Impacts of soil infiltration and its determinants on water resource management on semiarid conditions

Nelson Virgilio Piraneque-Gambasica*, Sonia Esperanza Aguirre-Forero, Laureano José Ordoñez-Thalliens

(*Department of Agricultural Sciences, Universidad del Magdalena, Santa Marta 470001, Colombia*)

Abstract: Infiltration is a critical process within the hydrological cycle and plays a fundamental role in agricultural activity, irrigation design, and soil and water conservation efforts. Various factors, including soil properties, precipitation patterns, and flow conditions, influence this complex process. Therefore, understanding the soil's hydraulic properties, including infiltration, is essential for efficient water resources management. With this in mind, a field study was carried out to assess soil water infiltration across 33 productive units under semiarid conditions. In each case, the predominant landform was characterized, infiltration rates were measured using a double-ring infiltrometer, and soil samples were collected to determine texture, bulk density, soil organic matter, saturation point, field capacity, and electrical conductivity. Based on these data, the infiltration rate, volumetric moisture content, retained water, irrigation interval, and irrigation time were established. The study revealed that the predominant soil types were inceptisols and entisols, which are commonly associated with landforms such as plains, alluvial plains, hills, foothills, and mountains. Soils in these regions primarily exhibited clayey, sandy loam, and sandy clay loam textures. Infiltration rates varied significantly depending on soil texture, ranging from less than 8.00 cm/h to 18.83 cm/h. Additionally, agricultural activities were found to reduce water infiltration rates, indicating that land use practices have a direct impact on this process. Electrical conductivity had a negative effect on infiltration rates in the study area. This research highlights the variables that influence infiltration across different landforms, textural classes, and infiltration types, demonstrating spatial variation. These findings have important implications for the development of sustainable agricultural systems that promote both water and soil conservation.

Keywords: soil and water conservation, sustainable agricultural systems, agricultural land use, soil hydraulic properties, water infiltration, irrigation, semiarid environment

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1 Introduction

Soil infiltration is an obligatory step in the hydrological cycle[1], affecting the moisture of the resource at different depths and thus controlling the availability of water and nutrients for crops, which is controlled by factors such as depth, geomorphology, hydraulic properties of the soil, and climatic properties[2]. Considering that soils are highly variable temporally and spatially, it is necessary to verify the characteristics that can influence water infiltration capacity under field conditions[2] and, with this input, to estimate when and how much to irrigate to control applications and thereby reduce the risks associated with excess surface water.

The Department of Magdalena (Colombia) is located in the intertropical convergence zone and is characterized by high climatic vulnerability, prolonged periods of drought, and heavy rainfall. The predominant soil moisture regime is ustic[3], with a temperature of 27.3°C, an annual average rainfall of 1332 mm, and 1820 mm of evapotranspiration. This generates 488 mm of water deficit, which is typical of tropical dry forest (BS-t), although there are wetlands and mangrove forests near Ciénaga Grande de Santa Marta[4]. However, the economic activity of the department is focused on the agricultural, tourism, and port sectors. The products grown are bananas, African palm, tobacco, cotton, rice, and some fruit trees and vegetables, with the implementation of irrigation systems. The trend in the territory shows an increase in air temperature and potential evapotranspiration, and a reduction in vegetation cover[5].

Therefore, it is essential to understand water infiltration, water retention, and movement in the soil to achieve optimal use of water resources and planning of land use and management, so it is necessary to have records, if possible, by specific site. However, this information is lacking, and it is important to implement infiltration tests that consider the irrigation rates and times per site and landform and their relationships with edaphic characteristics in the study area. The amount of water that infiltrates the soil per unit area and per unit time when the soil is saturated determines the infiltration rate[6], and the most widely used method is the double ring method because of its ease of access for estimating the hydraulic properties of the soil. However, the infiltration rate is affected by the following soil profile characteristics: texture, structure, presence of soil organic matter (SOM), minerals, and size and total volume of the pore space[7]. The size, shape, and continuity of pores are determinants of air and water movement and directly influence infiltration and permeability, and soil use and management practices have a marked effect on the soil water infiltration process[2].

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Biographies: Sonia Esperanza Aguirre-Forero, PhD, research interest: agricultural sciences, Email: saguirre@unimagdalena.edu.co; **Laureano José Ordoñez-Thalliens**, MS, research interest: agricultural sciences, Email: laureanoordonezjt@unimagdalena.edu.co.

***Corresponding author: Nelson Virgilio Piraneque-Gambasica**, Professor, research interest: agricultural sciences, Department of Agricultural Sciences, Universidad del Magdalena, Santa Marta 470001, Colombia. Tel: +57-3005545742, Email: npiraneque@unimagdalena.edu.co.

Thus, the soil infiltration capacity determines the rate at which water can be applied to its surface without runoff (sprinkler irrigation), which helps to identify the most efficient furrow length for surface irrigation. Hence, knowledge of soil hydraulic properties is essential for solving a range of problems, such as the predicted runoff from precipitation events, sediment transport, flood control, modeling of hydrological processes and their relationships with pollutant transport, and estimates of aquifer recharge, among others, making it central to soil conservation and sustainable agricultural production desirable in regenerative agriculture.

Most of the farmers in the department apply irrigation without knowing the soil moisture and water needs of their crops. This situation means that, despite the positive effects of irrigation, there are adverse effects on soil quality and poor management of water resources in rural areas; in this regard, many of the farms are supplied by groundwater (water for future generations), which contains salts such as chlorides, carbonates, and bicarbonates, thus increasing the risk of salinization because of the climatic conditions of the area. Therefore, the objective of this study was to evaluate edaphic and hydrological parameters in 33 productive units (PUs) in 11 municipalities located in different landforms of the Department of Magdalena with tropical dry climate conditions. Thus, the method of water resource management can be optimized, and sustainable water resource management can be achieved.

2 Methods

2.1 Location of the tested soils

The research was carried out in a significant number of 33 productive units (PUs) within the Department of Magdalena, Colombia, distributed across 11 municipalities: San Sebastián, El Piñón, Guamal, Santa Ana, Zona Bananera, Plato, Ciénaga, Ariguaní, Difícil, Santa Marta, Sitio Nuevo, and Pivijay. The study covered three life zones (tropical dry forest, very dry tropical forest, and premontane moist forest) and six landforms (mountain, foothills, plains, alluvial plains, and hills).

2.2 Field experimental design

For each sampling site, the precise location in the area, geomorphology and soil characteristics (plowing conditions, existing vegetation, cracks, humidity), and recent management practices were recorded. A 1 kg sample of soil was collected for laboratory analysis of the texture, bulk density (Bd), soil organic matter (SOM), saturation point (PS), and field capacity (Fc) obtained by capillary action using the undisturbed beveled cylinder at 48 and 72 h; finally, the soil electrical conductivity (EC) was determined (Table 1).

Table 1 Soil analysis

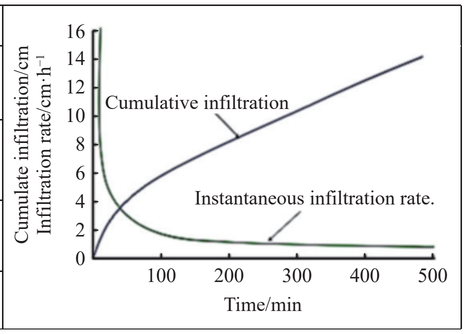
Property	Metodology	Unit
Texture	Bouyoucos	%
Bulk density (Bd)	Bevelled cylinder	$g\cdot cm^{-3}$
Saturation point (PS)	Capillarity	%
Field capacity (Fc)	Capillarity	%
Organic matter (SOM)	Walkley & Black	%
Electrical conductivity (EC)	Conductivity meter	$dS\cdot m^{-1}$

The infiltration tests were carried out at representative sites within the farms to be characterized. A double-ring infiltrometer was used to determine soil infiltration, as described by Forsythe, and the empirical model used was the Kostiakov model[8] adjusted to infiltration within the limits of agricultural interest[9,10]. These tests yielded results with significant implications, providing practical insights into soil management.

Two cylinders were installed: a 30 cm (diameter)×30 cm (height) inner cylinder, and a 50 cm (diameter)×20 cm (height) outer cylinder. The outer ring was inserted to a depth of 5 cm, and the inner ring was inserted to a depth of 10 cm. The outer ring was maintained with a 10 cm sheet of water during the test. The inner ring was filled and read with a graduated ruler at intervals of 1, 2, 3, 4, 5, 5, 10, 20, 20, 30, 45, 60, 90, and 120 min. The water level in the inner ring reached 7 cm at its lowest point. For each time interval, the infiltration rate per system was averaged.

Once the data were obtained, a curve was fitted using the Kostyakov equation, $I = a\cdot b\cdot t^{b-1}$ [11], where I is the infiltration rate (cm/h), t is the time (h), a is the intercept, and b is the slope of the curve. The average infiltration rate was estimated two hours after the beginning of the process. The accumulated infiltration rate calculations consider the sum of the point values of infiltration obtained from the instantaneous infiltration rate curve. Figure 1 illustrates the accumulated infiltration equation, which is derived by calculating the area enclosed by this curve and the axis by integrating its equation between the boundary values $t_{initial}$=0 and t_{final})[8].

Based on Equation 1:	$Inf=a\cdot b\cdot t^{b-1}$
Defining the integral area:	$A=\sum_{t=0}^{t} dt\times Inf \int_{t=0}^{t} Inf\times dt$
Substituting in the integral:	$A=Icum=\int_{t0}^{t} a\cdot t^{b}\times dt$
Integrating:	$Icum=\left(\frac{a}{b+1}\right)\times t^{b+1}$
Simplifying:	$Icum=At^{B}$



Note: $B=b+1$; $0<B<1$; $A=a/B$. Source: adapted by the authors.

Figure 1 Characteristic curves of infiltration rate and soil cumulative infiltration

The results were interpreted according to [12] and [13] (Table 2).

In the literature review, there are authors who consider soil texture to calculate the infiltration rate (Inf). Table 3 shows the ranges used in this research.

2.3 Data analysis

The infiltration rate (cm/h) per PU, sand content A (%), clay content Ar (%), bulk density Bd (g/cm^3), organic matter OM (%), field capacity Fc, saturation point SP, electrical conductivity EC ($dS\cdot m^{-1}$), texture classification, volumetric moisture VM (%), retained water (mm), irrigation interval TR, and irrigation time were measured in the soil of each property (PU). A database matrix was built with the records from the PU, with which a graphical and

Table 2 Interpretation ranges for soil infiltration rates

Interpretation type	Infiltration rate (Inf.)		
	Montenegro[11]	Bradbury(SCS)[12]	Authors*
	cm·h⁻¹	cm·h⁻¹	cm·h⁻¹
Very slow	<0.1	<1.3	<1.3
Slow	0.1-0.5	3.6-1.3	1.3-2.0
Moderately slow	0.5-2.0	-	2.0-3.8
Moderate	2.0-6.3	7.6-3.8	3.8-7.6
Moderately fast	6.3-12.7	-	-
Fast	12.7-25.4	>7.6	7.6-25.4
Very fast	>25.4	-	>25.4

Note: *: average ranges adapted by the authors; same as below.

Table 3 Infiltration rate ranges according to soil texture

Soil texture type	Inf./cm·h⁻¹	Infiltration type*
Sand	>2.0	Very fast
Silty sand	1.0-2.0	Moderately fast
Loam	0.5-1.0	Moderate
Clay	0.5-0.1	Slow-Moderately slow
Sodic clay	<0.1	Very slow

numerical interpretation of the variables analyzed in the 33 farms (PUs) during 2023 was carried out. The relationships between the infiltration rate and the measured variables were established through Spearman correlation analysis. A principal component analysis was performed to reduce the dimensionality of the information, followed by nonparametric tests. The data were organized using Euclidean distances and the *R* scale function to standardize the magnitude and the measured units, whereas the differences between landforms, textures, and infiltration types were evaluated with a two-way multivariate analysis of variance (PERMANOVA)[14]. A canonical discriminant analysis was conducted on the basis of a multivariate linear model to verify how the infiltration rate (Inf.) varies on the basis of landforms, texture, and infiltration type, where the transformation of continuous variables was carried out in a canonical space while controlling for model terms. Finally, a regression model was tested where the independent variable was time, and the dependent variable was the infiltration rate. The experimental data were processed using the *R* statistical software at https://www.r-project.org/.

3 Results

3.1 The soils of the experimental area

According to the soil study [4], the predominant soils in the experimental area belong to the Inceptisol and Entisol orders, with little evolution and conditioned by the climate (low rainfall and high temperatures), moderately deep as representative of the *Typic Haplustept*, well to imperfectly drained, with fine textures, and strongly acidic to alkaline. *Typic Humudepts* are soils with an udic moisture regime[3] and have either humic epipedon (18 cm deep with moderate to strong resistance to breakdown and rocky structure with fine stratification) or humic (thin horizon <18 cm, dark, rich in organic matter at the surface with moderate to strong resistance to breakdown, and rocky structure with fine stratification).

Typic endoaquepts are characterized by the water table being within the first 100 cm of soil during an average year, so there are traces of oxide-reducing conditions and grey colorations, which differ from those of *Vertic Endoaquepts* in that the latter have vertical properties with cracks greater than 5 mm and sliding surfaces. Finally, the *Typic ustipsamment*, Entisols are characterized by a ustic moisture regime with at least 35% rock fragments and fine sandy loam textures throughout the profile.

3.2 Landforms in the experimental field

With satellite images, different landforms were found: terrace fan, rows and beams, fluvio-marine terrace, structural hill, and glacis at a general level and in the production unit (PU). In the field, plains (40% of the PUs), alluvial plains (15%), hills (33%), mountains (6%), and foothills (6%) were found (Table 4), which allows us to verify their influence on climate, vegetation distribution, and animal life, characteristics that condition the water distribution, with surface outlets through bends, channels, streams and main channels, and where low slopes favor surface retention. However, as the slope increases, subterranean drainage deteriorates, particularly in soils with poorly consolidated materials, which are subject to landslide[15]. Thus, landforms contribute to soil (irrigation and tillage) and water management since they determine, to a greater or lesser extent, the use, degradation, and degree of soil erosion[16].

Table 4 Physical soil characteristics of the 33 farms surveyed

PU	Landform	Clay %	Sand %	Texture	OM %	Bd g·cm⁻³	EC dS·m⁻¹	Fc %	PS %
1	Alluvial plains	48	44	Clay	1.530	1.43	2.34	37	74
2	Plains	50	46	Sandy clay	0.650	1.51	0.32	18	37
3	Alluvial plains	52	40	Clay	1.810	1.38	5.00	31	62
4	Hills	30	66	Sandy clay loam	0.830	1.57	0.30	24	48
5	Hills	8	88	Loamy sand	0.770	1.55	0.22	13	25
6	Plains	12	84	Loamy sand	0.240	1.64	0.16	13	26
7	Plains	54	40	Clay	1.160	1.42	0.57	29	78
8	Alluvial plains	46	32	Clay	3.800	1.19	0.29	36	74
9	Mountains*	50	42	Clay	2.100	1.38	0.15	26	51
10	Mountains*	36	30	Clay loam	5.000	1.09	0.41	29	51
11	Plains	48	44	Clay	1.860	1.40	0.31	26	51
12	Hills	48	38	Clay	2.640	1.32	0.56	28	56
13	Hills	46	38	Clay	3.070	1.29	0.51	31	61
14	Hills	50	38	Clay	2.670	1.31	0.32	38	75
15	Plains	52	38	Clay	1.900	1.36	1.29	39	78
16	Alluvial plains	50	42	Clay	1.610	1.42	0.50	30	62
17	Hills	46	34	Clay	3.500	1.22	0.51	38	76
18	Hills	8	88	Loamy sand	0.820	1.54	1.05	17	34
19	Hills	48	42	Clay	2.900	1.32	0.40	30	60
20	Foothills	32	64	Sandy clay loam	0.730	1.58	0.23	16	32
21	Plains	54	38	Clay	2.400	1.32	1.27	41	83
22	Foothills	10	84	Loamy sand	0.624	1.59	0.47	16	32
23	Plains	12	84	Loamy sand	0.796	1.58	0.59	12	24
24	Plains	8	88	Loamy sand	0.796	1.54	0.19	13	27
25	Plains	8	82	Loamy sand	0.748	1.52	0.32	21	41
26	Plains	26	70	Sandy clay loam	0.759	1.60	0.46	21	41
27	Plains	8	88	Loamy sand	0.593	1.56	0.98	18	36
28	Plains	48	42	Clay	2.000	1.38	3.36	35	70
29	Alluvial plains	26	70	Sandy clay loam	0.710	1.61	0.44	25	51
30	Hills	58	36	Clay	1.280	1.38	0.54	39	78
31	Plains	12	84	Loamy sand	0.476	1.61	1.02	13	25
32	Hills	48	44	Clay	1.660	1.42	0.71	28	55
33	Hills	52	40	Clay	1.580	1.40	0.42	29	59

3.3 Soil properties in the studied production units

Table 4 summarizes the edaphic properties found in the 33 PUs analyzed during the research. The mean and median values are similar for each of the properties studied, indicating symmetrical distributions in OM, Bd, Fc, and PS.

Many factors affect the infiltration process in the soil system[17,18], including the type of flow, soil surface conditions, hydrophobicity of some compounds (aromatic oils, phenols), soil mechanical processes, climatic conditions of the area, and organic matter content, among others. As described above, the estimation methods vary from theoretical equations based on physics to in situ measurement methods. Herein, this study characterized those factors that could be measured in the field: soil texture, organic matter content, bulk density, electrical conductivity, soil field capacity, and the soil saturation point.

3.3.1 Soil texture of the tested soils

The sand, silt, and clay particles impact the infiltration rate. Coarser textures are fast, Inf.>2 (cm/h); finer textures are slower, with clays between 0.1-0.5 (cm/h) (Table 3). High infiltration rates can mean that water moves too fast through the soil profile, limiting the amount of water available to plants[19]. Among the 33 sites characterized, 54.5% were predominantly clay, 27.3% were loamy sand, 12.12% were sandy clay loam, 3% were sandy clay, and 3% were clay loam. In this respect, textural class affects the rate at which water drains through saturated soil, moving more freely through sandy soils than through clay soils. Clay soils have a relatively high water-holding capacity. However, some clay types swell during wetting and deflate when they lose water, and swelling inhibits infiltration, whereas shrinkage of clays can cause ground cracking and increased flow through micropores[20]. Notably, the type of clay was not determined in this work.

3.3.2 Organic matter of the tested soils

OM content affects porosity and bulk density, which causes the infiltration rate to change, leading to an increase in Inf[16,21]. The highest contents were found in the mountains, with values above 3%, which are high for warm climates, as opposed to those found in the foothills and plains, where averages were less than 1%, possibly resulting from the higher temperatures and lower rainfall that lead to higher rates of mineralization. The finer textures (clay loam and clay) presented the highest averages, with values above 2%; this is in contrast to the coarse textures, with averages below 1%, which affects properties such as aggregation, moisture retention, cation exchange capacity, and nutrient retention for plants. Stubble, fallow land, and poultry use showed the lowest values for the variable, again demonstrating the impact of these practices on the mineralization and/or loss of SOM.

The soil organic matter content in the study area tends to be low (<2%), which indicates that accelerated mineralization predominates because of the environmental conditions of the area (temperature above 22°C and low rainfall), which directly influences the vegetation cover, which is essential for the cycle of organic waste in the agroecosystem. Among the 33 points, the agroecosystems present in PUs 10 and 9 presented different behaviors, with higher percentages of SOM, as did those in PU 8 (3.8%), 17 (3.5%), 19 (2.9%), 21 (2.4%), and 28 (2.0%).

3.3.3 Bulk density of soils in the experimental area

A total of 45.5% of the plots had bulk densities lower than 1.4 g/cm^3. The highest values were found in foothills and plains (1.59 and 1.50 g/cm^3, respectively), with differences in hills and mountains (1.39 and 1.24 g/cm^3, respectively). Coarse textures, such as sandy clay loam and loamy sand (averaging 1.59 and 1.58 g/cm^3, respectively), contrasted with the clay and clay loam textures prevalent in 57.5% of the PUs. Fine-textured plots tend to reduce pore space and increase density, thus reaching the compaction limit for clayey textures. The uses did not differ; however, it should be noted that only poultry farming, extensive livestock farming, and mango cultivation presented mean densities lower than 1.4 g/cm.

3.3.4 Soil electrical conductivity of the experimental area

11% of the productive units (PUs) presented ECs greater than 2 dS/m (PUs: 1, 3, and 28), corresponding to plains and alluvial plains. In these areas, salts accumulate because of the prevailing edaphoclimatic conditions, characterized by temperatures exceeding 23°C and low precipitation (less than 800 mm/year). Although the percentage is not high, it remains a limiting factor for agriculture and indicates soil degradation. The alluvial plain had a significantly greater EC than did the other landforms, with a mean of 1.781 dS/m, whereas mountains had the lowest mean of 0.28 dS/m. The soil salt content can originate from irrigation water and accumulate in the soil profile.

In contrast, while some nutrients from these salts may benefit plants, others, particularly sodium (Na), can inhibit plant water availability and soil structure, reduce infiltration and potentially lead to crusting, significantly reducing water infiltration. These factors are correlated with hydrological variables in semiarid ecosystems. Electrical conductivity is a significant variable for predicting infiltration and erosion[22].

3.3.5 Field capacity of soils

Despite some differences, the alluvial plain presented the highest mean value for field capacity at 31.8%. Pie de Monte presented the lowest value at 16%. In terms of soil texture, the fine-textured soils (clay and clay loam) presented the highest values, with values of 32.83% and 29%, respectively. In contrast, the sandy clay texture had the lowest mean value, 15.11%. Additionally, the field capacity associated with poultry and pasture activities (39% and 37%, respectively) was greater than that associated with the stubble areas (13%). These findings suggest a more significant accumulation of sand in the foothills and stubble areas, where sandy textures predominate, which reduces the water retention capacity of the soil. Field capacity (*Fc*) is broadly defined as the volumetric water content that a soil retains after gravitational drainage, i.e., the water retained by the pore space. Depending on the soil type, this value may represent about 30% of the soil mass, with the matric potential at which Fc is defined ranging between –5 and –33 kPa[23]. Thus, soils with low moisture contents, such as those with loamy sandy textures (particle sizes greater than 0.02 mm) in this research, restrict the movement of water to plant roots, limiting nutrient uptake and negatively impacting seed germination. In contrast, land use practices in tropical climates with low rainfall involving the removal of vegetation cover lead to increased evaporation, which reduces water for crops. This forces plants to spend additional energy extracting water from the soil, which increases water stress and reduces the genetic yield potential of crops.

3.3.6 Soil saturation point

The alluvial plain presented a significantly greater soil saturation point at 64.6% than that of 32% in the Piedmont. As expected, soil texture influences the behavior of the variable, with clay having the highest mean (66.83%) and loamy sand having the lowest (30%). With respect to land use, poultry and grass cutting activities presented the highest saturation averages, at 78% and 74%, respectively, which were significantly different from the lower average in stubble (26%). The soil moisture content at the saturation point depends on the soil texture and is called saturation moisture. Fine-textured soils, which have a high proportion of particles smaller than 0.002 mm, require less water to reach saturation than do sandy soils. PS is fundamental for irrigation management and understanding the spatial arrangement of soil to prevent waterlogging and manage runoff pathways, which can lead to water loss or soil degradation. When the soil water content is sufficient to meet plant needs, the primary concern may shift to irrigation water quality. Water quality refers to characteristics that can negatively affect natural processes and plant development. Therefore, effective irrigation management requires studying the quantity of water applied and closely monitoring its quality to ensure optimal crop growth.

3.4 Land uses and soil hydrological properties

Table 5 summarizes the soil hydrological properties studied.

Table 5 Land uses and soil hydrological properties in 33 PUs in the Department of Magdalena

PU	Actual use	HV/ %	L/ mm	Inf. $cm \cdot h^{-1}$	Infiltration Type-Itype	Irrigation interval/ days	Irrigation time/ hoursTR
1	Cutting grass or Agricultural management	52.9	105.0	1.4	Moderately slow	7.6	3.7
2	Cutting grass	27.8	54.3	4.0	Moderately slow	3.8	0.7
3	Cutting grass	42.7	85.6	1.5	Moderately slow	6.1	2.9
4	Agricultural	37.8	75.3	6.9	Moderate	5.4	0.5
5	Stubble	20.1	40.3	25.6	Very fast	2.9	0.1
6	Fallow	21.3	42.6	12.9	Fast	3.0	0.2
7	Extensive livestock	41.1	82.3	26.0	Very fast	5.9	0.2
8	Extensive livestock	42.8	85.6	44.6	Very fast	6.1	0.1
9	Cutting grass	35.9	71.7	11.6	Fast	5.1	0.3
10	Agricultural (Coffee)	31.6	63.2	18.0	Fast	4.5	0.2
11	Agricultural (Mango)	36.4	72.2	0.2	Slow	5.2	2.3
12	Extensive livestock	36.9	73.9	3.8	Moderately slow	5.3	0.1
13	Extensive livestock	40.0	79.9	1.7	Moderately slow	5.7	2.3
14	Extensive livestock	49.8	99.5	7.9	Moderate	7.1	0.6
15	Agricultural	53.0	106.0	0.6	Very slow	7.6	8.9
16	Agricultural	42.6	85.2	2.7	Moderately slow	6.1	1.6
17	Agricultural	46.3	92.7	7.5	Moderate	6.6	0.6
18	Grassland	26.2	52.3	15.9	Fast	3.7	0.2
19	Fallow	39.6	79.2	22.2	Fast	5.7	0.2
20	Cutting grass	25.3	50.6	8.6	Fast	3.6	0.3
21	Agricultural	54.1	108.0	0.7	Very slow	7.7	7.4
22	Cutting grass	25.4	50.8	2.0	Moderately slow	3.6	1.3
23	Cutting grass	18.1	37.9	30.9	Very fast	2.7	0.1
24	Cutting grass	20.0	50.0	23.0	Moderate	5.9	0.7
25	Cutting grass	31.9	63.8	26.3	Very fast	4.6	0.1
26	Cutting grass	33.6	67.0	3.2	Moderately slow	4.8	1.0
27	Cutting grass	28.0	56.16	15.9	Fast	4.0	0.2
28	Extensive livestock	48.3	96.6	0.3	Very slow	6.9	15.5
29	Other activities (Poultry)	40.2	80.5	38.2	Very fast	5.8	0.1
30	Fallow	53.8	107.0	2.4	Moderately slow	7.7	2.3
31	Agricultural	20.9	41.8	17.0	Fast	3.0	0.1
32	Extensive livestock	39.8	79.5	1.8	Moderately slow	5.7	2.2
33	Cutting pasture	40.6	81.2	9.1	Fast	5.8	0.4

Source: The authors.

In the field, areas with low vegetation cover were identified as eroded and left fallow or abandoned, mainly due to the lack of irrigation and steep slopes. In 91% of the production units (PUs) studied, land use was focused primarily on agricultural production, including transitory crops (such as cereal crops) and pasture for livestock. However, one PU was identified with crop residues (stubble) from a previous harvest, and another was left fallow (abandoned land).

3.4.1 Land use of the productive units studied

In 39.6% of the productive units (PUs), land use is dedicated to cutting pasture, with these farms focused on supplying cattle feed. Natural pasture for extensive cattle raising was present on 21.2% of the farms. Transitory crops such as maize, melon, cassava, peppers, and pumpkins were reported on 18.1% of the farms. Coffee production, intermingled with trees, pastures, and some vegetables, was found on 3% of the farms, whereas another 3% reported mango crops grown alone. Currently covered by herbaceous plants, fallow lands account for 9%, while 3% have crop residues (stubble), and another 3% are dedicated to other activities, such as poultry farming. These results confirm that livestock farming drives the predominant land use pattern in the Department of Magdalena, with many former agricultural lands being converted into pastures. Among the characterized PUs, 36% exhibited moderately slow infiltration, 15% very slow infiltration, 6% slow infiltration, 12% very fast infiltration, 15% fast infiltration, and 15% moderate infiltration.

3.4.2 Soil infiltration velocity

The variable Inf. did not significantly differ between the landforms (p>0.010). However, the alluvial plain, plain, and mountain landforms presented the highest infiltration velocities, with averages of 17.68, 14.80, and 12.38 cm/h, respectively, which are considered fast. In contrast, the foothills had a mean infiltration velocity of 5.28 cm/h, which was categorized as moderate to moderately slow. The soil textures significantly differed (p<0.01), with loamy sand showing the highest average infiltration rate at 18.83 cm/h, whereas the lowest values were recorded for sandy clay and clay, with velocities below 8 cm/h. Land use also influenced infiltration (p<0.01), with fallow land, pasture, and extensive livestock use resulting in the highest infiltration rates at 17.20, 16.24, and 13.54 cm/h, respectively. Importantly, agricultural land consistently presented the lowest infiltration rates.

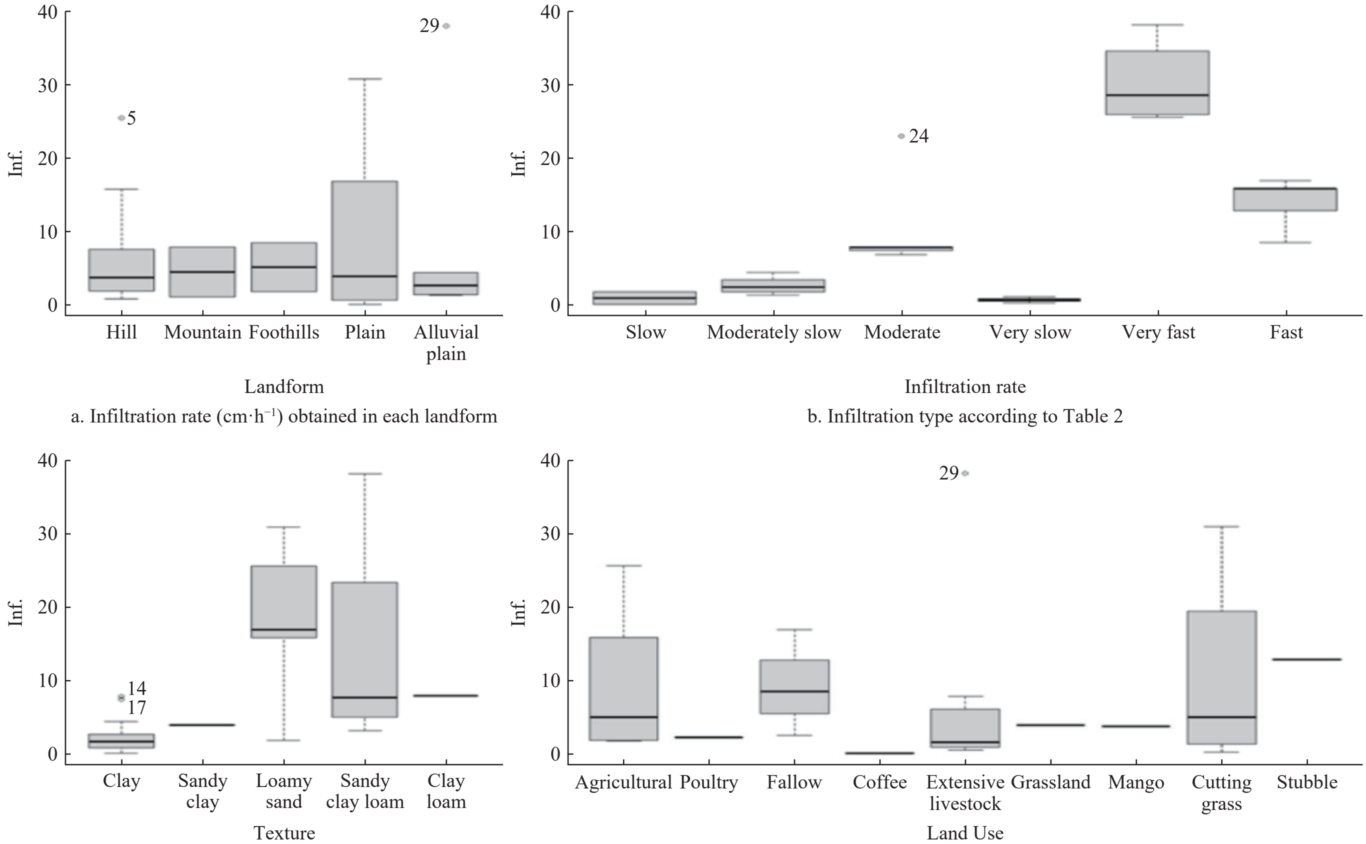
Figure 2c shows that clay-dominated textures have lower infiltration velocities than loamy and sandy textures. This pattern is evident in this research, where the clayey texture group exhibited very slow (<1.3 cm/h), slow (2 cm/h), and moderately slow (3.8 cm/h) infiltration rates. In contrast, faster infiltration rates were associated with loamy and sand textures (Figure 2b), particularly in the plains and alluvial plains (Figure 2a), where fallow land and agricultural uses presented the highest infiltration rates and the most significant values for the variable studied (Figure 2d).

These findings are essential for determining appropriate irrigation schedules and rates on the basis of infiltration velocity. Coarse-textured soils, which are predominantly found in hills and plains, require less frequent irrigation, whereas fine-textured soils, which have greater water retention capacity, necessitate less frequent irrigation.

3.5 Relationship of infiltration rate (Inf) with the variables measured

Correlation analysis was used to assess the statistical relationships (p<0.05) between the evaluated variables. Figure 3 shows that the infiltration rate was associated with all the measured variables. The contents of sand and bulk density (Bd) were positively correlated with Inf. (r=0.52 and r=0.48, respectively). In contrast, the contents of clay, organic matter (OM), electrical conductivity (EC), and irrigation time (TR) were negatively correlated with Inf. (r=–0.73, r=–0.49, r=–0.31, and r=–0.73, respectively).

Importantly, the correlation between Inf. and EC indicates that higher electrical conductivity corresponds to lower infiltration rates, impacting hydrological behavior. This finding aligns with the conclusions of[22], who reported that electrical conductivity is a significant variable for predicting infiltration and erosion rates in



a. Infiltration rate (cm·h^{-1}) obtained in each landform

b. Infiltration type according to Table 2

c. Predominant texture

d. Land use in the Production Units (PUs) evaluated

Figure 2 Variability of infiltration in relation to landforms, infiltration rates, soil textures, and land uses in the Department of Magdalena

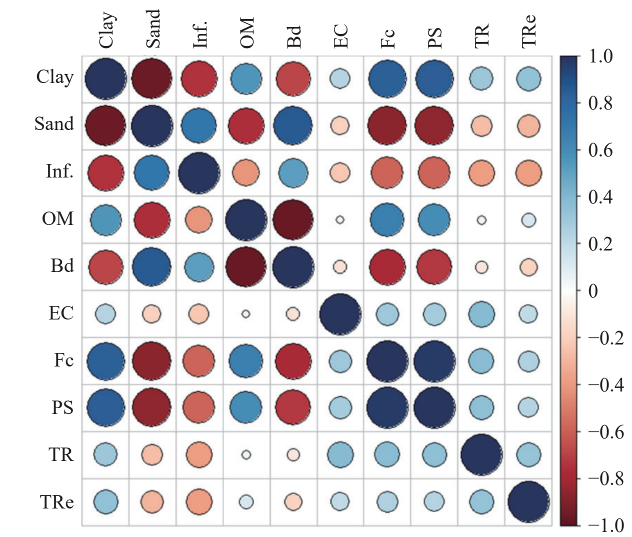


Figure 3 Relationship between infiltration rate (Inf.) with the variables measured in 33 PUs of the Department of Magdalena

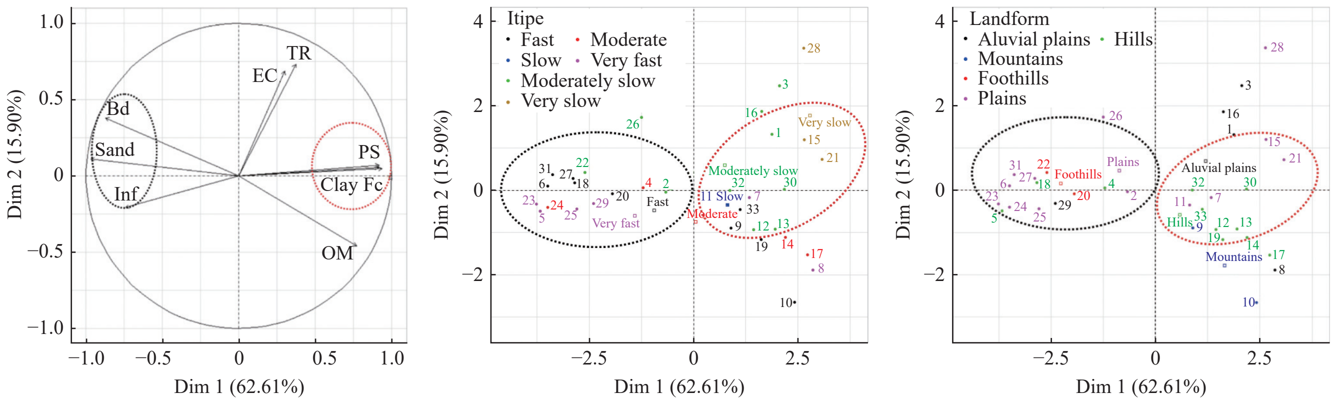
semiarid ecosystems.

Three principal components (PCA), PC1 to PC3, which were extracted from the original data and had latent roots greater than one, accounted for 86% of the total variation. The first component, termed “porosity,” is driven by the variables of sand content, bulk density (Bd), field capacity (Fc), and saturation point (PS). The second component, “irrigation,” is represented by electrical conductivity (EC) and irrigation time (TR). The third component is associated with salinity and is represented solely by EC.

The analysis revealed that infiltration (Inf.) behavior in the sampling units (PUs) varies based on landforms, infiltration type, soil texture, and land use. As shown in Figure 4a, the first two components explained 78.52% of the variance, indicating clear classification patterns. The geometric representation of the measured variables is significant, depicted as vectors originating from a common point, with lengths proportional to the standard deviation of the variable. Small angles between vectors indicate a strong positive correlation, angles of 90° represent no correlation, and angles of approximately 180° represent a strong negative correlation. Figure 3 shows that Inf. is positively correlated with sand and bulk density (Bd), whereas clay, which is positively associated with field capacity (Fc) and saturation point (PS), is strongly negatively correlated with Inf.

In contrast, fast and very fast infiltration, which is found in plains and piedmont areas, is associated with higher sand contents, whereas slow, moderately slow, and very slow infiltration, which is found in alluvial plains and hillsides (Figure 4b), is correlated with higher clay contents.

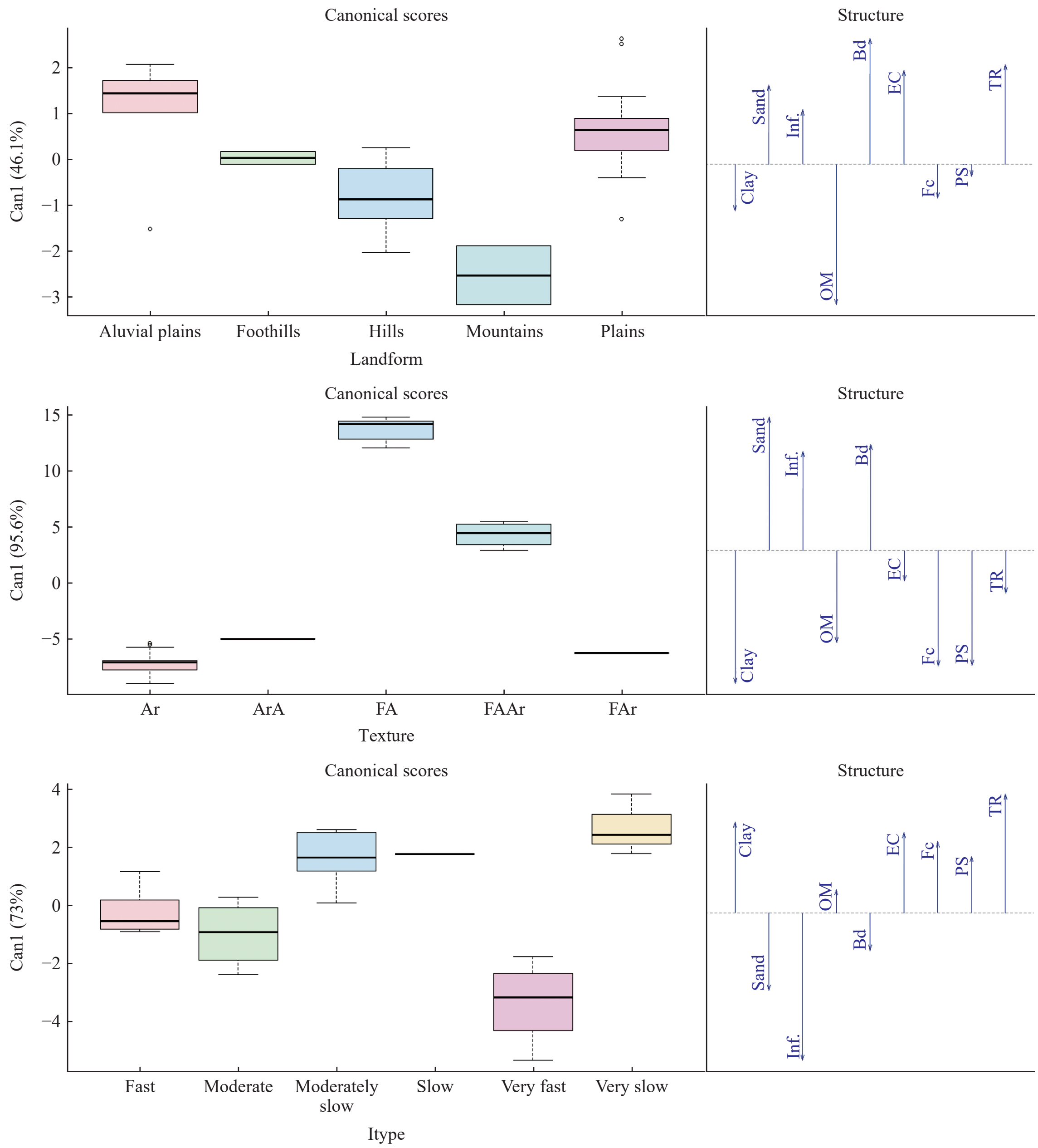
PERMANOVA revealed significant differences in landform, texture, and infiltration type, indicating that soil variables influence infiltration (Inf.) and should be identified. An analysis of classification discriminants (ACD) was applied to achieve this purpose, assigning equal classification probabilities on the basis of Bayes’ law. The probabilities of discrimination were 44.7%, 94.8%, and 74.6% for the landforms, textures, and infiltration types, respectively. The variables that differentiate the landforms, mountains, and hills are clay, OM, *Fc*, and PS. Moreover, Bd, TR, sand, EC, and Inf. characterize the foot hills, plains, and alluvial plain landforms, respectively (Figure 5). In contrast, Sand, Inf, and Bd differentiated the coarse-textured soils, whereas Clay, Fc, PS, OM, TR, and EC characterized the fine-textured soils. Finally, soils with high infiltration rates were defined by Sand, Bd, and Inf, whereas Clay, Fc, PS, OM, TR, and EC characterized soils with slow infiltration rates.



a. Projection of the measured variables and their relationship with Inf.

b. Ordination of landforms and type of infiltration

Figure 4 Relation between infiltration and the measured variables and ordination of infiltration type and land form based on linear relationships in 33 productive units (PUs) in the Department of Magdalena



Note: The canonical score (left) reflects landform, texture, and infiltration type differences. The structure (right) represents the vector projections of the measured variables, illustrating their relationships with landform, texture, and infiltration type.

Figure 5 The contribution of variables to the discriminant capacity of the analysis between Inf. and the variables measured in 33 PUs from the department of Magdalena

The regression analysis confirmed the relationship between Inf. and TR, demonstrating a high level of reliability (R^2=0.7595, p<0.001). The analysis revealed that TR decreases as the infiltration rate increases, supporting the strategy of applying smaller water volumes more frequently in soils. Additionally, the analysis revealed that the data fit a power model, yielding accurate predictions that can be used to effectively calculate irrigation times in the study area. This finding is illustrated in Figure 6, which compares the observed irrigation times (top) with those estimated by the model (bottom).

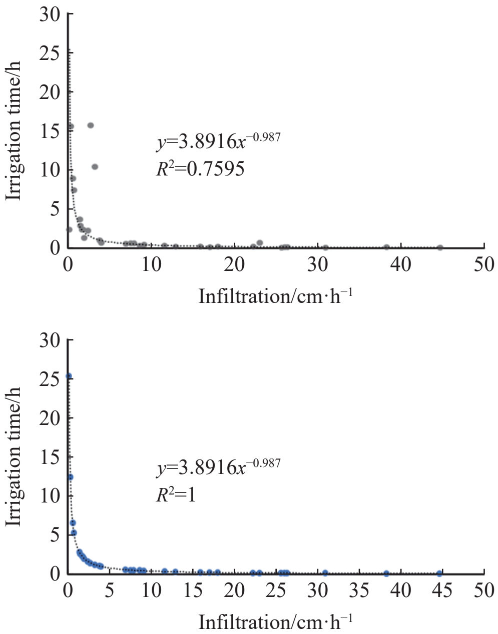


Figure 6 Observed and estimated irrigation time as a function of infiltration rate in 33 PUs in the Department of Magdalena

This study evaluated the infiltration rates of 33 PUs in the Magdalena Department, highlighting the predominance of soil with little to no vegetation cover. The vegetation cover, physiography, and topography of each PU were characterized in situ. The laboratory results indicated that the soils were predominantly clayey, had low OMS content, and had an average Bd of 1.44 g/cm^3. These findings are consistent with those of the Magdalena soil study by [24], which highlighted that the soils of Magdalena are highly susceptible to extreme climatic conditions, particularly salinization. This susceptibility is further confirmed by [25], who reported a gradual increase in regional temperatures and a decline in natural vegetation cover. These changes negatively affect soil moisture retention and disrupt the water balance, because increased runoff reduces the amount of water available for infiltration, thereby worsening the warming trend in the area.

The results indicate a predominance of fine-textured soils that are low in SOM and have Bd values near the upper limit, which negatively impacts the infiltration and water storage capacity of the soil. These findings are consistent with those of [26] and [27], who reported high variability in soil infiltration associated with textural class, bulk density, and soil porosity. Specifically, soil texture, especially clay content, was the variable with the greatest negative explanatory power for infiltration (r=–0.73). Clay soils, representing 54.5% of the cases analyzed, presented the lowest infiltration rates, which is consistent with their lower proportion of macropores and greater potential for swelling and shrinkage; however, this study did not identify the mineralogical type of clay present in the profiles. This issue is an important limitation, given that certain minerals, such as montmorillonite, can further reduce infiltration by forming poorly permeable lamellar structures when hydrated. Future studies should incorporate mineralogical analyses to differentiate between clay types and their direct influence on soil hydraulics.

Infiltration was significantly correlated with physical properties (Figure 3). Its behavior was positively correlated with the sand content and negatively correlated with the clay content, indicating that areas with high sand contents (plain and foothills) had, on average, infiltration rates that were 1.91 times higher than those with predominantly clayey soils (alluvial plains, hills, and mountains). Bulk density also showed a significant positive correlation with infiltration rate, exhibiting spatial dependence, with an inverse relationship with sand content and a direct correlation with clay content.

Since the infiltration rate (I) is a crucial soil parameter that affects leaching, runoff, and water retention, the data reported in this study highlight its role in regulating water entry into the system. Therefore, maintaining vegetation cover is a critical priority, as numerous studies have shown that bare soil experiences a loss of structural stability, leading to increased bulk density, greater compaction, reduced infiltration rates, and increased runoff, erosion, and sediment transport[28,29]. Vegetation cover helps protect soil, preserves its properties, and supports the provision of ecosystem goods and services, as well as sustainable agricultural production.

Although a moderate negative correlation was identified between infiltration and soil organic matter (SOM) (r=–0.49), this result could be influenced by the low vegetation cover, the high mineralization rates associated with the hot and dry climate of the area, and the spatial distribution of SOM in the profiles. In semiarid tropical contexts, SOM plays key roles in enhancing aggregation, increasing porosity, and facilitating preferential water flow; however, its effect may be attenuated at low levels, as in most evaluated units (<2%). This finding reinforces the need to promote agricultural practices that increase SOM, such as the use of organic fertilizers, covering crops, conserving tillage, and improving soil structure and infiltration capacity in the medium term.

Rapid water infiltration into the soil is essential, as it reduces evaporation and improves the availability of water resources for plants, promoting the conservation of vegetation and biodiversity. In this context, these results indicate that studying infiltration in arid and semiarid regions is fundamental for understanding or predicting how much water moves from the surface through the soil. This water can either remain available for plant growth or percolate to deeper layers, recharging vital aquifers in the department. Moreover, effective infiltration management can help minimize the risk of waterlogging during years of heavy rainfall or intense precipitation events. In this context, Govaerts et al.[30] emphasized that reducing tillage depth or adopting no-tillage practices without understanding soil conditions and incorporating and retaining organic residues can lead to crust formation. This process results in poor soil aggregation and reduced infiltration due to the sequential loss of SOM. Similarly, a long-term study conducted in Haryana, India, demonstrated that among three soil types (sandy loam, loam, and clay loam), there was a significant increase of 28% in the IR observed in clay loam soil associated with a decrease in the soil organic carbon content (COS)[31].

Similarly, the results indicate that irrigation times should be reduced as the soil infiltration capacity increases to prevent excessive leaching of soil and plant nutrients. This finding has practical implications for those managing plant nutrition programs, as it suggests that lower doses of fertilizer should be applied more frequently to minimize leaching losses in soils with high sand contents.

Infiltration, water transport, and the subsequent movement of soluble salts in soils are critical to consider when managing areas affected by saltwater, such as those irrigated with water from aquifers. Studies have shown that saline conditions can significantly impact hydraulic properties across various soil types[32,33]. Therefore, the influence of saltwater on soil water flow is contingent upon the EC and the amount and type of clay, which were not assessed in this study[32]. It is also essential to recognize that water movement in the soil is limited by how much soil salt is removed through leaching. This observation emphasizes the importance of using high-quality irrigation water, which prevents the complete removal of electrolytes from the soil. Such removal poses risks of physical damage, including soil destructuring[33] and the loss of essential nutrients for plants. This issue warrants further investigation in the study area, where soils are highly susceptible to salinity due to the prevailing conditions of low rainfall, high temperatures, and elevated evapotranspiration rates.

Electrical conductivity (EC) is a crucial indicator of soil salinity, and its impact on water infiltration is significantly regulated by osmotic and structural mechanisms[34]. High EC levels augment the osmotic potential of a soil solution, diminishing plant water availability and impeding its infiltration into the soil matrix. Elevated salinity levels can cause salt deposition in soil pores, physically hindering water movement and diminishing infiltration capability. Furthermore, when saline conditions coincide with elevated sodium concentrations, indicated by a high sodium adsorption ratio (SAR), they further undermine the structural integrity of the soil. Sodium replaces calcium and magnesium at exchange sites, resulting in clay dispersion, aggregate disintegration, and surface crust formation. These effects diminish macroporosity and significantly impair water entry and percolation. Moreover, moderate salinity may contribute to flocculation and soil stability due to the presence of calcium and magnesium; however, excessive salinity, especially in combination with sodicity, results in severe degradation of infiltration characteristics. Therefore, EC must be considered as a chemical indicator of salinity stress and a proxy for understanding hydrophysical limitations in salt-affected soils under irrigated and rainfed agricultural practices.

In contrast, Zribi et al.[35] identified the benefits and potential drawbacks of mulching and incorporating organic residues. Among the benefits, these practices regulate direct water evaporation from the soil, reduce the concentration of salts in the soil solution, and minimize surface runoff and erosion by protecting the soil structure. This protection increases porosity and plant root density, improving water and nutrient absorption. Similarly, Franzluebbers[36] emphasized that the SOM content is a critical quality that influences soil aggregation and water infiltration. In this context, 93% of the sampling units (PUs) presented low to minimal organic matter contents, reducing buffering capacity and increasing the vulnerability of resources to extreme events.

The results underscore the need to study further key factors affecting water infiltration in soils under semiarid conditions. In addition to electrical conductivity (EC), whose negative influence on the infiltration rate was statistically significant, the soil texture, particularly the clay content, and soil organic matter (SOM) were notable. Clay presented a strong negative correlation with infiltration, suggesting that, beyond the percentage, identifying the mineralogical type of clay is crucial, since expansive minerals such as montmorillonite can drastically alter water dynamics in the soil profile. Similarly, the low MOS content observed in most of the productive units and its negative correlation with infiltration, in contrast to what has been reported in other regions, merits specific studies to evaluate its direct influence under controlled conditions, incorporating management practices such as the addition of compost, biochar, or vegetative cover. These studies will allow researchers to isolate individual effects, better understand the interactions between physical and chemical soil properties, and improve water and soil management strategies in vulnerable agroclimatic contexts.

4 Conclusions

The results indicate a marked heterogeneity in the soil properties and infiltration rates across the different production units (PUs) under semiarid conditions. In accordance with the proposed methodology, productive units (PUs) with high and low infiltration rates were identified in a straightforward and cost-effective manner by considering landscape features, site-specific characteristics, and specific land uses.

The infiltration and soil property analysis across the study area revealed significant variability in the soil characteristics. The infiltration rates are inversely proportional to the pore space (as indicated by the soil texture) and bulk density. Therefore, the inverse relationship between infiltration and bulk density, with low organic matter content and low water-holding capacity, highlights the increasing vulnerability of soils in terms of their ability to sustain long-term agricultural productivity. These factors and rising temperatures point to rapid degradation of ecosystems unless sustainable soil and water management interventions are implemented.

The combination of low soil water retention, a tendency to increase bulk density, low levels of organic matter (OMS), rising temperatures, and reduced infiltration capacity suggests that the ecosystems in the study area will likely undergo significant short-term alteration and that soil management practices should be adapted to specific textural characteristics to improve water use efficiency and promote soil conservation.

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