v. 5, n. 3, 2025

Journal of Engineering Research

Acceptance date: 20/03/2025

HYDRAULIC CONDUCTIVITY OF AN *Alnus acuminata* AND *Coffea arabica* AGROFORESTRY SYSTEM IN THE MUNICIPALITY OF ZIPACÓN, COLOMBIA

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Abstract: The behavior of the hydraulic conductivity of an agroforestry system of Alder *(Alnus glutinosa)* and Coffee *(Coffea arabiga)* *(SAF-AC)* was studied, under the hypothesis that it is a behavior that favors the flow of sub-surface water, which can contribute to the flow of natural streams, or contribute to aquifers. The hydraulic conductivity of the SAF-AC was assessed using the borehole method and compared with that obtained with a coffee-only cover and with a managed pasture cover. The arrangement of the measuring devices was completely random, and the characteristic infiltration capacity curves of each vegetation cover considered were initially determined, and from there the characteristic hydraulic conductivity curves of each cover were determined. Finally, the differences in the behavior of the SAF-AC versus the Coffee and Pasture coverages were statistically established. The differences in the infiltration capacity and hydraulic conductivity of the three vegetation covers under study were not significant, but since the agroforestry covers, such as alder with coffee, are the most favorable in these processes, these can promote the recharge of aquifers and subsurface flows by facilitating the occurrence of gravitation water that contributes to groundwater, these can promote the recharge of aquifers and sub-surface flows by facilitating to a greater extent the occurrence of gravitational waters that contribute to groundwater, as they are implemented on a larger scale, offering a contribution to their eco-systemic function of regulating the waters of the hydrological cycle, in addition to the productive benefit of coffee, in this case.

INTRODUCTION

In the municipality of Zipacón, there has been an increase in the urbanization process for resting lands, changing the use of the soil by eliminating vegetation cover, increasing pressure on the soil and reducing its water storage and the possible recharge of aquifers, which could lead to a reduction in the flow of the Apulo River (Cundinamarca), in whose basin the study area is located.

Agroforestry systems are proposed as an option to agricultural systems such as coffee and pasture managed, evaluating their behavior in relation to hydraulic conductivity, understood as the ease of water flow through the soil, but taking into account each of the proposed vegetation cover options, from which the alternative of implementing agroforestry systems towards a better water management of the basins can be verified.

The department of Cundinamarca has developed the agro-industrial sector, with degradation of the quality and regulation of water resources, causing an imbalance that is reflected in a significant decrease in the water supply in a critical way for human supply and agricultural activity (Vice Ministry of Environment, 2010).

In the project area, Laguna Verde, there are large areas of managed pastures that cover more than half of the municipality, on slopes greater than 50%, and on slopes less than 50% there are unmanaged pastures in the southwest and northeast of the municipality. (Municipality of Zipacón, 2020) The predominance of pastures is ratified at the level of the department of Cundinamarca, where 70.9% of the area is dedicated to livestock activities, equivalent to 1,443,915 hectares, (Gobernación de Cundinamarca, 2023). These abundant pasture covers that fulfill an eco-systemic function are susceptible to be improved for the promotion of infiltration, sub-surface flows, gravitational flows, aquifer recharge and finally the regulation of minimum and average flows, in this case of the Apulo river basin.

The water regulation function of forests and their organic matter-rich soils in baseflow supply and peak flow reduction is known and has been qualitatively estimated. The quantification of this type of eco-systemic services of forests, such as those that can be derived from the hydraulic conductivity that privileges, is important to find ways to ensure the water sustainability of watersheds, and even more relevant when taking into account the importance of such contributions in the presence of climate change, (Garcia O, 2022). The eco-systemic forest function in interaction with agricultural crops such as coffee can bring important benefits to the hydrology of the area and its productivity using this type of arrangement.

A SAF-AC system was established three years ago in the "La Libertad" farm, Laguna Verde, municipality of Zipacón, as a demonstrative option for conservation and productivity, whose valuation in terms of its benefits in terms of the increase in sub-surface flows and their capture by the aquifers that will feed the flows of the natural streams of its basins. This benefit can be verified through research, and its possible replication in the municipality in principle can improve the water supply of the region, in addition to the benefit in productivity by having an agricultural activity accompanied by the benefits offered by forest cover, in terms of shade and favorable environmental conditions for the development of coffee.

The project intends that, by assessing the behavior of each of these covers with respect to hydraulic conductivity, and that these results allow in a new phase of research to establish their verification in the quantification of water regulation, in a longer term process to verify these very important benefits.

The project manages the concepts of hydraulic conductivity within the scope of vegetation covers of coffee (*coffea arabica*), alder (*alnus acuminata Kunth*) and managed pastures. A forest cover of *alnus acuminata kunth* (alder), an agricultural cover of *coffea arabica* (coffee) and a cover that can be called livestock, managed pasture, have been considered. Each of them has root systems characteristic of each species, which may imply significant differences in their hydrological behavior.

To implement a PFS, land use management techniques must be applied, combining multiple-use and timber trees with perennial agricultural crops. The aspects that stand out from PFS are the optimal use of physical space, increased levels of soil organic matter, carbon dioxide capture, biodiversity conservation, water conservation, weed control, microclimate improvement, soil protection against erosion and degradation, nutrient recycling, production diversification, sustainability of agricultural and forestry components, timber production and promotion of greater socioeconomic stability, (National Forestry Office, 2013).

Agroforestry systems of coffee plantations with shade reduce water losses due to the presence of leaf litter and shade, reducing runoff, (Velazquez-FS., 2009).

In the property "La Libertad", municipality of Zipacón (Cundinamarca) the SAF-AC of *Alnus acuminata* when planted with *Coffea arabica* can have the following advantages, according to the traditional knowledge in the area given by (García-V.C.A., 2021):

- Staggered" design with 1.5 m spacing offers aeration that is favorable against pest proliferation.
- Adequate shade for an agroforestry system.
- Association with Frankia mycorrhiza, which favors nitrogen fixation.
- Adaptation of *Alnus glutinosa* to clay loam soils.

Hydraulic conductivity is understood as the ease with which water flows in a porous medium. This ease of water flow is greater in saturated soils because the pores are filled with water and contribute more to water flow, driven by the hydraulic load gradient acting directly on it, but if the pores are not saturated there is a degree of resistance to flow, depending on the characteristics of the soil, and other components that can be found as the root systems of vegetation covers there, but that can also favor soil saturation. The presence of the root systems of the vegetation cover increases the ease of water flow deep in the soil, and even more so in the case of tree species.

Among the soil characteristics that have the greatest influence on hydraulic conductivity are texture and structure. In general, it can be said that the hydraulic conductivity of sandy soils is more influenced by texture, where granulometry is very indicative, and in clay soils the soil structure has a greater influence, where the distribution and organization of the particles is very important (Salgado S, 1985).

When a soil is saturated the hydraulic conductivity depends on its granulometry, pore water characteristics, temperature, and the shape, connection and pore size distribution (DTP), (Gallegos-F.G., 2011).

Hydraulic conductivity is usually not the same in all directions. The heterogeneity of the porous medium due to the varying physical characteristics of the soil strata causes these differences in hydraulic conductivity when the fluid interacts with the porous medium, which is influenced by its mineralogical characteristics such as the water flowing through the soil, the pressure of the air trapped in the pores, the existence of microorganisms and their decomposition that can clog the pores, the cracks and cavities caused by the root systems present, the presence of earthworms and their degree of activity.

METHODOLOGY

CHARACTERIZATION OF THE STUDY AREA

The study was conducted at the La Libertad farm south of the municipality of Zipacón on the border with the municipality of Cachipay, Cundinamarca, Colombia, (Corporación Autónoma Regional de Cundinamarca, CAR, 2011).

The study area has an average altitude of 1710 m.a.s.l., average temperature of 20 °C, average annual rainfall of 1000 mm, and its climate is more closely related to the municipality of Cachipay.

According to Estudio detallado de suelos de Cundinamarca, del IGAC, (Instituto Geográfico Agustín Codazzi, 2013), the soils in the study area are of Textura Franco Arcillosa, with an average grain size of 24.5% sand, 32.6% clay and 42.9% silt.

Some properties of the soils are presented referenced to the sites where their vegetation covers are found in the experimental area, important for their hydraulic conductivity, determined up to 30 centimeters depth, according to (Garcia-OCF & Álvarez-ACG., 2024). In Table 2 they are identified according to the symbols "n" for porosity, "þ" for bulk density, "m.o." for organic matter, "h_a" the depth of horizon "a", and "R_p" the penetration resistance.

VEGETABLE COVERINGS

The cover crops under which the hydraulic conductivity tests were conducted are an agroforestry system of Alnus glutinosa (alder) and Coffea arabica (coffee), a Coffea arabica crop and a managed pasture cover. All of the cover under the same conditions of slope, soil and climate.

They were characterized in terms of circumference at breast height, "CAP_m", diameter at breast height, "DBH_m", total height, "h_{tm}", mean crown diameter, "D_{mc}", mean crown cover area, "A_{mc}", and plant density per hectare.

Vegetative cover	n (%)	Þ$_b$ (grams/cm^3)	m.o. (%)	$h_{a\,(m)}$	R_p (kg/cm^2)
Alnus acuminata with *coffee arabica*	56.70	1.02	15.0	35.0	97.0
Arabica coffee	68.70	0.97	17.5	31.0	136.0
Managed pasture	68.15	0.78	19.0	36.0	98.0

Table 1. Properties of the soils under the coverages in reference. Source: (García O.C.F. & Álvarez A.C.G., 2024).

Coverage vegetable	CAP_m (cm)	DBH_m (cm)	h_{tm} (m)	D_{mc} (m)	A_{mc} (m^2)	Density (No./ha)
Alnus acuminata Kunth (agroforestry)	36,20	5,42	9,83	3,72	17,91	772
Coffea arabica L (agroforestry)	9,10	1,00	1,72	1,12	1,33	4630
Coffea arabica L	6,60	4,05	1,67	0,97	1,44	5663

Table 2. Mean values of the dimensions of the species *Alnus acuminata Kunth* and *Coffea arabica L.*

AGROFORESTRY DESIGN SAF-AC

It is illustrated in Figure 1. Coffea arabica (coffee) was developed in an area with similar characteristics, and the managed pasture system developed in a similar site, is typical of the area, and serves as a reference for the hydraulic conductivity results of the other vegetation covers.

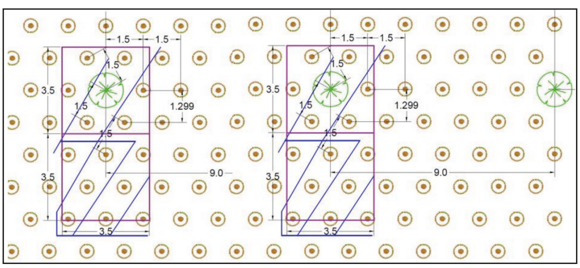

Figure 1. Plan design of the SAF-AC. system of *Alnus acuminata kunth* (alder) and *Coffea arabica L.* Source: (Aponte, 2023).

EXPERIMENTAL DESIGN

A representative tree was selected in each planted area. Around each representative tree, radial lines were drawn every 120 degrees, and the sites for the hydraulic conductivity tests by the borehole method were located on them, at distances of 3, 6 and 9 meters (Figure 2).

A total of nine borehole hydraulic conductivity tests were performed at each site, and for three coverages, a total of 27 borehole tests were performed.

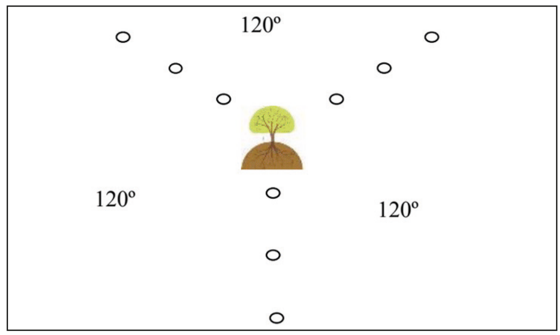

Figure 2. General scheme of the experimental design.

EXPERIMENTATION

The determination of the behavior of the hydraulic conductivity was made by the method of the inverted borehole, making a circular hole of a diameter of twelve centimeters in the ground, made with an auger, to a depth of fifty centimeters, and filled with water, leaving a free edge of five centimeters. The water level in the well is immediately measured every minute until five minutes, then every five minutes until thirty minutes, then every fifteen minutes until ninety minutes, and then every thirty minutes until one hundred and eighty minutes, or sooner if the water level in the well has stabilized.

This level measurement was made with a device designed with an icopor float supported on the tip of a cylindrical balsa rod of four millimeters in diameter that has a scale in centimeters along its entire length, and that by means of a system of support with iron rods is kept vertical and centered at the mouth of the well, and with it the level drops are measured.

This test is carried out with an inverted borehole, because normally the water table in the experimental area is at depths that do not allow easy access to it. For each of the tests, the soil moisture under which each of them was performed will be referenced.

PROCESSING INFORMATION AND OBTAINING RESULTS

The borehole tests were associated according to their moisture content ranges for initial soil moisture grades of high (60 to 80%), medium (40 to 60%) and low (20 to 40%) and the infiltration capacity curves were obtained by fitting the experimental curves to the Horton, Philip, Kostiakov and modified Kostiakov models using the Matlab program, and then with the R^2 indicator, the best fitting model was selected for each of the soil moisture ranges. Table 3 shows the mathematical expressions of the models used.

Author	Equation
Horton	$f(t) = f_c + (f_o - f_c)e^{-kt}$
Philip	$f(t) = st^{-0.5} + C$
Kostiakov	$f(t) = abt^{b-1}$
Kostiakov Modified	$f(t) = f_c + \alpha t^{-\beta}$

Table 3. Equations for infiltration capacity

Where: t = time elapsed since surface saturation of the soil, in minutes, k = decay constant, f(t) = infiltration rate at time t, in mm/h, f_0= initial infiltration rate (t = 0), in mm/h, f_c = basic infiltration rate, (asymptotic), in mm/h, s= sortivity of Philip's equation, obtained by regression, C= transmissivity of Philip's equation, obtained by regression, a, b= parameters of Kostiakov's equation, obtained by regression, α, β= parameters of modified Kostiakov›s equation, obtained by regression.

According to these chosen models, the hydraulic conductivities were calculated with which the corresponding hydraulic conductivity characteristic curves were found. The equation of (Kessler, 1977); (Reynolds, 1983); in which K_{is} is the field saturated hydraulic conductivity ($cm.s^{-1}$), R is the radius of the well (cm), H_1= height of the water column inside the well at time t_1, in seconds and H_2 is the height of the water column inside the well at time "t_2, in seconds:

$$K_{is} = \frac{R}{2[t_2 - t_1]} Ln \left[\frac{2H_1 + R}{2H_2 + R}\right] \quad (1)$$

RESULTS AND DISCUSSION

The capacity models selected were those that reached the highest values of the squared regression coefficient, when the experimental curves were associated according to the value of the initial soil moisture. Table 3 shows the relationship of the selected models.

Soil moisture	Species	R^2	Model
Low initial humidity	alder plus coffee	0,922	Kostiakov Mod.
	coffee	0,969	Kostiakov Mod.
	Managed pasture	0,980	Horton
Average initial humidity	alder plus coffee	0,946	Kostiakov Mod.
	coffee	0,900	Kostiakov
	Managed pasture	0,727	Kostiakov
High initial humidity	alder plus coffee	0,801	Horton
	coffee	0,768	Kostiakov
	Managed pasture	0,394	Kostiakov

Table 4. R^2 values of the selected infiltration capacity models.

As can be seen in Table 3, the model fitted in most cases was the Kostiakov and modified Kostiakov model.

Figures 3, 4 and 5 show the curves of the different models, with adjustment to the points of the experimental curves.

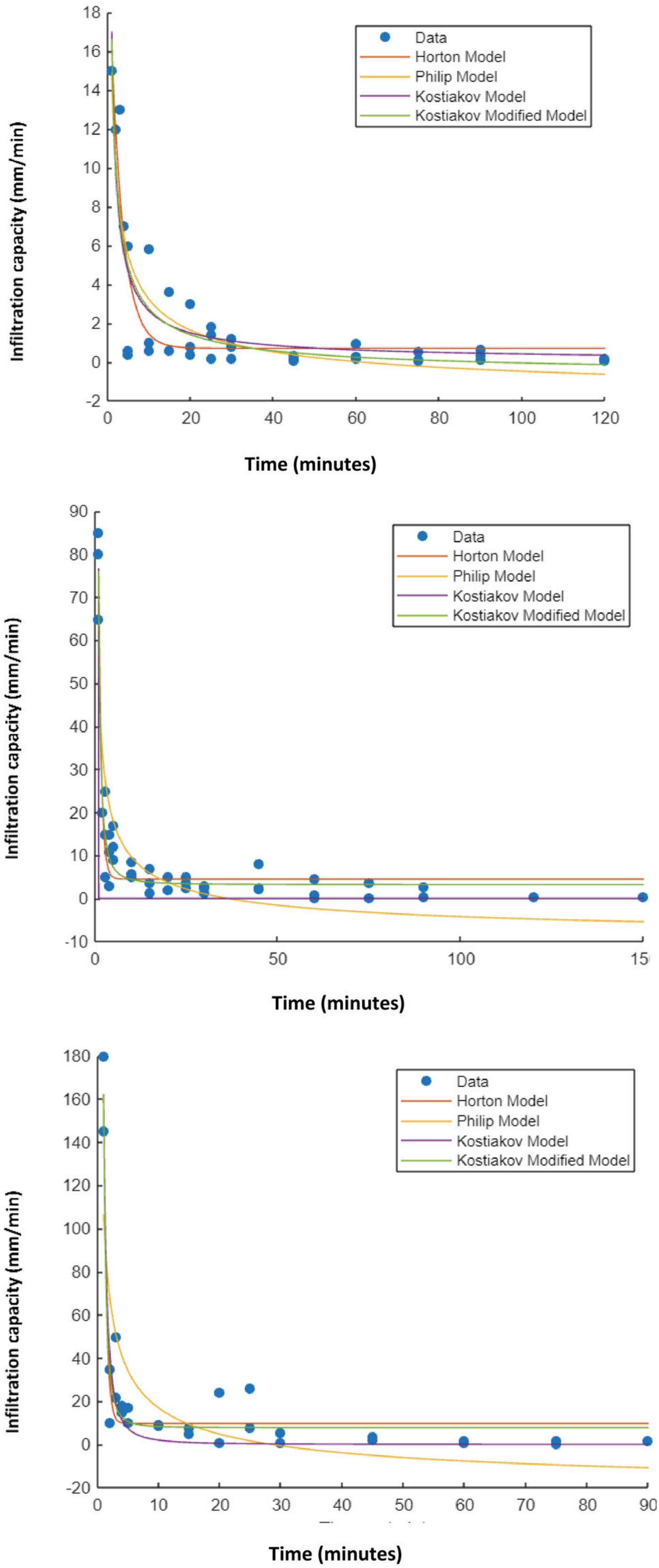

Figure 3. Infiltration capacity curves according to the models, under *alnus acuminata* and *coffee arabica*, for high, medium and low initial soil moisture.

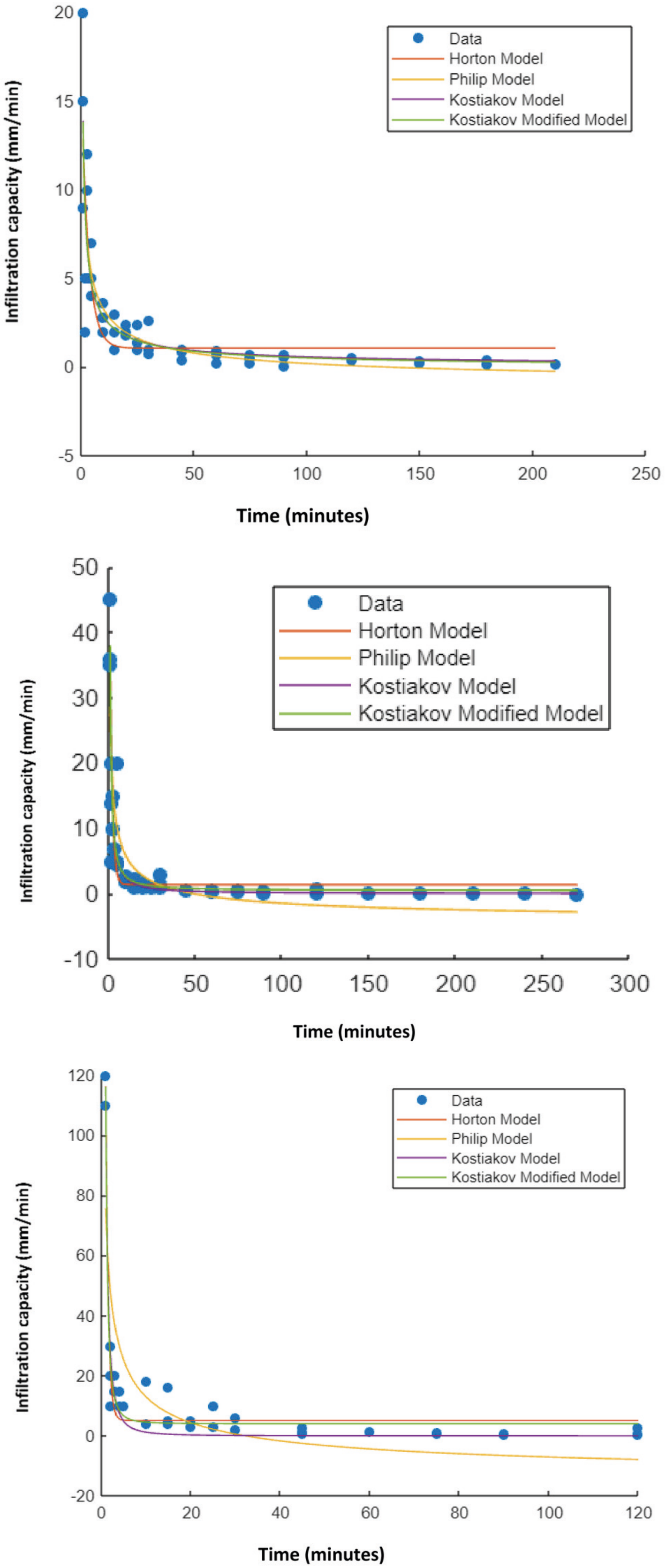

Figure 4. Modeled infiltration capacity curves. under *arabica coffee*, for high, medium and low initial soil moisture.

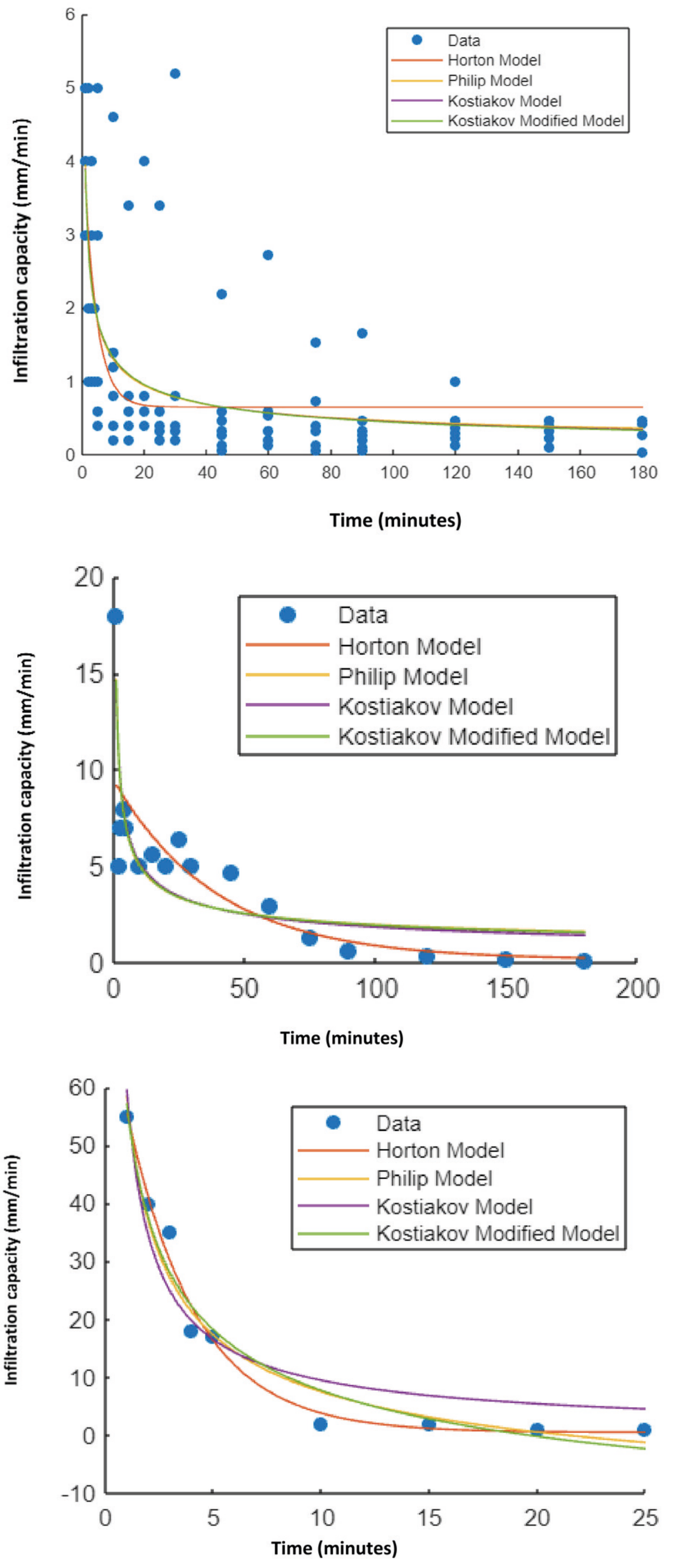

Figure 5. Modeled infiltration capacity curves. under managed pastures, for high, medium and low initial soil moisture.

According to the curves in Figure 6, it can be observed that, for high initial soil moisture, greater than 70%, the differences in infiltration capacity are only observed in the first ten minutes with respect to grass, which has a lower infiltration capacity, which can be interpreted by its finer root systems, with fewer cracks, but there are no differences between the agroforestry system and coffee. After ten minutes there are no appreciable differences between the curves of the three vegetation covers.

For medium humidity levels, between 30 and 70%, in the first ten minutes there is a greater infiltration capacity in the agroforestry system and in the pasture, but after thirty minutes the agroforestry infiltration capacity becomes greater with respect to the pasture and coffee. This greater agroforestry infiltration capacity is consolidated and after eighty minutes, the agroforestry infiltration capacity is definitely greater with respect to the pasture and coffee, a fact that can be considered due to the more robust root systems of the "*alnus acuminata*", identified as alder.

For initially low degrees of soil moisture, less than 30 %, in the first ten minutes no differences in infiltration capacity are appreciated, but then the agroforestry cover is defined with a higher infiltration capacity, then the coffee 'and the lowest levels with the grass, for the same reason of the root systems of the alder, which are larger,

The behavior of hydraulic conductivity over time is influenced by various factors that act dynamically in addition to human intervention, and according to the predominance of the processes that occur, three phases of the hydraulic conductivity curve over time are identified, Salgado S, L. (1985).

Figure 4 shows the characteristic curves of hydraulic conductivity, where those obtained from initial soil moisture greater than 70%, initially show differences of less than 3 mm/h, and these curves can be identified in phase one, where the wetting of soil particles and the leaching of electrolytes can explain the decrease in hydraulic conductivity over time, Salgado S, L. (1985). However, when these curves were obtained from humidities between 30 and 70 %, a higher hydraulic conductivity was observed for the agroforestry cover, and then for coffee, and with very low values for the pasture. It is observed that the agroforestry curve and the coffee curve first come from phase one, but these then pass to phase two, where the hydraulic conductivity increases, which can be attributed to the dissolution of the air found in the soil pores and eliminated by the water, Salgado S, L. (1985), but where the grass curve continues in phase one. Already with initial humidities lower than 30 %, in general the agroforestry cover is still the one with the highest conductivity and in an increasing direction; then the pasture, but with a decreasing tendency, while coffee shows a very low hydraulic conductivity, with a very slight tendency to increase. In this case the agroforestry curve is in phase two; the coffee curve comes from phase one and passes with a slight increase in phase two, but in this case the pasture curve is still in phase one.

It can be seen that the agroforestry hydraulic conductivity curve under low soil moisture behaved in phase one, but with medium and low soil moisture the curve shifted from phase one to phase two. Initially the hydraulic conductivity decreases due to soil wetting, and this decrease is very fast when the soil is very wet, since the soil is already very wet, but then it increases as the number of pores decreases, a fact that occurs in a short time when the initial soil moisture is of a medium or low value.

The hydraulic conductivity curve of coffee under high initial soil moisture was located mainly in phase one and moved slightly to phase two, but under medium initial moisture it also moved from phase one to phase two, but in the latter with greater increases in

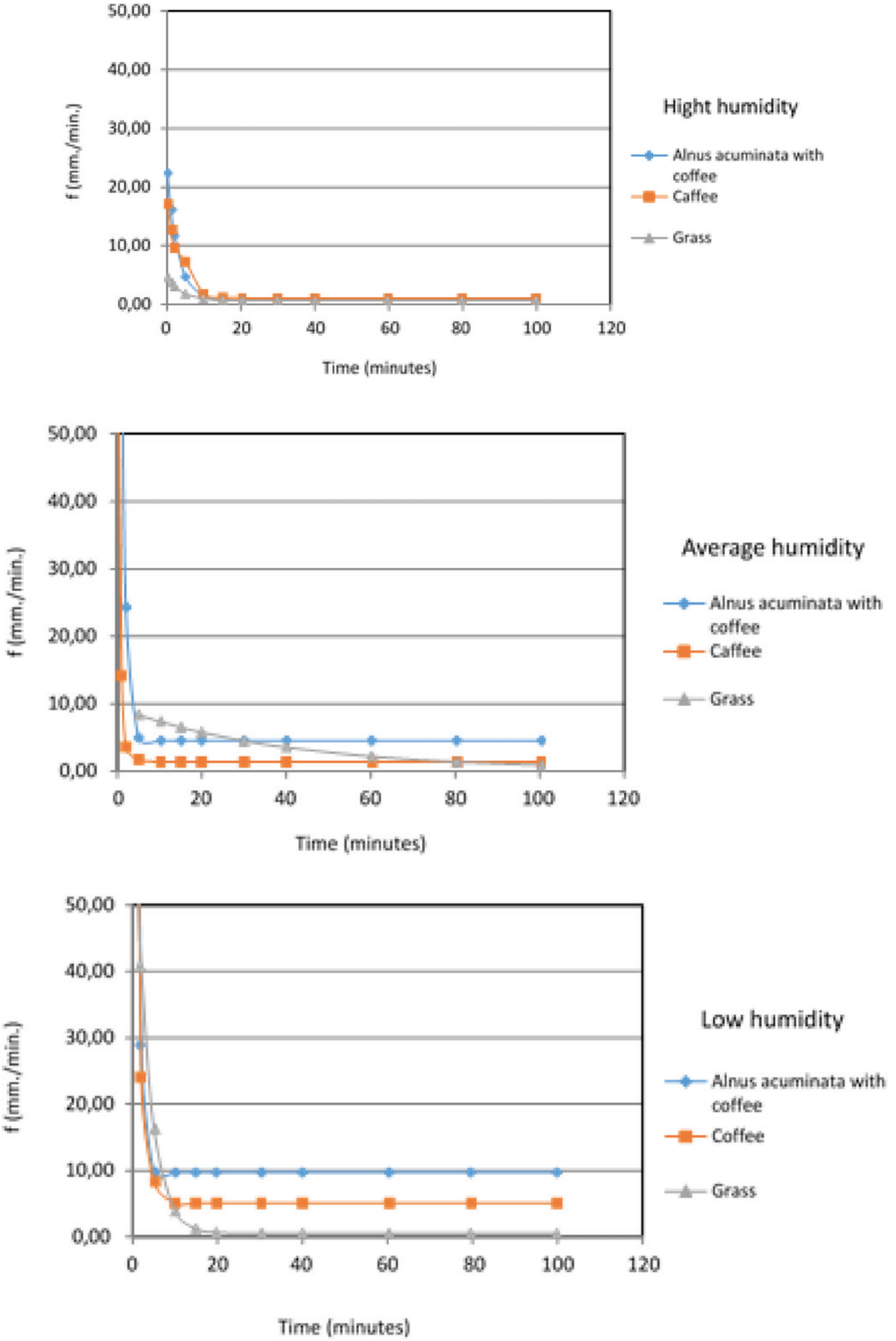

Figure 6. Infiltration capacity characteristic curves.

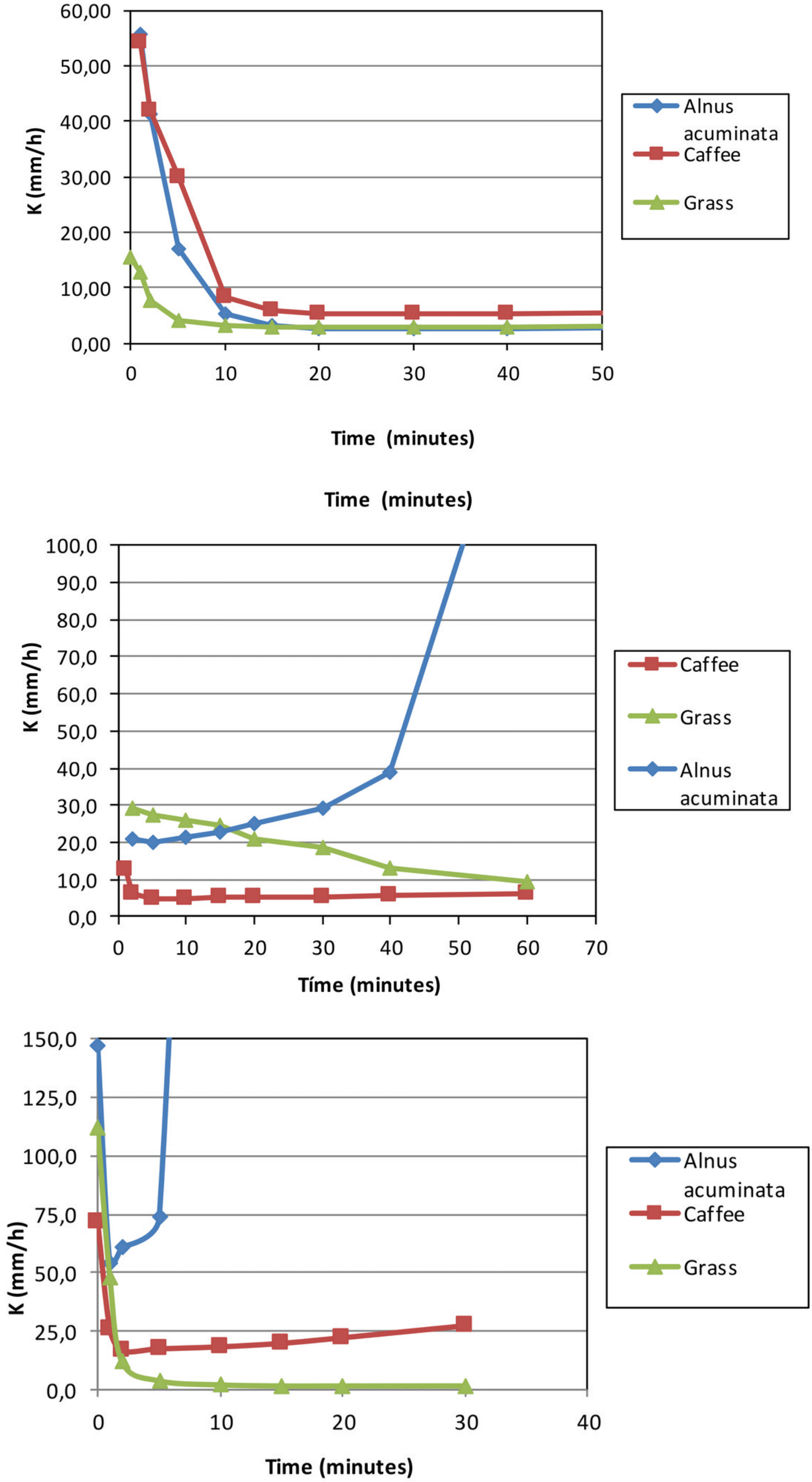

Figure 4. Characteristic curves of hydraulic conductivity, for Initial high, medium and low humidity.

hydraulic conductivity. For low initial moisture the curve is in phase one and with very slight increases in hydraulic conductivity in phase two. In general, it can be affirmed that the behavior of hydraulic conductivity under coffee cultivation followed the same tendencies of the agroforestry curves, but with lower values due to the more robust root systems of the agroforestry cover.

For the grass cover under all degrees of humidity, hydraulic conductivity remained in phase one, but with more distributed decreases over time under low initial soil moisture. In general, hydraulic conductivity under grass cover is lower than under agroforestry and coffee cover, although the differences are minimal when initial soil moisture is high.

Analysis of variance was performed for the behavior of infiltration capacity with the inverted sweeping well and hydraulic conductivity under the three vegetation covers under consideration. Tables 3 and 4.

Analysis of variance of basic infiltration capacity between coffee agroforestry and pasture.						
Source of variation	Sum of Squares	Degrees of freedom	square	F Ratio	Fo	P-value
Treatment	28	2	14	1,64	5,14	<0,05
Error	51	6	8			
Total	78	8	10			

According to Table 3, there are no significant differences in the basic infiltration capacity, with the inverted borehole method, of the three vegetation covers under consideration. However, the agroforestry infiltration capacity of the alder and coffee AFS system is greater than that of coffee alone, and of coffee alone in relation to the managed pasture, due to the larger root systems of the alder, which favor a greater size and number of cracks that facilitate the entry of a greater amount of water into the soil, as occurs in the agroforestry system in relation to coffee, and of coffee in relation to pasture.

Although soil properties in terms of porosity, bulk density and organic matter content are less favorable for the agroforestry system, and more favorable for the coffee and pasture covers, these did not cause significant differences in infiltration capacity.

Analysis of variance of saturated hydraulic conductivity between agroforestry, coffee and pasture.						
Source of variation	Sum of Squares	Degrees of freedom	square	F Ratio	Fo	P-value
Treatment	4295	2	2148	0,84	Fo=3.463	<0,01
Error	15331	6	2555			
Total	19627	8	2453			

According to Table 3 there are no significant differences between the hydraulic conductivities of the three vegetation covers, but there are differences in the agroforestry hydraulic conductivity which is higher than that of coffee, since when this conductivity increases the air pros are more easily filled with water in the agroforestry system, given the greater size and quantity of pores that are more easily filled with water given also a lower pressure of pros than in the coffee only system, For the pasture the pressure of pros is even greater so the hydraulic conductivity there is decreasing.

The differences found in soil properties under the three vegetation covers did not lead to significant differences in hydraulic conductivity between the three vegetation covers under study.

CONCLUSIONS

In general, the soils do not show important differences that would lead to significant differences in the infiltration capacity or hydraulic conductivity of the vegetation covers considered.

The infiltration capacity measured by the inverted auger well method, in the "Laguna Verde" village of the municipality of Zipacón (Cundinamarca), under the agroforestry system of alder with coffee is greater than under the coffee-only cover, and this in turn greater than that of grass only, depending on their root systems: those of greater size induce a greater infiltration capacity, but these differences are not statistically significant. These differences are observed when initial soil moisture contents are low to medium, but when moisture contents are higher (60 to 80 %), the differences in infiltration capacity are smaller.

The hydraulic conductivity under the above scenario shows a decreasing tendency in a first phase under the three coverages, due to the wetting of the soil particles, but for the agroforestry and coffee systems, the second phase is one of increasing hydraulic conductivity, as the soil pores fill with water, but with higher values of hydraulic conductivity for the agroforestry system, where the pore pressure is lower. Despite the above, these differences are not significant.

In general, taking into account the behavior of the infiltration capacity and hydraulic conductivity of the three vegetation covers, the values are generally higher under the agroforestry cover,

Although the differences in the infiltration capacity and hydraulic conductivity of the three vegetation covers under study are not significant, when agroforestry covers such as alder with coffee are applied, they can promote the recharge of aquifers and subsurface flows by facilitating to a greater extent the occurrence of gravitational waters that contribute to groundwater, as they are implemented on a larger scale, offering a contribution to their eco-systemic function, in addition to the productive benefit of coffee, in this case.

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