According to Pérez and Romance (2012), models that are fitted to the field measurements due to the different soils, climates, vegetation, and management conditions are considered in order to determine the infiltration process. Mathematical models have been developed for measuring the infiltration; in general, they are divided into three groups (Collis, 1977; Pérez and Romance, 2012): 1) theoretical, 2) semi-empirical, and 3) empirical. The present study used models of the third type for the modeling of the infiltration, as they do not consider those factors that intervene in the infiltration process: the texture, or the moisture content or the soil temperature, among others.

The purpose of the study was to model the infiltration process based on the measurements performed *in situ* using the methodology of the double-ring infiltrometer, which were adjusted to the parameters of the Kostiakov, Horton and Lewis-Kostiakov models (Weber and Apestegui, 2016) by means of the analysis of their functioning in five different forestry stands (three regeneration cuttings, a post-fire regeneration area, and a reference stand) in temperate forests of *Durango* State, Mexico.

Materials and Methods

Study area

The infiltration tests were carried out in the forests of La Ciudad *ejido*, located in the massifs of the Western *Sierra Madre* within the municipality of *Pueblo Nuevo*, *Durango*, where the dominant vegetation consists of *Pinus duranguensis* Martínez, *Pinus cooperi* C. E. Blanco, *Pinus ayacahuite* Ehrenb. ex Schltdl., *Juniperis deppeana* Steud., and *Quercus sideroxyla* Bonpl. (González-Elizondo *et al.*, 2012). The predominant soil type is Umbrisol (INEGI, 2005) (Figure 1). The mean annual precipitation is 1 200 mm, and the mean annual temperature is 18 ºC, with a maximum temperature of 22 ºC and a minimum temperature of 3 ºC (Zúñiga *et al.*, 2018).

order to prevent lateral flow. Once the test began, measurements were registered (in cm) by minute every five minutes during the first hour of assessment; during the second hour, measurements were taken every ten minutes, and in the third hour, every fifteen minutes, and the last two readings were taken after thirty and sixty minutes, adding up to a total of 270 minutes (4.5 hours) of evaluation. When the level of the water reached 8 cm, the inner cylinder was recharged, depositing the water slowly; the outer cylinder was refilled when its level diminished. Before starting the infiltration tests, soil samples were drawn in order to determine the gravimetric moisture content (Woerner, 1989).

Certain characteristics of the soil and the vegetation of the sites are shown in Table 1, as their importance for the hydrological processes varies.

Table 1. Average values of the characteristics of the vegetation and soils in the studied stands.

Characteristics	Vegetation				Soil	
Stand	Density (individuals ha^{-1})	ND (>7 cm)	Height (m)	CD (m)	AD (g cm^{3})	DAL (cm)
Clear-cutting	160	7.72	3.21	1.92	0.51	1.05
Seed-trees	80	38.16	18.2	7.34	0.72	2.29
Selective cutting	250	26.88	15.4	5.26	0.80	3.31
Post-fire	6 400	8.13	7.42	1.33	0.58	7.00
Reference stand	660	21.25	16.23	5.30	0.58	5.70

ND = Normal diameter, CD = Crown diameter, AD = Apparent density, DAL = Depth of accumulated litter.

Infiltration rate

The infiltration rate was estimated based on field data (Zhang *et al.*, 2017; Yáñez-Díaz *et al.,* 2019), using the equation:

$$I = \frac{HR \times 10 \times 60}{t}$$

Where:

I= Infiltration rate (mm h^{-1})

HR= Difference between readings (cm)

10= Factor of conversion of cm into mm

60= Factor of conversion of minutes into hours

t= Time (min)

The cumulative infiltration (*Ci*) was determined through the total sum of the volumes of infiltrated water, considered as the integral of the infiltration rate during those periods:

$$Ci = \int_0^t I\,(t)\,dt$$

Fit of the models

After the infiltration curve was obtained by means of a test, the models were fitted. The parameters of these models were estimated using the least (non-linear) squares method, which minimizes the errors of fit of the model using the Solver tool available in the Microsoft Excel spreadsheet (Weber and Apestegui, 2016).

The infiltration rate was estimated using the following fitted models:

Kostiakov type model (Rodríguez-Vásquez *et al.,* 2008). It is expressed with the following equation:

$$I = at^b$$

Where:

I = Infiltration rate (mm h^{-1}) in a given time period

t = Time (minutes)

a and b = p fitting parameters; the former is associated to the initial infiltration, and the latter, to the change rate

Horton type model. It corresponds to a three-parameter model: *Bi*, *Ii* and *K* (Weber and Apestegui, 2016):

$$I(t) = Bi + (Ii - Bi)e^{-Kt}$$

Where:

$I(t)$= Infiltration rate (mm h^{-1}) in a given time

Ii = Initial infiltration rate (mm h^{-1})

Bi = Basic infiltration rate (mm h^{-1})

K = Parameter representing a change ratio

t = Time (minutes)

Lewis-Kostiakov type model. Modification of the original Kostiakov model, which adds to its formula the basic infiltration value, estimated based on the average of the values of the rate for the last three instants (180, 210 and 270 minutes) of the infiltration test (Yáñez-Díaz *et al*., 2019):

$$I(t) = Bi + at^{-b}$$

Where:

$I(t)$ = Infiltration rate (mm h^{-1}) in a given time

Bi = Basic infiltration rate (mm h^{-1})

a = Parameter associated to the initial infiltration (mm h^{-1})

t = Time (minutes)

b = Parameter of fit

Statistical analyses

The hydrological variables initial infiltration (*Ii*), basic infiltration (*Bi*) and cumulative infiltration (*Ci*), as well as gravimetric moisture, were subjected to the Kolmogorov-Smirnov test (Romero, 2016) in order to verify the normality assumptions and the homogeneity of variances. The variable *Ii* met these assumptions, and therefore, a variance analysis was performed to determine the existence of significant differences between the various stands, with a significance level of $p<0.05$. The variables gravimetric humidity, *Ci* and *Bi* were subjected to the Kruskal-Wallis non-parametrical test (Berlanga and Rubio, 2012) in order to determine the existence of significant differences ($p <0.05$) when there is a type I error. The data were analyzed using the Statistical Package for the Social Sciences, version 22 (IBM, 2013).

Results

The average values of initial infiltration, basic infiltration rates and accumulated infiltration for the various stands are shown in Table 2, in which the Reference stand (control) exhibited a better hydrodynamic behavior, unlike the Clear-cutting treatment, which had the lowest values for *Ii*, *Bi* and *Ci*. The *Ii* variable registered significant differences, and was therefore analyzed using the Tukey test; *Bi* and *Ci* exhibited significant differences according to the Kruskal-Wallis test.

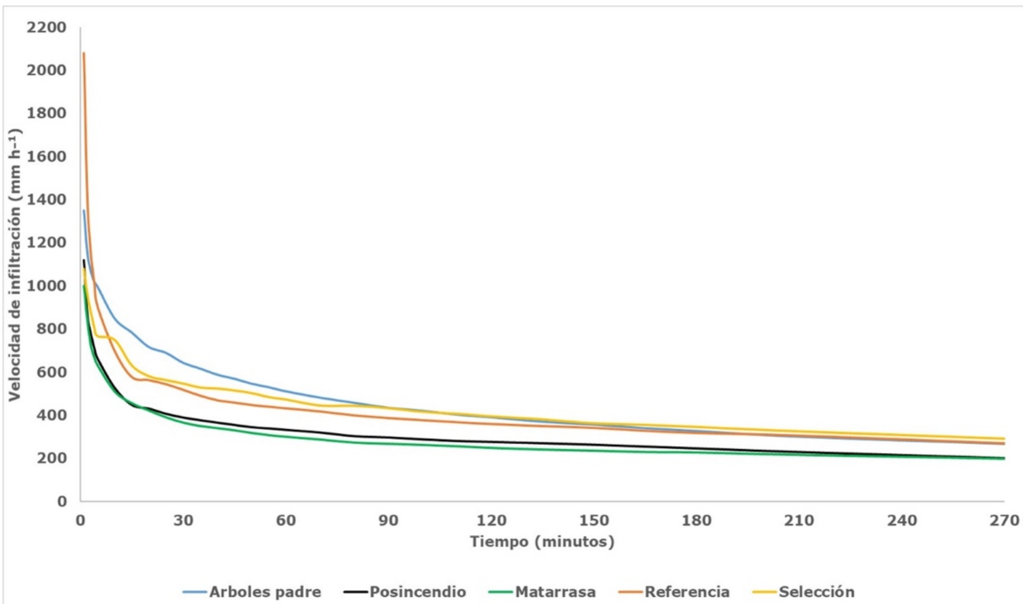
Comparison tests allow observing highly significant differences between the Reference treatment and the other analyzed stands, particularly in variable *Ii*, which was reduced by 45 %, while the *Bi* increased slightly in the Seed Trees and Selective Cutting treatments, unlike in Clear-cutting and Post-Fire Cutting, for which decreases by 28 and 23 %, respectively, were determined. On the other hand, *Ci* diminished in all the stands, except for the Seed Trees area, which registered 4.7 % above the Reference stand. The initial moisture content of the soil between the stands exhibited significant differences (Kruskal-Wallis test, $p<0.05$); therefore, it is considered to play a significant role in the baseline and final conditions of the infiltration.

Table 2. Mean values of the hydrological variables in the various treatments.

Treatment	***Ii*** **(mm h^{-1})**	***Bi*** **(mm h^{-1})**	***Ci*** **(mm)**	***M*** **(%)**
Clear-cutting	1 000 ^{a}	214.09	10 904.95	56.23
Seed-trees	1 350 ^{b}	299.56	17 203.79	77.70
Selective cutting	1 080 ^{ab}	322.08	15 224.30	51.52
Post-fire cutting	1 120 ^{ab}	226.95	11 724.95	36.12
Reference stand	2 080 ^{c}	297.93	16 428.29	76.61

Ii = Initial filtration; *Bi* = Basic infiltration; *Ci* = Cumulative infiltration; *M* = Gravimetric moisture. Different letters indicate significant differences (*Tukey*, *p= 0.05*).

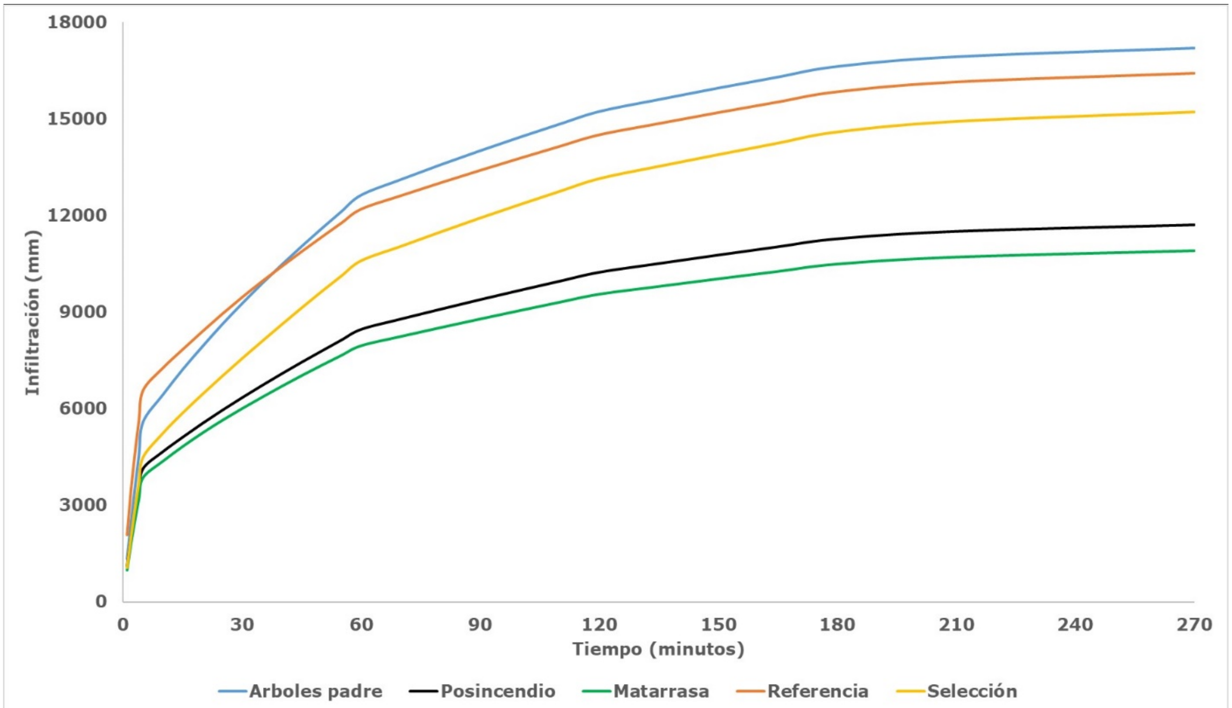
Figure 2 describes the behavior of the infiltration rate observed in the various stands. In general, there are three distinct periods: initially, the infiltration rate is high and is kept constant during a short time (<15 min); then the infiltration rate diminishes significantly (15-60 min), and this leads to a third, stabilization period known as basic infiltration rate, which may be observed in all the treatment 200 minutes after the application of the test.



Árboles Padre = Seed tres; *Posincendio* = Post-fire; *Matarrasa* = Clear-cutting; *Referencia* = Reference; *Selección* = Selective; *Tiempo* (*minutes*) = Time (minutes); *Velocidad de infiltración* = Infiltration rate.

Figure 2. Infiltration rate observed in forestry stands.

The accumulated infiltration process proved that the Seed-trees and Reference stands had the highest volumes of infiltration, followed by the area exploited through Selective Cutting and those of Post-fire and Clear-Cutting. The accumulated infiltration grew constantly during the first 60 minutes; subsequently, it began to experience growth with more stable segments, and the infiltration became slower and longer after 200 minutes (Figure 3).



Árboles Padre = Seed tres; *Posincendio* = Post-fire; *Matarrasa* = Clear-cutting; *Referencia* = Reference; *Selección* = Selective; *Tiempo* (*minutes*) = Time (minutes); *Infiltración* = Infiltration.

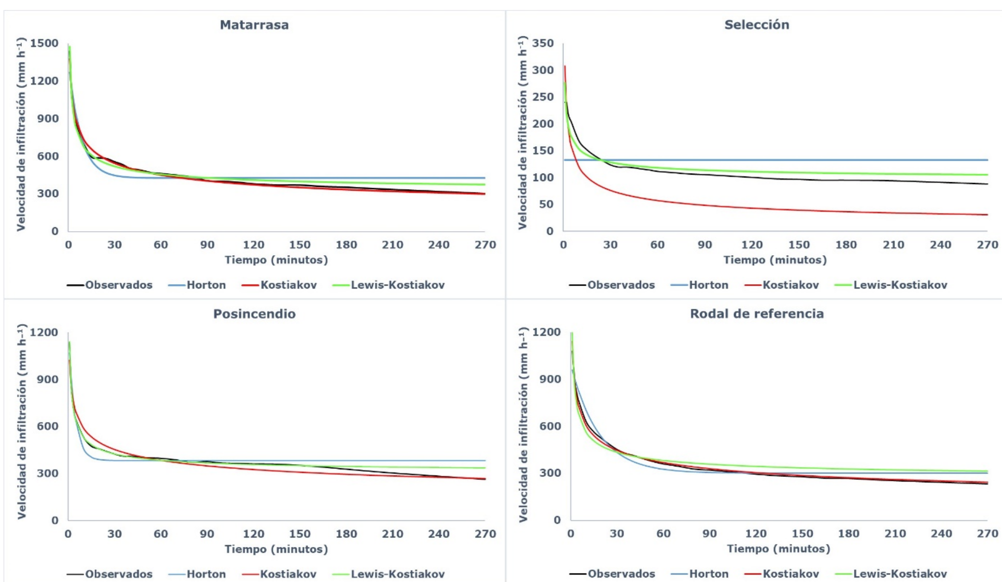
Figure 3. Accumulated infiltrations observed in the forestry stands.

Table 3 summarizes the parameters of the three fitted models, as well as the value of the determination coefficient (R^2), which is a measure of the degree of goodness of the utilized equation. As may be seen in this Table, The values of R^2 were highest, in every case, for the Kostiakov and Lewis-Kostiakov models; furthermore, the parameters associated to the initial and cumulative infiltration (*Ii* and *Ci*) exhibited a similar tendency to that observed in all the analyzed stands.

Table 3. Parameters of the adjusted models and coefficients of determination (R^2).

Treatments	Measurement	Kostiakov			Horton				Lewis-Kostiakov			
		a	*b*	R^2	*Bi*	*Ii*	*K*	R^2	*a*	*b*	*Bi*	R^2
Clear- cutting	1st	1 141	-0.27	0.96	304	993	-0.05	0.92	942	-0.48	254	0.97
	2nd	759	-0.38	0.94	172	1075	-0.34	0.70	719	-0.74	137	0.92
	3rd	1 144	-0.28	0.96	300	996	-0.06	0.92	948	-0.48	251	0.97
Seed trees	1st	1 191	-0.34	0.95	202	977	-0.05	0.93	1081	-0.47	146	0.99
	2nd	1 671	-0.21	0.98	508	1392	-0.02	0.95	1266	-0.37	453	0.98
	3rd	248	-0.23	0.97	93	278	-0.16	0.80	189	-0.61	85	0.92
Selective cutting	1st	371	-0.12	0.98	111	323	-0.01	0.80	203	-0.23	168	0.99
	2nd	1 158	-0.25	0.97	250	926	-0.02	0.95	838	-0.42	322	0.97
	3rd	308	-0.41	0.93	133	2615	-422.6	0.31	184	-0.48	93	0.95
Post-fire cutting	1st	714	-0.33	0.95	185	908	-0.27	0.74	644	-0.75	167	0.90
	2nd	1 510	-0.32	0.95	309	1263	-0.05	0.76	1346	-0.46	215	0.89
	3rd	1 025	-0.24	0.97	383	1262	-0.24	0.75	844	-0.56	299	0.94
Reference stand	1st	2 112	-0.43	0.91	413	3244	-0.41	0.64	2076	-0.76	300	0.93
	2nd	2 214	-0.43	0.92	407	2973	-0.32	0.71	2130	-0.67	263	0.96
	3rd	1 379	-0.27	0.96	428	1387	-0.13	0.82	1177	-0.49	300	0.97

By way of example, Figure 4 shows the behavior of the infiltration rate observed and estimated, based on the adjusted models of the third test for the Control, Selective Cutting, Clear-cutting and Post-Fire Cutting areas; it can be clearly seen that, since the initial infiltration, the Kostiakov model has a better arrangement, unlike the Horton model, which does not estimate the infiltration adequately during the first moments, and after 30 minutes tends to overestimate the infiltration. In general, this behavior was found in most tests. However, the Lewis-Kostiakov model had a correct performance in the fit, when low initial infiltration rates occurred (*Ii*<300 mm h^{-1}), unlike the Horton model, which overestimated the infiltration, and the Kostiakov models which underestimated it, as may be clearly seen in the Selective Cutting area.



Árboles Padre = Seed tres; *Posincendio* = Post-fire; *Matarrasa* = Clear-cutting*;* *Referencia* = Reference; *Selección* = Selective; *Tiempo* (*minutes*) = Time (minutes); *Velocidad de nfiltración* = Infiltration rate.

Figure 4. Adjustment of the infiltration rate based on the Horton, Kostiakov and Lewis-Kostiakov models.

Discussion

Di Prima *et al*. (2017) point out that opening the canopy is an important practice that influences the relationships between water and the soil. Based on the results of the present study, the differences between the initial, basic and accumulated infiltrations in the stands are determined by the type of disturbance or by the forestry treatment utilized. According to Dueñez *et al.* (2006) and Landini *et al.* (2007), the intensity of the cutting is an important factor that determines the levels of interception of rainfall, luminosity, moisture content, depth of organic matter in the soil, etc., and, therefore, has a direct effect on the hydraulic properties of the soil.

Bens *et al.* (2007), Wagner *et al*. (2011) and Archer *et al*. (2013) state that the depth and amount of organic matter contribute to improve the edaphic structure and increase the capacity of infiltration, water storage and hydraulic conductivity; this can be verified based on the results for *Ii*, *Bi* and *Ci*, as well as on the physical characteristics of the soil and the vegetation that is prevalent in the studied stands, particularly in the Clear-cutting stand, whose properties were considerably affected by the intensity of the applied cuttings, leading to a reduction in the hydrological variables.

The values of the infiltration variables indicate that the stage of growth of the forest is a relevant factor that determines the hydrological characteristics of the soil, as suggested by Hümann *et al*. (2011), Marshall *et al*. (2014) and Archer *et al*. (2016). This agrees with the results of the study documented herein, in which the Clear-cutting and Post-Fire Cutting areas are forest masses that exhibit a similar maturity status, unlike the Seed Trees, Selective Cutting and Reference stands, which include superior forest trees.

As for the values of the statistic R^2, there is little variation between the Kostiakov and the Lewis-Kostiakov models, which adequately represent the evolution of the infiltrated sheet in the infiltration tests of the various assessed stands. This is confirmed by Návar and Synnott (2000), Weber and Apestegui (2016), Sihag *et al.* (2017), according to whom the best predictions are generally obtained with the Lewis-Kostiakov model, as its parameters are more sensitive to the Umbrisol soil types, characterized by exhibiting a thick, dark horizon unsaturated in bases and rich in organic matter (Casanova *et al.*, 2007). In this regard, decreases in organic matter have an effect on the stability of the aggregates, dispersing fine texture particles and thereby favoring a reduction of the porosity and, consequently, leading to decreased infiltration (García-Hernández *et al.*, 2008).

It should be noted that information about hydrological topics and their relationship with forest management is scarce and limited. Hence, the relevance of the present study.

Conclusions

The initial (2 080 mm h^{-1}), basic (297.93 mm h^{-1}) and accumulated (16 428.29 mm h^{-1}) infiltration rates observed in the Referent stands evidence significant statistical differences in regard to other analyzed stands; therefore, the modifications in the forest structure cause a negative effect on the hydrological variables *Ii*, *Bi* and *Ci*.

The variables that make up the infiltration process are arranged in decreasing order as follows:

- Initial infiltration: Reference > Seed Trees> Post-fire cutting > Selective cutting > Clear-cutting
- Basic infiltration: Selective cutting > Reference > Seed Trees > Post-fire cutting > Clear-cutting
- Accumulated infiltration: Seed trees > Reference > Selective cutting > Post-fire cutting > Clear-cutting

Characteristics like the maturity status of the vegetation, structure, composition, and the edaphic variables apparent density, thickness of the organic layer, and moisture, cause variations in the infiltration rates of the various stands analyzed.

The results of the fit of the models, based on the coefficient of determination (R^2), show that both the Kostiakov and Lewis Kostiakov models are good enough for predicting infiltration in the different forest conditions studied herein; specifically, the

Lewis Kostiakov model estimates the infiltration better for the Selective Cutting and Reference areas, while those of the Seed Trees, Clear-cutting and Post-fire Cutting areas are best described by the Kostiakov model.

The parameters of the infiltration models are highly important for estimating the recharge of aquifers, superficial runoffs, and soil erosion, and therefore they facilitate sustainability-based decision making.

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Conflict of interest

The authors declare that they have no conflict of interests.

Contribution by author

Erik Orlando Luna Robles: development of the field and desk research and structuring and design of the manuscript; Israel Cantú Silva: editing of the manuscript and statistical analysis; María Inés Yáñez Díaz: contribution of analytical information to the manuscript; Humberto González Rodríguez: review and editing of the manuscript; José Guadalupe Marmolejo Monsiváis: review and editing of the manuscript; Silvia Janeth Béjar Pulido: manuscript data collection and processing.

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