

Further the tested hypothesis explains partially the spatial variation of *Kfs* as a surrogate property of land cover.

This study showed that in certain plant cover types and conditions the occurrence of a dense tree canopy is related to *Kfs* values increase (Secondary Pine-Oak Forest), but in others is not (*Cupresus* Afforestation). This variation is better explained by the unburing of soil horizons related to land use history.

Infiltration and the field saturated hydraulic conductivity quantified at a specific site or plot in certain time is not the exclusive result of present processes and events; but related and strongly influenced by land use management history as well as natural plant succession patterns.

Under dense tree cover such as the Cupresus Afforestation (CuA), *Kfs* (as *lnKfs*) was statistically equal to that of the Fallow Land (FL) or the Gully (G), while the Secondary Pine-Oak Forest (SPOF) *Kfs* values were an order of magnitude higher of those present at the Cupresus Afforestation, indicating a relationship of high *Kfs* with intense soil bioturbation.

The ecosystem services approach may be enriched by hydropedology. The latter may provide methodologies and concepts that would allow a better assessment of ecosystem services programs such as those driven by the federal government in Mexico.

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Table 1. Soil descriptions.

Site	Horizon	Depth (cm)	Description
SPOF	A_{11}	0–5	Weak red (10R 5/2 dry) and dusky red (10R 3/2 moist) sandy clay loam. Angular blocky structure of biogenic origin (10–30 mm) strongly developed, strong macroinvertebrate biological activity. Many biogenic medium and coarse pores, many fine and very fine intertitial and tubular exped pores. Many very fine and fine roots. Soil surface irregular with strong bioturbation features. Clear and smooth boundary.
	A_{12}	5–12	Weak red (10R 4/3 dry; 10R 4/4 moist) sandy clay loam, subangular blocky structure of biogenic origin (15–45 mm), strongly developed. Charcoal presence (less than 10%). Many biogenic medium and coarse pores and many fine intertitial, tubular and exped pores. Many very fine and fine roots. Clear and smooth boundary.
	AB	12–32	Same colors as horizon above, clayley. Angular and subangular blocky moderately developed structure (10–80 mm), many biogenic medium and coarse pores, abundant medium and fine interstitial and tubular pores. Inped clay films and organic matter films of biogenic pores. Common very fine and fine roots. Gradual and smooth boundary.
	2AB	32–38	Weak red (10R 4/4 dry; 10R 3/4 moist) clayley. Subangular blocky moderately developed structure (10–50 mm), many medium and fine interstitial and tubular pores, clay film in few medium and coarse biogenic pores and root channels. Clear and abrupt boundary.

Table 1. Continued.

Site	Horizon	Depth (cm)	Description
SPOF	2 Bt_1	38–52	Weak red (10R 5/4 dry) and dusky red (10R 3/4 moist) clayley, similar to the horizon above but with presence of coarse pyroclastic material (lapilli) highly weathered (<5%) and moderately few very fine and fine roots. Gradual and smooth boundary.
	2 Bt_2	52–76	Brown (7.5YR 5/2 dry; 7.5YR 4/4 moist) clayley. Subangular strongly developed blocky structure (15–80 mm). Common fine and medium interstitial and tubular pores, few coarse pores from decaying root origin. Common small exped reddish yellow (5YR 7/6) distinct mottles. Few clay films in root channels. Few very fine and fine roots. Gradual and smooth boundary.
	2BC	>76	Reddish yellow (7.5YR 6/6 dry) and strong brown (7.5YR 5/6 moist) clayley. Subangular blocky structure, strongly developed (10–60 mm). Common medium and fine interstitial pores, roots absent. Few medium yellow (10YR 7/6 moist) saprolite mottles. Clay coating in external ped faces.
PA	Ap	0–12	Weak red (10R 4/3 dry) and dusky red (10R 3/2 moist), silty loam. Subangular blocky moderately developed structure (5–30 mm), stoniness <1%. Many very fine and fine roots. Gradual and smooth boundary.
	Ap_2	12–27	Similar to horizon above, silty loam. Subangular blocky strongly developed structure (10–35 mm), common very fine and fine roots. Clay film (<1 mm) in ped faces and root channels. Charcoal presence <1% (0.5–2 mm). Diffuse and wavy boundary.

Table 1. Continued.

Site	Horizon	Depth (cm)	Description
PA	Bt	27–43	Strong brown (7.5YR 5/6 dry; 7.5YR 4/6 moist) clayley. Subangular blocky strongly developed structure (5.0–55 mm), moderately few very fine and fine roots. Clay films in root channels. Diffuse and wavy boundary.
	BC	43–67	Yellow (10YR 7/6 dry) and brownish yellow (10YR 6/8 moist) calyley. Subangular blocky structure strongly developed (7.0–70 mm). Common fine and medium reddish yellow (7.5YR 7/6 dry) mottles 3.0–15 mm. Very few very fine and fine roots. Few clay films in exterior ped faces and root channels. Diffuse and broken boundary.
	Cw	>67	Yellow (10YR 7/6 dry) and yellowish brown (10YR 7/6 moist) clayley. Ignimbrite saprolite.
G	A	0–21	Weak red (10R4/2 dry) and dusky red (10R3/2 moist) clayley. Subangular blocky structure moderately developed (5.0–50 mm), many very fine and fine roots, strong macroinvertebrate biological activity. Presence of rounded quartz crystals (0.5 mm). Gradual and smooth boundary.
	Bt	21–43	Red (10R 5/6 dry) and dark red (10R 3/6 moist) clayley. Subangular blocky structure strongly developed (5.0–80 mm). Few clay and Manganese coatings in exterior ped faces. Many prominent black (7.5YR 2/1) mottles manganese mottles coarse size with irregular forms and abrupt boundaries, size 5.0 to 15.0 mm. Few slickensides, many medium and fine roots. Gradual and wavy boundary.

Table 1. Continued.

Site	Horizon	Depth (cm)	Description
G	2A	43–72	Red (10R 5/6 dry) and dark red (10R 3/6 moist) clayley. Subangular blocky structure strongly developed (10–70 mm). Moderate root density. Clay and manganese films in exped faces and clay coatings in root channels. Few medium black (7.5YR 2/1) mottles. Common medium brownish yellow (10YR 6/6) mottles. Common faint slickensides. Diffuse and irregular boundary.
	2 Bt	>72	Red (10R 5/6 dry) and dark red (10R 3/6 moist) clayley. Subangular blocky structure strongly developed (5–35 mm). Without roots, few clay coatings on root channels and exped faces. Common medium black (7.5YR 2/1) irregular mottles, and Common medium brownish yellow (10YR 6/6) rounded mottles.
FL	Ap	0–18	Weak red (10R 4/4 dry) and dusky red (10R 3/4 moist) sandy loam. Microgranular moderately developed and subangular blocky weakly developed (10–40 mm) structures. Many very fine and fine roots. Intense biological activity, macroinvertebrate larvae (coleoptera) and vertebrates *Pappogeomys tylurhinus* (gopher). Gradual smooth boundary.
	Ap_2	18–42	Brown (7.5YR 5/4 dry) and strong brown (7.5YR 5/6 moist) loam. Microgranular moderately developed and subangular blocky weakly developed (10–50 mm) structures. Common very fine and fine roots. Biological activity similar to horizon above. Gradual smooth boundary.

Table 1. Continued.

Site	Horizon	Depth (cm)	Description
FL	AB	42–59	Dark yellowish brown (10R 4/4 dry; 10R 3/4 moist) silty loam. Subangular blocky structure moderately developed (5.0–50 mm). Very few very fine and fine roots. Clay films in exped faces. Gradual wavy boundary.
	Bt	59–70	Dark yellowish brown (10R 4/6 dry; 10R 3/4 moist) clayley. Subangular blocky structure moderately developed (11–55 mm). Few very fine and fine roots. Diffuse wavy boundary.
	Bt	>70	Red (10R 4/6 moist) and dusky red (10R 3/4 moist) clayley. Angular blocky structure strongly developed (5.0–90 mm). Very few very fine and fine roots. Few clay coatings and manganese films in exped faces. Few prominent black (7.5YR 2/1) manganese mottles coarse size with irregular forms and abrupt boundaries. Slickensides present in exped faces.
CuA	Ap	0–19	Dark yellowish brown (10YR 3/6 dry) and dark reddish brown (5YR 3/2 moist) clayley. Mixed structure; granular moderately developed and blocky subangular strongly developed. Common very fine and fine roots. Common fine, medium and coarse pores. Gradual wavy boundary.
	Bt_1	19–36	Yellowish red (5YR 5/6 dry) and dark reddish brown (2.5YR 2.5/4 moist) clayley. Subangular blocky strongly developed structure (5.0–60 mm). Many very fine and fine roots, common medium and coarse roots. Common fine and medium irregular pores. Gradual wavy boundary.
	Bt_2	36–76	Similar to above horizon but with presence of clay films in exped faces and root channels. Diffuse wavy boundary.

Table 1. Continued.

Site	Horizon	Depth (cm)	Description
CuA	Bt_3	76–99	Yellowish red (5YR 4/6 dry) and dark red (2.5YR 4/6 moist) clayley. Similar to horizon above but with presence of clay films in exped faces and clay coatings in root channels. Diffuse and wavy boundary.
	Bt_4	99–146	Red (2.5YR 4/8 dry) and dark red (2.5YR 3/6 moist) clayley. Similar to above horizon but <1% of peds exhibit very dark bluish gray (5BG 3/1) fine mottles. Diffuse and wavy boundary.
	Bt_5	146–178	Yellowish red (5YR 5/8 dry) and dark red (2.5YR 3/6) clayley. Similar to horizon above but subangular blocky structure shows larger peds 5.0–350.0 mm, also red films inside macropores (10R 5/8) not present above. Very dark bluish gray (5BG 3/1) fine mottles also present in peds. Gradual wavy boundary.
	Bt_6	>178	Similar to horizon above. Common clay coatings on root channels and exped faces, few prominent black (7.5YR 2/1) manganese films on exped faces and few manganese mottles coarse sized with irregular forms and abrupt boundaries. Presence of fine and medium rounded quartz.

Table 2. Values of *Kfs* (in mm h^{-1}) for the studied sites.

Site	Minimum	Maximum	Mean	Standard deviation	N
SPOF	1.90	5817.24	1578.57	1576.78	43
PA	15.31	2144.38	378.94	465.97	42
G	0.34	975.25	160.76	246.41	49
FL	2.76	420.33	99.72	92.02	48
CuA	0.11	1282.83	264.30	393.47	49

SPOF: Secondary Pine-Oak Forest. PA: Pasture. G: Gully. FL: Fallow land. CuA: *Cupresus* afforestation

Table 3. Shapiro-Wilk test of normality for *Kfs*.

Field saturated hydraulic conductivity (*Kfs*)				
Site	Mean mm h^{-1}	Std. deviation	*W*	*p*
SPOF	1578.57	1576.78	0.34461	0.0000**
PA	378.94	465.97	0.72766	0.0000**
G	160.76	246.41	0.63695	0.0000**
FL	99.72	92.02	0.80768	0.0000**
CuA	264.30	393.47	0.68945	0.0009**
Logarithmic transformation for field saturated hydraulic conductivity (*lnKfs*)				
Site	Mean mm h^{-1}	Std. deviation	*W*	*p*
SPOF	5.30	1.17	0.98505	0.84871
PA	7.13	7.36	0.94353	0.12408
G	4.08	1.57	0.96488	0.15029
FL	4.17	1.05	0.94498	0.08532
CuA	4.22	2.24	0.88700	0.06136

Shapiro-Wilk statistic (*W*) and it's probability (*p*), significance * $p<0.05$ and ** $p<0.01$. SPOF: Secondary Pine-Oak Forest. PA: Pasture. G: Gully. FL: Fallow land. CuA: *Cupresus* afforestation.

Table 4. Square matrix of P values for Tukey SHD test for *lnKfs* in the five studied sites *$p<0.05$, **$p<0.01$.

Error=2.6249 Degrees of freedom: 226				
SITE	PA	SPOF	G	FL
PA				
SPOF	0.000017**			
G	0.003265**	0.000017**		
FL	0.009041**	0.000017**	0.998614	
CuA	0.137900	0.000017**	0.998278	0.999982

SPOF: Secondary Pine-Oak Forest. PA: Pasture. G: Gully. FL: Fallow land. CuA: *Cupresus* afforestation

Table 5. Significative correlations between *lnKfs* and physicochemical soil properties at the site level (*p<0.05, **p<0.01).

Site	Variable	r	p	N
SPOF	% WSA 2–4	0.5358	0.002**	43
	% Silt	0.3994	0.029*	43
	BD	0.4408	0.015*	43
CuA	% Silt	0.2862	0.026*	48
	OrgC	0.6891	0.002**	49
PA	OrgC	0.3152	0.045*	42

SPOF: Secondary Pine-Oak Forest. CuA: Cupresus Afforestation. PA: Pasture. % WSA 2–4: Percentage of water stable aggregates with apparent diameter 2.0–4.0 mm. % silt: Percentage of silt. BD: Bulk density. OrgC: Soil organic carbon.

Table 6. Correlation matrix for *lnKfs* and another variables, statistical significance *p<0.05, **p<0.01.

		%WSA 2–4	%WSA 0.25–2	% Sand	% Clay	% Silt	BD	θ_0	θ_2	Org C
lnKfs	R	0.4869	0.3123	0.2557	−0.3312	0.1774	−0.3047	−0.1755	0.0192	0.4217
	p	0.0001**	0.0001**	0.002**	0.0001**	0.033**	0.0001**	0.035**	0.818	0.0001**

% WSA 2–4: Percentage of water stable aggregates with apparent diameter 2.0–4.0 mm. % WSA 0.25–2: Percentage of water stable aggregates with apparent diameter 0.25–2.0 mm. % Sand: percentage of sand. % Silt: percentage of silt. % Clay: percentage of clay. BD: Bulk density. θ_0 : Initial water content. θ_1 : Final water content. OrgC: Soil organic carbon.

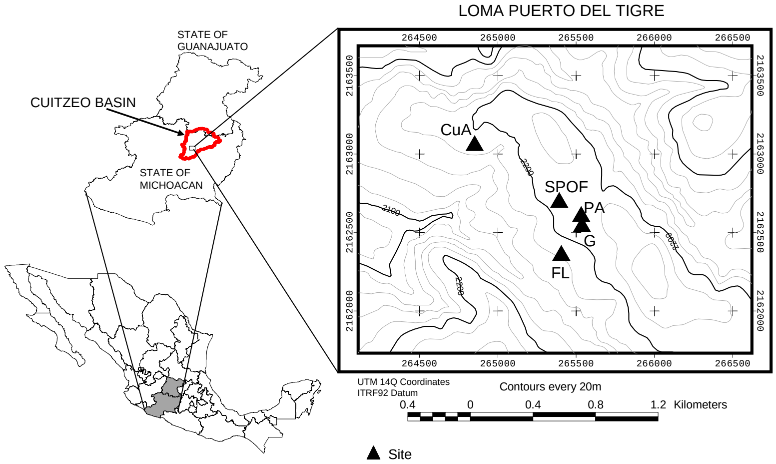

Fig. 1. Study area location. Secondary Pine-Oak Forest (SPOF), Pasture (PA), Fallow Land (FL), Cupresus Afforestation (CuA) and Gully (G).

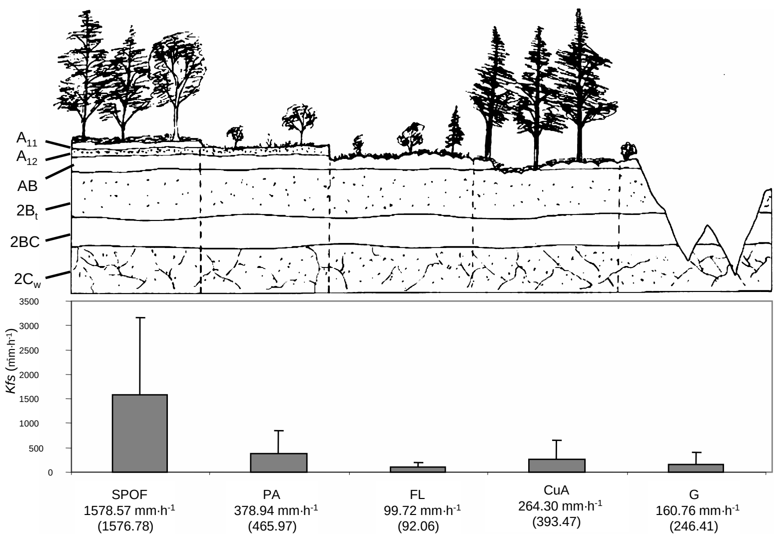

Fig. 2. Land cover type and land use, vertical variation of the analyzed sites and the field saturated hydraulic conductivity (*Kfs*), mean values and (standard deviations); Secondary Pine-Oak Forest (SPOF), Pasture (PA), Fallow Land (FL), Cupresus Afforestation (CuA) and Gully(G).