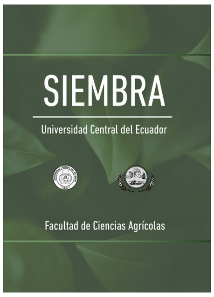
Original Article

Generation of soil maps permeability. Case study in two cantons of Loja province, Ecuador

Generación de mapas de permeabilidad de suelos. Estudio de caso en dos cantones de la provincia de Loja, Ecuador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Abstract

The generation of permeability maps is based on the analysis and interpretation of geology, environmental morphology, land use, and slope, which enables the selection of sampling areas with similar characteristics. The method represents the integration of the physical characteristics of the study area and then determines the infiltration capacity differences in the most representative geopedologic units. In determining the basic data, minidisc infiltrometers were used to perform seventy-two infiltration tests in different types of soils with varying organic matter content, texture, soil structure, and vegetation cover, which showed the spatial variability that exists in two cantons of Loja province, Ecuador. In addition, it was observed that the infiltration rate depended mainly on the content of the organic matter in the soil and is consistent with information collected on permeability worldwide. In this study, generated pedotransfer function (FTP) coefficient of determination R^2 0.78, the determination of the coefficient indicates a satisfactory estimate of the permeability with the variables that were analyzed; in addition, the methodology for assessing the permeability was suitable for the conditions of this investigation. For this reason, the method described here should be tested in other areas of the country with a greater number of field trials and with more variable contents of organic matter and soil textural classes.

Keywords: pedotransfer, GIS, soil mapping, soil physical properties, permeability

Resumen

La generación de mapas de permeabilidad se basa en el análisis e interpretación de la geología, la morfología ambiental, el uso del suelo y la pendiente, lo que permite seleccionar áreas de muestreo con características similares. El método representa la integración de las características físicas del área de estudio y luego determina las diferencias de capacidad de infiltración en las unidades geopedológicas más representativas. En la determinación de los datos básicos se utilizaron infiltrómetros minidisco para realizar setenta y dos pruebas de infiltración en diferentes tipos de suelos con diferente contenido de materia orgánica, textura, estructura del suelo y cobertura vegetal, lo que permitió evidenciar la variabilidad espacial que existe en dos cantones de la provincia de Loja, Ecuador. Además, se observó que la tasa de infiltración dependía principalmente del contenido de materia orgánica en el suelo y es consistente con la información recopilada sobre permeabilidad a nivel mundial. En este estudio se generó el coeficiente de determinación de la función de pedotransferencia (FTP) R2 0.78, la determinación del coeficiente indica una estimación satisfactoria de la permeabilidad con las variables que se analizaron; además, la metodología para evaluar la permeabilidad fue adecuada para las condiciones de esta investigación. Por esta razón, el método aquí descrito debería ser probado en otras zonas del país con un mayor número de ensayos de campo y con contenidos más variables de materia orgánica y clases texturales del suelo.

Palabras clave: pedotransferencia, SIG, cartografía de suelo, propiedades físicas del suelo, permeabilidad

1. Introduction

Infiltration is a complex, highly variable process that directly depends on the physical-chemical characteristics of soil (Bens et al., 2006; Bosch & West, 1998; Byers & Stephens, 1983; Espinosa & Rivera, 2016; Kirkham, 2005; Lal & Taylor, 1970; Moglen et al., 2022; Monsalve, 2006; Shukla et al., 2003). Its variability is related to differences in soil texture, slope, climate, vegetation, and farming practices (Bouyoucus, 1927; Salton & Mielniczuck, 1995). Infiltration has a fundamental role in the transport processes of water and contaminants, such as groundwater recharge and pollutant transport. Therefore, improving knowledge of the dynamics of water movement and solute flow in the soil allows better water management at both the farm and watershed scale (Bouyoucus, 1927; Casanova et al., 2003; Hincapié Gómez & Tobón Marín, 2012; Varni et al., 2005).

Infiltration refers to the maximum water entering into the soil profile. It differs from the percolation process because the latter is the downward movement of water from or through the unsaturated zone (Monsalve, 2006). The **initial** infiltration rate depends on the soil's antecedent moisture content before the water's introduction. When the infiltration rate reaches a plateau, it is equivalent to the saturated hydraulic conductivity. Thus, the hydraulic conductivity represents the degree of ease with which water passes through soil (Ankeny, 1992; Ankeny et al., 1991, 1988; Babalola 1978). On the other hand, permeability is the infiltration rate per unit gradient of the hydraulic head. Hence, infiltration rate, hydraulic conductivity, and permeability are closely related concepts, but permeability depends on the boundary conditions and mainly on the size and distribution of soil grains and the antecedent soil water content (Guatibonza et al. 2009; Monsalve, 2006).

The proper knowledge of these parameters – both temporally and spatially – allows the planning and designing of water systems. For instance, a correct estimation of infiltration rates allows the design of irrigation systems that apply the right amount of water, thus, avoiding agronomic issues, saving energy, and avoiding erosion problems (Tornés Oliveras et al., 2013)

The infiltration process can be described quantitatively by solving the complete transport equation[43] or by considering a relationship between cumulative infiltration and time, expressed in terms of parameters with a physical or empirical base (Haverkamp et al., 1990). Several field instruments exist to estimate the infiltration rate (Angulo-Jaramillo et al. 2000; Reynolds et al., 2002), but the disc infiltrometer is the main tool that helps in gathering information in the field and results in a considerable cost reduction (Sivapalan & Wood, 1986).

Most field instruments give information about the conductivity or infiltration rates referred to the point level. Consequently, it becomes difficult to determine the spatial variation of these parameters. Moreover, the variability of an area is influenced by factors such as vegetation cover, the presence of macropores, or systems of cracks on a small scale. This has a special influence on the determination of soil permeability, the infiltration rate per unit of land and its spatial variability (Williams et al., 1992).

In Ecuador, there is not a methodology to incorporate the criteria of soil texture, vegetation coverage, slope, and geomorphology, among others, into the permeability measure of the soil. The method commonly used is the infiltrometer cylinder, which requires large amounts of water and this hampers their use in slope conditions and difficult-to-access sampling points; thus, a low-cost method for quickly gathering information with little water consumption is a priority for use in the topographical conditions where this study was conducted.

Given the importance of permeability in the management of natural resources - especially land change- the main goal of this study is to analyze the variability of soil permeability within Loja Province using field infiltration tests. The specific objectives were (1) to analyze the influence of the bulk density, the soil organic matter, the permanent wilting point, and the field capacity on the spatial variation of the soil permeability, (2) to estimate the unsaturated hydraulic conductivity at sampling points based on infiltration rate data (3) to estimate the unsaturated hydraulic conductivity at sampling points based on pedotransfer functions in areas with similar geological, and morphological characteristics, and (4) to generate thematic maps of soil permeability.

The scope of this study is to establish a methodology for obtaining basic information that assists in the generation of soil permeability maps as an effective tool for territorial planning and irrigation system design (Meijerink, 1988; Zinck, 1988).

2. Materials & Methods

2.1. Thematic mapping

Thematic mapping is a technique that generates information on landforms, geomorphic processes, structure, composition and dynamics of soil and water, as well as information about soil, climate, slope, geomorphology, and land use (Carlón Allende & Mendoza, 2007; Meijerink, 1988; Zinck, 1988). Our approach integrates knowledge and data of morphology and slopes to identify areas of similar characteristics, with soils that are suitable for irrigation and susceptible to erosion (Carlón Allende & Mendoza, 2007; Zinck, 1988).

2.2. Selection and definition of variables

For infiltration mapping, the following layers were used (Centro de Levantamientos Integrados de Recursos Naturales por Sensores Remotos [CLIRSEN], 2010a, 2010b, 2010c, 2010d, 2010e), geology, morphology, and slope. To our knowledge, no systematic empirical research exists in Ecuador relating to the interactions between landscape morphology, the characteristics of rainfall, land use, surface properties, and their relation to water flow in soil. Additionally, the spatial variability of the land use is typically not integrated into the study because the area analyzed is an agricultural zone with a high rotation of crops.

Geological Units (Figure 1A) define landforms that share composition and structure (Winckell et al. 1991, 1997, 2000). The presence of Quaternary deposits and water infiltration increases the surface impact generated by the phenomena of washing and erosion; depending on the mobility of water transport in the territory, these phenomena can favor chemical weathering processes, increase vegetation activity or set a constant dynamic of erosion that can change the appearance of the terrain (Rodríguez Vidal, 1987).

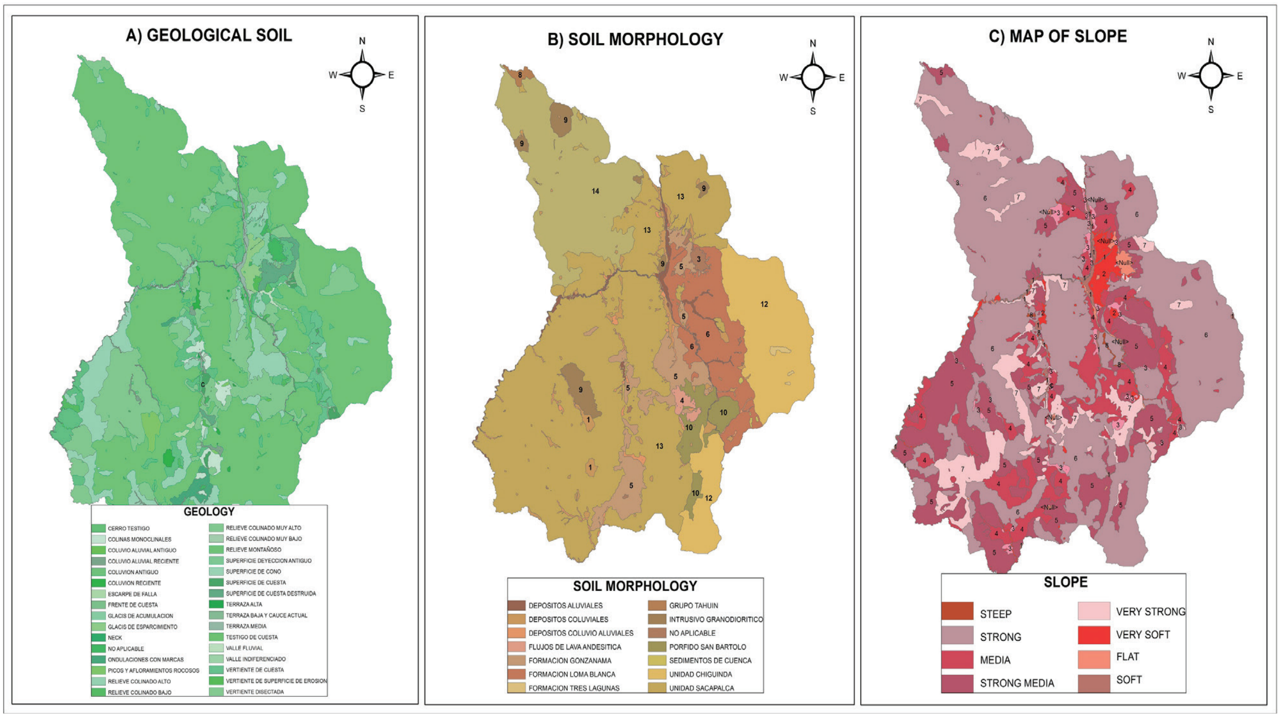

Figure 1. A) Categorization of geology, B) Categorization of morphology in the study area, C) Categorization of slope in the study area.
Figura 1. *A) Categorización geológica, B) Categorización morfológica, C) Categorización de la pendiente en la zona de estudio.*

Morphological Units (Figure 1B) detail landforms by describing soil horizons in terms of shape, composition, structure, organization, and color. These unique units refer to homogenous areas. Slope (Figure 1C) refers to the steepness with respect to the horizontal expressed as a percentage. This factor influences the movement of surface water, determining the effective contact time between water and soil. The classification of this parameter is important to determine land use, the magnitude of infiltration, and the surface and subsurface runoff (Gavin & Xue, 2008; Hincapié Gómez & Tobón Marín, 2012; Miyazaki, 1993; Philip, 1991). Despite its importance, there is little information regarding the effect of slope on water dynamics and soil hydraulic properties, and this information is even scarcer for Andisols.

2.3. Study Area

The study area is located in the southern part of Ecuador (Figure 2A), Loja Province. The height ranges from 800 to 1,700 meters above sea level, with an area of 76,000 hectares. The average rainfall is in the range of 250 - 1750 mm yr^{-1} (Figure 2B), the average temperature range is 11 - 23 degrees Celsius (Figure 2C). The soil and weather conditions favor livestock and agricultural production, which are 80 % and 15 % of the total production in the province respectively (Instituto Nacional de Estadística y Censos [INEC], 2000). The agriculture sector uses low-tech systems, and the main crops are sugar cane, tomatoes, peppers, and corn. There is no planning of natural resources in the province for production purposes.

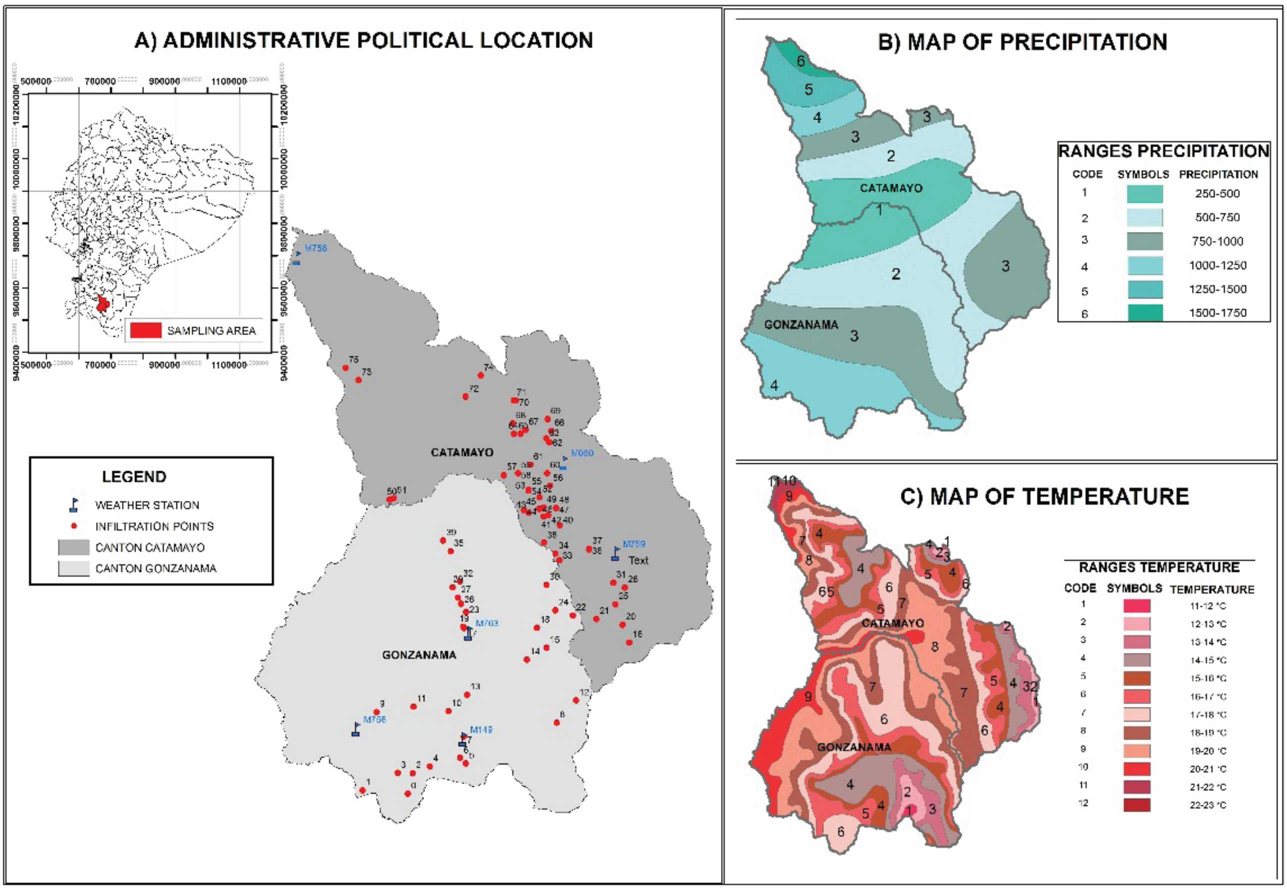

Figure 2. A) Administrative policy location of the study area in the Ecuadorian territory with the geographical location of the sampling points with methodology. B**)** Rainfall map C**)** Temperature map.
Figura 2*. A) Ubicación política administrativa del área de estudio en el territorio ecuatoriano, con la ubicación geográfica de los puntos de muestreo con metodología aplicada, B) Mapa de precipitación, C) Mapa de temperatura.*

2.4. Collection of information and field work

The process of identifying sampling sites was performed by characterizing known environmental units as homogeneous units. The identified areas provide relevant information in the study area because they integrate the information of morphology, geomorphology, and slope to locate spatial units of interest. The information generated about permeability is added through pedotransfer functions to be evaluated in response to the proposed classification of permeability (Table 1), with the specific goal of generating the theme map. At the same time, the permeability of the soils provides the basis for territorial planning of the irrigation areas in terms of land use and exploitation.

Table 1. Permeability rating methodology (Cisneros, 2001).
***Tabla 1**. Metodología de clasificación de la permeabilidad (Cisneros, 2001).*

Class	Designation	Rank (mm h^{-1})
1	Very fast	> 250
2	Fast	150 - 250
3	Moderately fast	65- 150
4	Moderate	20 - 65
5	Moderately slow	5 - 20
6	Slow	1.5 - 5
7	Very slow	< 1.5

We collected infiltration information by using a minidisc portable tension infiltrometer, The minidisk allows the quantitative identification of the relative contribution of the key hydrodynamic parameters that depend on the flow of infiltrated water and pressure during the water application, which is the unsaturated hydraulic conductivity (Angulo-Jaramillo et al., 2000; Aoki & Sereno, 2005; Wilson & Luxmoore, 1988). The infiltrometer is fixed to the ground with a ring to create tension between the soil and the water in the tank so that measurements can be performed based on the time elapsed to infiltrate all water contained in the tank, The potential is controlled by a cylinder bubbler connected to the reservoir (Ruiz Sinoga et al. 2003).

The main advantages of use of the infiltrometer (Romero Díaz et al., 2010) are that (1) it allows a large number of measurements in less time because it reaches the stable rate of infiltration faster; (2) it has easy-to-use instrumentation; (3) there is no need to calibrate the tension, the method accepts the textural parameters of the Van Genuchten floor; thus, it is necessary to have previously analyzed the texture and set it to the 12 classes (Babalola, 1978; Bosch & West, 1998); (4) the infiltrometers can be easily transported due to their small size and low water requirements; and (5) they do not need much smooth surface in the field because the diameter of the cylinder is small. This is a very important advantage on hillsides or where the slope is high, approximately 20 %. Fieldwork using the minidisc has been successfully carried out by Zhang (Aoki & Sereno, 2005; Ruiz Sinoga et al., 2003; Zhang, 1997; Zhang et al., 1999).

The 77 sampling points were georeferenced by GPS measurements (Juno 5B, Trimble. Precision 2 m). Samples were taken from different sites to capture the variability of the slope, geology, morphology, and soil coverage. The extent of the area, the ease of access, and the spatial density influenced the sample number. Additionally, we sampled soil at a 30 cm depth using a Kopecky cylinder to determine gravimetric moisture, porosity, void ratio, and bulk density (Guatibonza et al., 2009). The textural class was based on the Bouyoucos method (Bouyoucus, 1927; Ritsema et al., 1996) and organic matter was determined by the Walkley and Black method (Nelson & Sommers, 2018; Walkley & Black, 1934; Walkley, 1947).

The methodology used for this study was chosen to define the effects of water in the soil; the data obtained on the permeability were subsequently evaluated with the model proposed by Zhang in 1997 (Ruiz Sinoga et al., 2003). The resulting values were reclassified to a scale applied in land use capacity for agriculture irrigation (Cisneros, 2003), which allowed information to be simplified to known ranges.

To estimate hydraulic properties, such as hydraulic conductivity and water holding capacity, we used pedotransfer functions in the points where sampling for information about permeability could not be made; at these points, the hydraulic conductivity was not saturated by integrating the textural class (Rawls & Brakensiek, 1985; Vereecken et al., 1989; Zimmermann & Basile, 2007, 2008). Although these functions cannot replace direct measurements of some soil properties, they can improve the prediction of field data in areas that are difficult to access, i.e., to extend from the pedón level to broader map units (Casanova et al., 2003), whereby it was possible to predict the values of permeability to areas where no measurements are taken in situ.

2.5. Analysis of patterns

Differences in the infiltration data can be explained by the fact that Zhang's method applied to infiltration values and different textural parameters from Genuchten. To find similar textural characteristics, the conductivity values must be similar, so the method exerts direct influence on the hydrodynamic behavior of the soil; in addition, other physical factors influence this methodology (Romero Díaz et al., 2010; Ruiz Sinoga et al., 2003), to evaluate pedotransfer functions. Therefore, the data obtained from the infiltration tests results are the associated texture (% clay, % sand, % silt) and organic matter of the physical analysis for each soil sampling point because the data have similar values and the soils tend to have conductivity (Reynolds et al., 2002).

3. Results

According to the pedotransfer function [equation 1] for permeability with a goodness of fit $R^2 = 0.78$, permeability values could be estimated for the different areas where permeability information cannot be obtained. The percentage of organic matter constitutes the most significant independent variable ($p < 0.05$), which is consistent with several studies mentioning the effects of organic matter on the behavior of hydraulic conductivity (Casanova et al., 2003; Genuchten, 1980). These studies concluded that there is an intimate relationship between this parameter and increased permeability.

$$Perm = -89.988 + 0.378\,(\%\,clay) + 0.133\,(\%\,sand) + 0.2657\,(\%silt) + 11.893\,(\%M.O.)^{*} \quad [1]$$

* Perm: Soil Permeability; M.O: Organic matter.

The locations of the field tests are shown in Figure 2A, while Figure 3 shows the map with the reclassified data according to Table 1. The values of the magnitude of the soil parameters are similar to Aoki and Sereno (2005) and White and Sully (1987), who worked with pressure 1 cm in a loam soil, obtaining values of hydraulic conductivity (Ko) of 12.6 m h^{-1}). Smettem et al. (1994), estimated a Ko of 56 mm h^{-1} using a sandy loam soil, with a water application pressure of 2 cm.

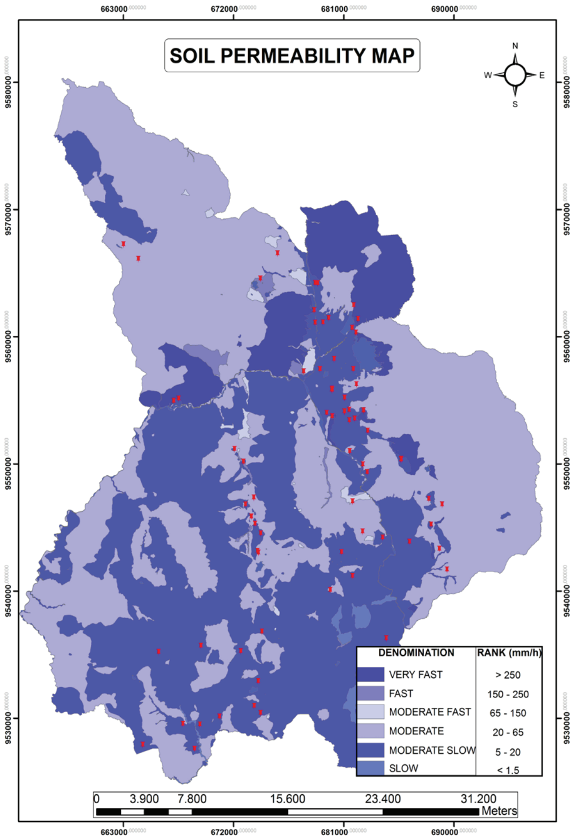

Figure 3. Permeability map of the study area.
Figura 3*. Mapa de permeabilidad de la zona de estudio.*

Following the classification rules (CLIRSEN, 2010a), areas with permeability values above 180 mm h^{-1} (fast drainage, low water holding capacity) or below 3.6 mm h^{-1} (low drainage capacity) are not suitable for irrigation systems (8.3 %, 11,065 ha). Figure 4 shows that the study areas of Class 4 (moderate) and Class 5 (moderately slow) soils predominate. Both classes present the irrigation potential, with an organic matter content in the range of 2 - 6 % and textures of loam clay, silty and clay, loam silt clay; these classes present good opportunities for irrigation. The infiltration rate is mainly affected by the amount of organic matter as it shows strong spatial correlation (Rawls & Brakensiek, 1985; Williams et al., 1992; Zimmermann & Basile, 2008).

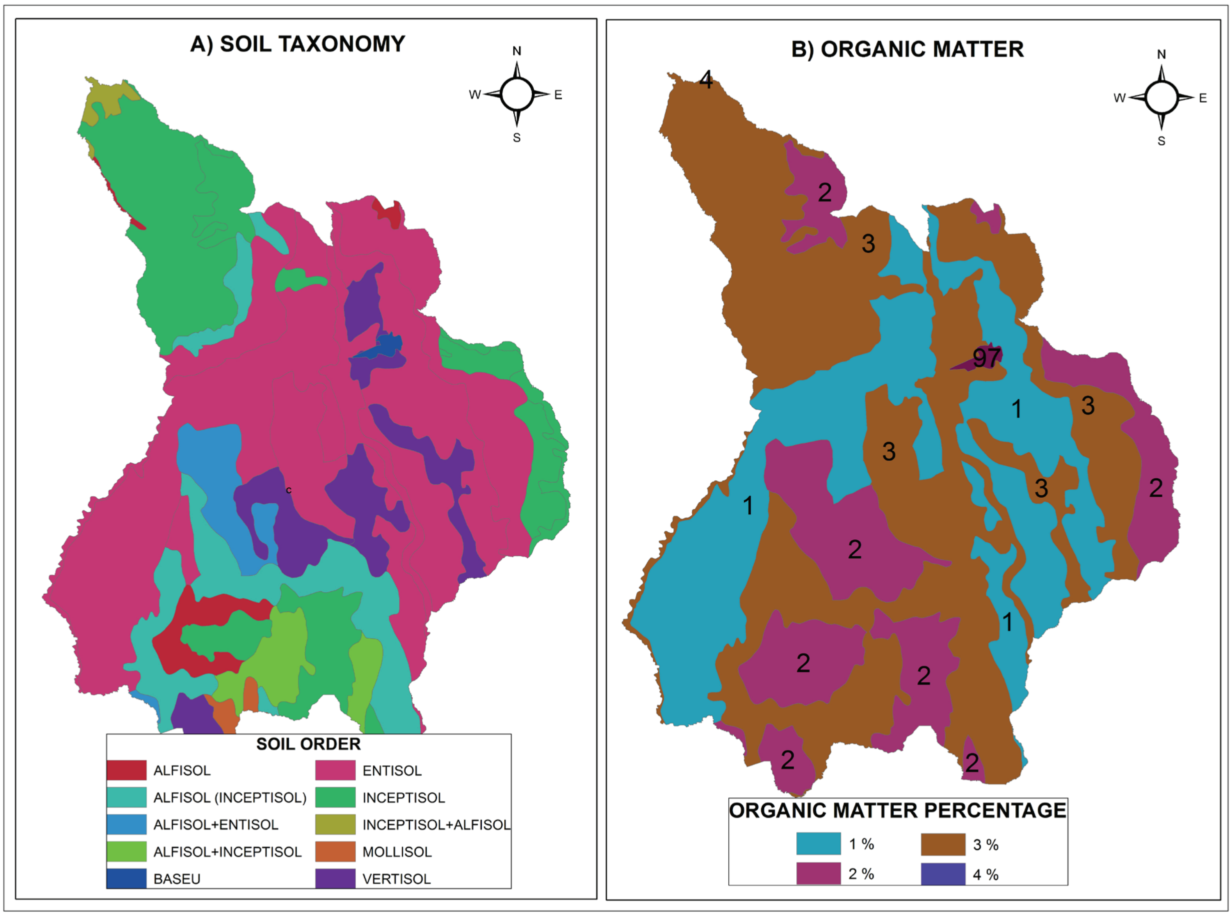

Figure 4. A) Map Soil taxonomy, B) Map Organic matter.
Figura 4*. A) Mapa taxonómico del suelo, B) Mapa Materia orgánica.*

4. Discussion

From the methodological point of view, we note that the method can obtain satisfactory results that can be adjusted to other methods; moreover, easy handling and the speed of obtaining reliable data given the small area of hydraulic contact with soil, together with the ability to reproduce in situ various experiments and intensify sampling areas, are favorable circumstances for the implementation of this methodology (Romero Díaz et al., 2010; Ruiz Sinoga et al., 2003) (Figure 5).

Note also that the results obtained in this paper with the application of the pedotransfer function methodology improve the prognosis of the soil hydraulic parameters, (Figure 5), which is mainly due to the inclusion of additional variables, such as bulk density, particle size composition (Zimmermann & Basile, 2007, 2008).

The concept of environmental units allowed the integration of sectorial reporting of climate, geology, slope, geomorphology, and vegetation to detect areas homogeneous both in their physical characteristics and behavior with internal consistency.

The integrative use of fieldwork and pedotransfer functions provides a “smoother reality” (Paz González et al., 2001), and it allows the definition or extraction of relevant information for soil use and management.

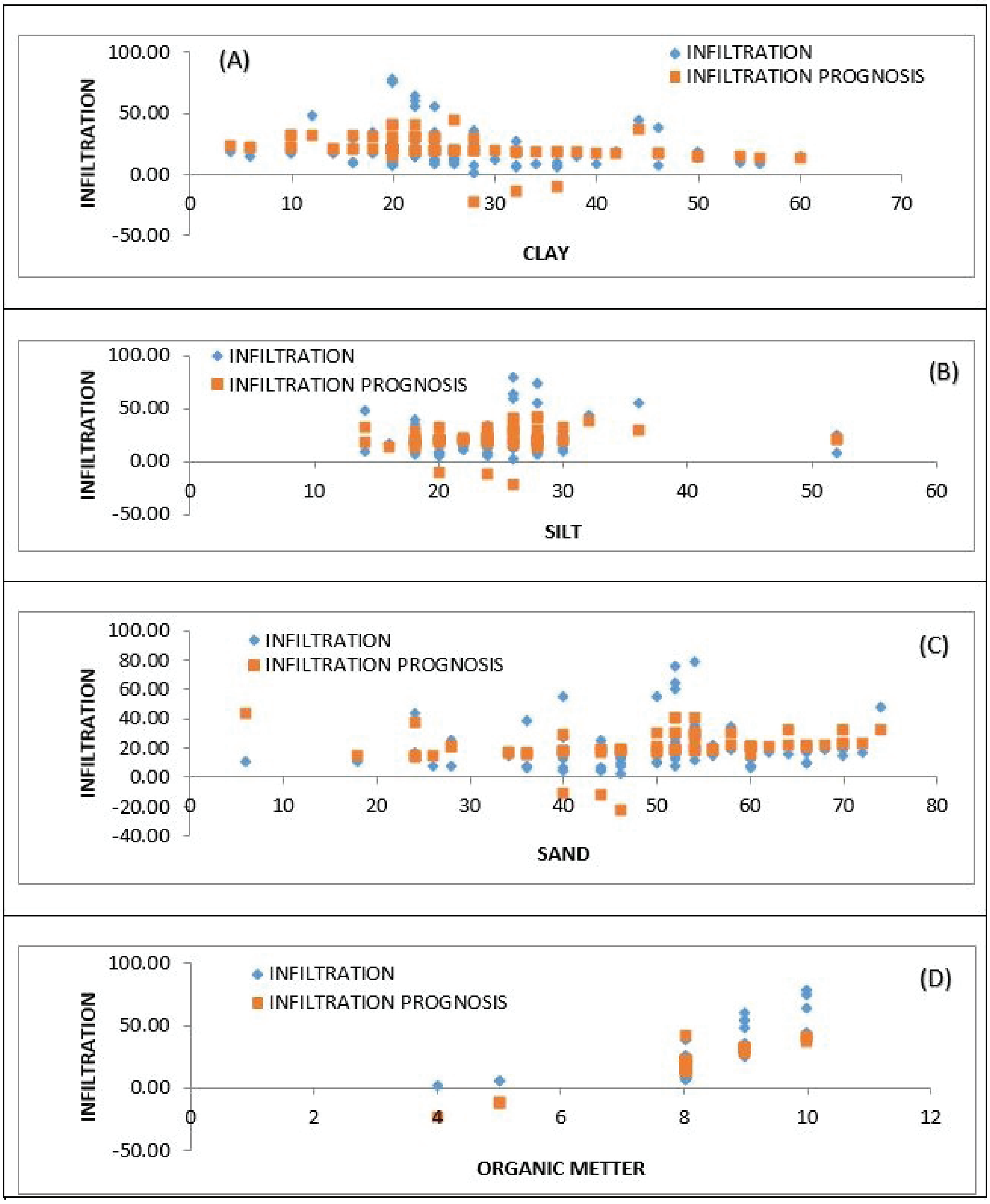

Figure 5. Prognosis of infiltration whit pedotranfer function A) Clay, B) Silt, C) Sand, D) Organic matter.
Figura 5*. Pronóstico de infiltración con función pedotranfer A) Arcilla, B) Limo, C) Arena, D) Materia orgánica.*

5. Conclusions

The multiple linear regression equations acceptably estimated the permeability values from a minimum of information available from the soil mapping (Li et al., 2019).

The generated permeability map and the proposed methodology provide a clear conception of system variability in the structure of soil properties. It was possible to demonstrate the usefulness of incorporating environmental physical heterogeneity into the theoretical models referenced by graphical representation, which also served to analyze the uncertainty of the obtained results by simulation (Comegna & Vitale, 1993; Rawls et al., 1983).

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Contributor Roles

- Jorge Andrés Espinosa Marín: conceptualization, investigation, methodology, resources.
- Diego Rivera: validation, formal analysis, writing – review & editing.
- Renato Haro Prado: visualization.

Ethical Issues

Ethics approval Not applicable.

Conflict of Interest

The authors declare that they have no affiliation with any organization with a direct or indirect financial interest that could have appeared to influence the work reported.

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