EVALUATION OF GREEN-AMPT INFILTRATION EQUATION IN SOME AGRICULTURAL SOILS IN MEXICO, USING USDA INFORMATION AND A MODIFIED METHOD FROM BROOKS AND COREY

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SUMMARY

An adequate representation of the water infiltration process in the soil allows improving the efficiency in application and the uniformity of surface irrigation. The Green-Ampt model has shown to be a good representation of the process, and researchers from the United States Department of Agriculture (USDA) determined the values of their parameters for USA soils, which are shown in tables or through functional relationships. This information is used as a reference in several parts of the world, although there is no certainty that they are representative of the local soils, as is the case in Mexico. In this study, the parameters of the Green-Ampt equation were determined and evaluated in some soils of agricultural importance in Mexico. The parameters were obtained in four manners: one of them applied a methodology adapted from Brooks and Corey to quantify the wetting front capillary pressure head and used an permeameter under constant hydraulic head to determine the saturated hydraulic conductivity, and the other three consisted in taking them from three studies reported by the USDA. The values of the parameters suggested in Mexico drastically underestimated the results with relative errors (RE) in the range of -49.0 to -94.0%. The most representative ones were those obtained with the methodology proposed in this research, with RE of -15.0 to 6.0%.

The surface irrigation method is the one most frequently used to apply water in the different districts and irrigation units in Mexico, used in 92% of the area under irrigation (Rendón *et al*., 2003). However, it is the method with the lowest application efficiency, which means that a large part of the water volume applied is lost. Thus, it is essential to increase the efficiency of application of this irrigation method. For this purpose, it is necessary to have a detailed understanding of the infiltration process, since it allows to calculate an optimal

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irrigation time and increase the efficiency of application. However, the complex infiltration process can only be approximately described through mathematical equations.

A simple theoretical approach, although useful, was suggested for the infiltration process in 1911 by Green and Ampt in their classical article about the flow of air and water through soils (Green and Ampt, 1911). The Green-Ampt infiltration model can be used to represent the infiltration of water in surface irrigation (Killen and Slack, 1987), in addition to being useful for to design sub-superficial agricultural drains, to represent the wetting patterns for surface emitters in trickle and sprinkler irrigation and to estimate the superficial runoff in watersheds (DeBoer and Chu, 2001; Schmidt and Govindaraju, 2003; Sepaskhah and Chitsaz, 2004; Baiamonte and Singh, 2015).

The combination of simplifying water infiltration hypotheses introduced by Green and Ampt (1911) leads to the following equation (Fuentes, 2007; Rendón *et al.*, 2012):

$$I(t) = K_s t + \gamma \ln\left(1 + \frac{1}{\gamma}\right) \text{with } \gamma = (h + \psi_f)(\theta_s - \theta_i) \quad (1)$$

where I(t): amount of infiltration (cumulative infiltrated depth; cm) in time t(h); ψ_f: wetting front capillary pressure head (cm); h: water depth on the surface (cm); θ_s: soil water content at saturation ($cm^3 \cdot cm^{-3}$); θ_i: initial soil water content ($cm^3 \cdot cm^{-3}$); and K_s: hydraulic conductivity at saturation ($cm \cdot h^{-1}$).

The wetting front capillary pressure can be obtained from the integration of the Brooks and Corey equation of relative hydraulic conductivity (Brooks and Corey, 1964), through the expression (Brakensiek, 1977; Rawls *et al.*, 1983; Ogden and Saghafian, 1997):

$$\psi_f = \frac{2 + 3\lambda}{1 + 3\lambda}\left(\frac{\psi_b}{2}\right), \quad (2)$$

where ψ_b: bubbling pressure and λ: pore-size distribution index.

From the laboratory experimentation with many types of soils, the authors (Brooks and Corey, 1964; Corey and Brooks, 2009) concluded that ψ_f can be expressed as a logarithmic function of effective saturation (Se)

$$S_e = \left[\frac{\psi_b}{\psi}\right]^{\lambda} \text{ for } \psi \geq \psi_e \quad (3)$$

where Se: effective saturation, ψ_b: bubbling pressure, ψ: capillary pressure that corresponds to moisture θ, and ψ_e: air entry pressure.

The effective saturation is the relationship between available moisture and the maximum moisture content possible, expressed as

$$S_e = \frac{\theta - \theta_r}{\eta - \theta_r} \quad (4)$$

where θ: soil water content, θ_r: residual soil water content, and η: total soil porosity.

According to Corey and Brooks (2009), θ_r, ψ_b and ψ_e are curve fitting parameters determined from a plot of the capillary pressure as a function of Se on a log-log plot. The parameter θ_r is defined as that saturation value which provides the best fit to straight line, for saturations greater than a critical capillary pressure called ψ_e. The exponent λ is the negative of the slope straight line. The intercept at the ordinate where $\ln(S_e)=0$ defines $\ln(\psi_b)$, and the point where the measured curve intersects the straight line determines $\ln(\psi_e)$. Some researchers assume that the bubbling pressure ψ_b and the air entry pressure ψ_e are similar (Brakensiek, 1977; Saxton and Rawls, 2006).

For the design of surface irrigation in Mexico, Fuentes (2007) and Rendón *et al.* (2012) suggest using the parameters of the Green-Ampt function obtained by researchers of the United States Department of Agriculture (USDA) and reported by Brakensiek *et al.* (1981) and Rawls and Brakensiek (1982). A more complete and recent database that integrates and complements the prior studies, was generated from the study of 5000 soil horizons in the USA and reported by Rawls *et al.* (1983); however, the standard deviation of their values for a same textural class is very broad. To overcome this problem, the wetting front capillary pressure for a soil of well-identified texture can be obtained through the bubbling pressure in function of the soil water content at saturation (Saxton *et al.*, 1986) and the contents of sand, clay and organic matter (Saxton and Rawls, 2006).

The application of the Green-Ampt equation in Mexico with the values of the parameters reported by the USDA researchers, as suggested by some researchers and government institutions (Fuentes, 2007; Rendón *et al.*, 2012), does not guarantee a good representation of water infiltration due to the heterogeneity of the soils in the country. Therefore, the objective of this research was to obtain the parameters K_s and ψ_f of the Green-Ampt Eq. 1 with information from the USDA and from a laboratory procedure in some soils of agricultural importance in Mexico, and to evaluate their accuracy through the comparison of the accumulated infiltration depths estimated with field measurements to determine the most appropriate for soils in Mexico.

Materials and Methods

Soils studied

The determination of the parameters was carried out in ten soil samples from soils with agricultural use, seven of them under irrigation and three under rainfall. Sampling was performed in the Mexican states of Michoacán, Oaxaca, Sinaloa, Estado de México, Sonora and Baja California.

Five samples were taken in the state of Michoacán: two samples (Samples 1 and 2) in an agricultural and three samples (Samples 8, 9 and 10) in a rain fed agricultural zone within a small micro-basin (El Malacate) with forestry as primary land use. Each of the remaining five samples corresponded to one of the other previously mentioned states and were collected from irrigated agricultural areas.

Determinations performed in the soils

In each case, five samples of soil were taken from the terrain, at a depth of 30cm and were mixed to form a homogeneous compound sample.

To find the parameters of the Green-Ampt equation in each of the samples, the following were determined: texture, initial soil water content (θ_i), soil water content at saturation (θ_s), residual soil water content (θ_r), particle soil density (ρ_s), bulk soil density (ρ_b), saturated hydraulic conductivity (K_s) and the water retention curve.

The saturated hydraulic conductivity was determined in laboratory with a permeameter under constant hydraulic head and applying the Darcy law. We used this method because it is employed as a reference to evaluate the accuracy of other methods (Dirksen, 2009) and because the determination of the parameter in the field is difficult to obtain due to the entrance of atmospheric air into the soils (Faybishenko, 2009). The texture and real density were found applying the AS-09 and AS-04 methods, respectively, from the *Norma Oficial Mexicana* NOM-021-SEMARNAT-2000 (SEMARNAT, 2016). The apparent density was determined with the test tube method, using 50g of dry sieved soil.

The water retention curve was obtained by following the procedure indicated in the AS-06 method of

NOM-021-SEMARNAT-2000. The volumetric moisture content was determined at tensions of 0.01, 0.05, 0.1, 0.2, 0.33, 0.5, 1.0, 3.0, 5.0, 7.0, 9.0, 11.0, 12.0, 13.0, 15, 16.0 and 17.0atm, using a pressure cooker for low tensions and a pressure membrane for high tensions.

To calculate effective saturation with Eq. 4, the residual soil water content obtained at 17atm of tension was considered, and total porosity obtained as a function of ρs and ρb.

For the application of Eq. 1 soil water content at saturation, referred to a soil tension of 0atm, was used.

Green-Ampt models analyzed

The difference between the models that are described hereafter consisted in the way of obtaining parameters K_s and ψ_f of Eq. 1, since in every case a θ_s was used which resulted from laboratory determinations, and θ_i is a variable that takes the value of the moisture content prior to the infiltration.

Model from the water retention curve

This model was called 'retention curve', where the K_S was taken up again from the data obtained in the laboratory with the permeameter under constant hydraulic head method and the parameter ψ_f was obtained by solving Eqs. 2, 3 and 4 with information from the water retention curve.

The pressure in the wetting front capillary pressure was obtained from the water retention curve of the soil in a similar way as done by Brooks and Corey (1964) and Brakensiek (1977); the difference in the method applied in our study is that we used a retention curve in a range of 0.01 to 17atm, as pointed out above, and that parameters ψ_b and λ were obtained by solving simultaneously Eqs. 3 and 4 by the method of minimum squares instead of a graphic method.

The reason to use a water retention curve in such a broad range of tensions instead of using a curve in a much smaller range, from 0 to 0.5atm as Brooks and Corey (1964) and Brakensiek (1977) did, was because of the limitations of Mexican laboratories that do not allow measuring soil moisture at such low tensions nor distinguishing moisture differentials with small tension differentials.

Model based on data reported by Rawls et al. (1983)

This model was called this way because the values of parameters K_s and ψ_f were taken from the study carried out by Rawls *et al.* (1983).

Model based on the equation reported by Saxton et al. (1986)

This model was based on the equation found by Saxton *et al.* (1986) to calculate parameter ψ_b as a function of the soil water content at saturation θ_s.

With the ψ_b value obtained, Eqs. 3 and 4 were solved by the minimum squares method to obtain the value of λ, using the information from the retention curve, and then Eq. 2 was applied to obtain the value of parameter ψ_f. The value of K_s obtained from the laboratory determination was used.

Model based on the equations obtained by Saxton and Rawls

This model was called 'Saxton and Rawls' because the equations found by Saxton and Rawls (2006) to calculate the parameter ψ_b and one of the two contemplated values of K_s, were used, as a function of the content of clay, sand and organic matter.

The calculation of parameter λ was similar to that performed in the method denominated Saxton *et al.* (1986). The other value of K_S employed was taken from the laboratory result.

Evaluation of the Green-Ampt models

The representativeness of the models considered was evaluated by comparing their results to those obtained from an infiltration test performed through the double ring infiltrometer method. The comparison was made in the soil of the experimental agricultural field of the *Universidad Autónoma Chapingo* (UACh; Sample 5) and in the three soils of the micro-basin of the state of Michoacán (Samples 8, 9 and 10).

Prior to the beginning of the infiltration test, a small soil sample was taken with a drill to determine the initial moisture content in the four sites analyzed.

The evaluation of the degree of accuracy in the estimation of the infiltrated depth from the models analyzed was carried out with the standard error (SE), average error (AE) and relative error (RE). It is considered that the model has a good accuracy to predict the observed values as the values of the statistical parameters SE, AE and RE approach zero (Gutiérrez and de la Vara, 2009).

Results and Discussion

The analyzed soils correspond to six of the twelve textural classes that the USDA considers, covering from loam to clay (Table I).

Table I shows that the total porosity (η) of Sample 8 is quite similar to the mean reported by a soil in the USA with the same texture (Rawls *et al.*, 1983); in contrast, the rest of the soils studied (Samples 1, 2, 3, 4, 5, 6, 7,

TABLE I
CHARACTERISTICS OF THE ANALYZED SOILS

Sample	State of origin	Sand (%)	Clay (%)	Silt (%)	Texture	η (cm^3 cm^{-3})	θ_e (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	OM (%)
1	Michoacán	8.9	71.8	19.3	Clay	0.50	0.04	1.35	–
2	Michoacán	8.9	73.8	17.3	Clay	0.59	0.11	1.40	–
3	Oaxaca	54.9	21.8	23.3	Sandy clay loam	0.57	0.45	0.66	–
4	Sinaloa	36.9	37.8	25.3	Clay loam	0.50	0.40	0.75	–
5	México	48.9	25.8	25.3	Sandy clay loam	0.55	0.44	0.72	1.75
6	Baja California	40.3	23.4	36.3	Loam	0.52	0.41	0.80	0.75
7	Sonora	18.3	37.72	44.0	Silty clay loam	0.54	0.42	0.83	1.61
8	Michoacán	32.0	32.5	35.5	Clay loam	0.48	0.274	0.48	4.80
9	Michoacán	28.0	25.0	47.0	Loam	0.57	0.246	0.57	7.30
10	Michoacán	34.0	15.6	50.4	Silty loam	0.81	0.477	0.81	8.40

9 and 10) presented higher total porosity values than the mean values corresponding to soils with equivalent texture. In general, the total porosity values found are more similar to the higher limits of the intervals of total porosity in Rawls *et al.* 1983. However, although the total porosity of the samples analyzed is relatively high, the values are within the interval described in the literature, where it is mentioned that the porosity of a soil can reach up to 60% and can further increase in the presence of organic matter (Flint *et al.*, 2009; Stolf *et al.*, 2011).

The values obtained for effective porosity (θ_e) turned out to be similar to the mean values found in soils of the same texture in the USA in Samples 6, 7, 10. In Samples 1, 2, 8 and 9 they were lower (89.6, 71.4, 12.8 and 43.3%, respectively) and in Samples 3, 4 and 5 they were higher (36.4, 29.4 and 33.3%, respectively). The differences in Samples 1 and 2 are notable, and the very small θ_e values in Table I are attributed to their high residual humidity.

In Samples 1 and 2 the soil water content at saturation turned out to be >100%. These high contents of moisture are attributed to the percentage of clay in the samples (>70 %). The class to which these clays belong to is inferred to be montmorillonites, due to the behavior shown during the determination of water retention curves and according to the place where the samples were extracted. According to the Edaphology of the Digital Map of Mexico (INEGI, 2016), Samples 1 and 2 were obtained from a soil belonging to the order of vertisols, which are characterized by having montmorillonite clays, of type 2:1. This class of clay has the capacity of expanding to many times its original volume when water is added. This behavior, analogous to that of a hydrogel, explains the high percentage of saturation moisture in these samples.

Table II shows the values found for parameters ψ_f and K_s from the Green-Ampt equation, obtained for the models of retention curve and Rawls *et al.* (1983). The order in which the results are presented corresponds to the increasing fineness of the textures found in the soils studied, so as to ease their analysis. The results from these models are reported in the same table because it would be expected for those of the retention curve to be the most precise ones and because the Rawls *et al.* (1983) model is the one suggested for Mexico. Notable differences are seen in the values of ψ_f in all the soil textures analyzed. In nine out of the ten soils, the retention curve model found values that were within the range that the Rawls *et al.* (1983) model reports, and in most of the cases they were higher than the mean values.

Concerning the values of saturated hydraulic conductivity presented in Table II, in nine of the ten samples analyzed they were higher in the retention curve model and the difference was noticeable in five of the soils analyzed. The discrepancy could be due to differences in the physical properties of the soils and because in our study the parameter was determined with the constant head permeameter method and making use of altered samples; in contrast, in the study carried out by Rawls *et al.* (1983), the saturated hydraulic conductivity was obtained through a semi-empirical equation as a function of some physical characteristics of the soil and which has adjustment errors, using the following equation (Brutsaert, 1967):

$$K_s = \alpha \frac{\theta_e^2}{\psi_b^2}\left[\frac{\lambda^2}{(\lambda+1)(\lambda+2)}\right] \quad (5)$$

where α: constant that represents the effects of various fluid constants and of the acceleration of gravity, and is equal to $21 cm^3 \cdot s^{-1}$ (Rawls *et al.*, 1983).

In Table III, the wetted front capillary pressure and the saturated hydraulic conductivity of the Saxton *et al.* (1986) and Saxton and Rawls (2006) models are shown. In columns 4, 5 and 6 only the values for Samples 5, 6, 7, 8, 9 and 10 are included, as they were not calculated for the rest of the samples because their organic matter content, a necessary piece of data to apply the Saxton and Rawls (2006) equations, was not determined (see Table I).

The values of parameter ψ_f turned out to be different in the four models (Tables II and III). The values of parameter K_S obtained in the laboratory also turned out to be different, as well as those calculated with the Saxton and Rawls (2006) equations, particularly in the soils of Samples 8, 9 and 10. This behavior can be attributed to the fact that these soils have high organic matter contents, as they are agricultural soils in a micro-basin with predominately forestry use, a situation that is not contemplated by the mentioned equations because the average value of the analyzed USA soils was 0.6 and 2.8% for the horizons B-C and A, respectively (Saxton and Rawls, 2006). In Figure 1, the evolution of the accumulated infiltration depth obtained with the double ring infiltrometer (Sample 5, measured at the experimental field at UACh) and with the four models considered in an agricultural soil of Sandy clay loam texture is presented. In the figure, two Saxton and Rawls (2006) models are shown; the one indicated by Saxton and Rawls 1 (2006) used the value of parameter K_S calculated with the Saxton and Rawls (2006) equations (column 5 of Table III), and the one labelled as Saxton and Rawls 2 (2006) used the value obtained in the laboratory (column 6 of Table III).

In Figure 1 it can be appreciated that the retention curve model underestimated the results but it was the one that best represented the amount of infiltration, followed in decreasing order of accuracy by the Saxton and Rawls 2 (2006) model, which also underestimated them, Saxton and Rawls 1 (2006) with overestimation, Saxton *et al.* (1986) with overestimation and Rawls *et al.* (1983) with an important underestimation. It must be emphasized that the results of the Saxton and Rawls 2 (2006) model turned out to be quite similar to those of the retention curve, with the disadvantage that during long periods of time the infiltration amount is made slightly slower and is more distant from the measured values. The Saxton and Rawls 1 (2006) model had a greater error in the estimation of accumulated infiltrated depth than the Saxton and Rawls 2 (2006) model because the calculation of the hydraulic conductivity at saturation was calculated as a function of the soil water content at saturation, at field capacity and perma-

TABLE II
GREEN-AMPT PARAMETERS OBTAINED WITH THE RETENTION CURVE (RC) AND RAWLS *et al.* (1983) MODELS

Sample	ψ_f (cm)		K_s ($cm \cdot h^{-1}$)	
	RC	Rawls *et al.* (1983)	RC	Rawls *et al.* (1983)
6	63.90	8.89 (1.33-59.38)	0.78	0.68
9	40.50	8.89 (1.33-59.38)	17.00	0.68
10	69.10	16.68 (2.92-95.39)	19.00	1.30
3	9.81	21.85 (4.42-108.0)	2.48	0.30
5	10.60	21.85 (4.42-108.0)	1.20	0.30
4	9.98	20.88 (4.79-91.10)	0.36	0.20
8	53.00	20.88 (4.79-91.10)	6.72	0.20
7	86.74	27.30 (5.67-131.5)	0.93	0.20
1	91.67	31.63 (6.39-156.5)	0.10	0.20
2	7.40	31.63 (6.39-156.5)	0.19	0.06

The values in column 3 correspond to the textural class. Number in parenthesis is ±standard deviation.

TABLE III
VALUES OF ψ_f Y K_s USED BY THE SAXTON *et al.* (1986) AND SAXTON AND RAWLS (2006) MODELS

Sample	Saxton *et al.* (1986)		Saxton and Rawls (2006)		
	ψ_f (cm)	KS from laboratory ($mm{\cdot}h^{-1}$)	ψ_f (cm)	K_S from laboratory ($mm{\cdot}h^{-1}$)	K_S from equations ($mm{\cdot}h^{-1}$)
1	166.90	0.10	–	–	–
2	157.20	0.19	–	–	–
3	9.14	2.48	–	–	–
4	50.20	0.36	–	–	–
5	29.57	1.20	28.44	0.61	1.20
6	21.22	0.78	42.26	0.61	0.78
7	34.30	0.93	66.32	0.17	0.93
8	57.81	6.72	51.26	0.25	6.72
9	82.20	17.00	63.03	0.45	17.00
10	145.92	19.00	57.14	0.93	19.00

nent wilting point, which in turn were obtained with empirical equations found for USA soils (Teh and Iba, 2010).

The better approximation of the Saxton and Rawls (2006) models compared to those of Saxton *et al.* (1986) and Rawls *et al.* (1983) can be explained because they contemplate the particular characteristics of a soil from its texture and its organic matter content, in addition to being sustained by a larger database. Instead, the use of average values of parameter ψ_f from a textural class in the Rawls *et al.* (1983) model generates strong errors because the range of variation of its values is very broad (column 4 of Table II).

The statistical descriptors SE (cm), AE (cm) and RE (%) allow specifying the power of estimation and quantifying the errors made with the application of each one of the Green-Ampt models analyzed in the soils from Samples 5, 8, 9 and 10. (Table IV). It is clear that the Rawls *et al.* (1983) model suggested for Mexico is inadequate because in the four soils evaluated there had very high values for the three descriptors: from 3.97 to 82.14cm in SE, from -3.37 to -64.45cm in AE, and from -49.0 to -91.0% in RE. The Saxton *et al.* (1986) model improved substantially the estimation of the infiltration amount because it included the parameter θ_S, a property that is characteristic of a soil, sustained by the analysis of a much broader database. The retention curve and Saxton and Rawls 2 (2006) models were the best and can be considered similar in their predictive quality, except in the soil from Sample 9, where the retention curve model overestimated the results to a lower degree.

In the four evaluated soils, all the Green-Ampt models considered had a lower accuracy in the soil of Sample 10, which has a high content of organic matter and Silty loam texture. Because of the physical characteristics of this soil, it could be said that the flow is applied in piston flow and the other hypotheses suggested by Green-Ampt, so the decrease in the quality of performance from the models is attributed to the use of an altered sample of soil, which could not be the most advisable way to estimate the hydraulic conductivity at saturation in the laboratory for soils with high contents of organic matter, and to the use of equations and a database that also do not contemplate soils with high contents of organic matter.

The good accuracy of the retention curve model suggests that the hypotheses suggested by Green-Ampt are fulfilled in the evaluated soils and that the procedures followed in this model to obtain parameters ψ_f, K_S and θ_S are adequate.

The Saxton and Rawls 2 (2006) model resulted in a similar accuracy to that of the retention curve; however, once the parameter ψ_b is estimated, the water retention curve is required to calculate the parameter λ and with them the parameter ψ_f, and in addition it used the parameter K_S obtained in the laboratory and not the one estimated with the empirical equations found by Saxton and Rawls (2006). If the Saxton and Rawls 1 (2006) model, in which the parameter K_S was estimated as a function of the texture and the content of organic matter, had been found to be more accurate, the value of λ could be obtained through an inverse process using an infiltration test executed in the field. The inconvenience of obtaining the values for K_S and ψ_f inversely is that there is a risk of not representing the hydrodynamic characteristics of the soils if there is not enough experience, since these parameters could satisfy only one numerical solution, so that in order to guarantee a good result one must

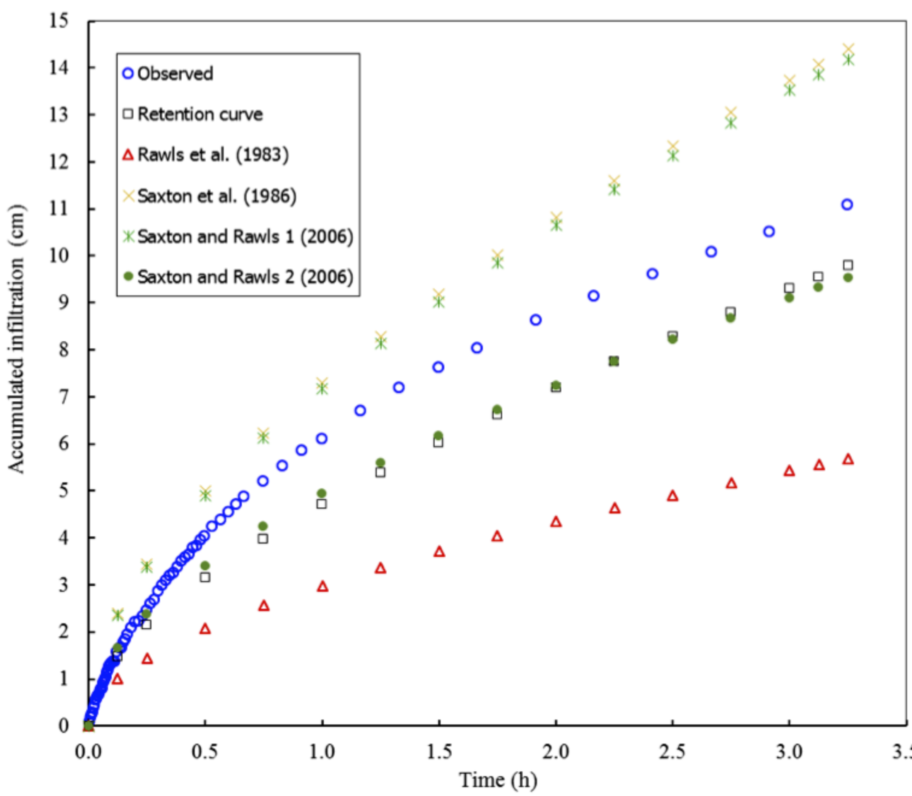

Figure 1. Accumulated infiltration depth in the soil from Sample 5.

TABLE IV
STATISTICAL PARAMETERS OF THE ESTIMATED INFILTRATED DEPTH

Model	Sample 5			Sample 8			Sample 9			Sample 10		
	SE	AE	RE	SE	AE	RE	SE	AE	RE	SE	AE	RE
Retention curve	1.32	-1.05	-15.0	1.03	0.52	6.0	3.41	0.63	1.0	10.60	-8.33	-12.0
Rawls *et al.* (1983)	3.97	-3.37	-49.0	9.19	-7.89	-90.0	52.07	-43.60	-94.0	82.14	-64.45	-91.0
Saxton *et al.* (1986)	2.24	1.94	28.0	2.85	2.21	25.0	18.89	15.45	33.0	20.76	16.84	24.0
Saxton and Rawls 1 (2006)	1.32	1.79	26.0	8.48	-7.28	-83.0	49.90	-41.71	-90.0	77.72	-60.87	-86.0
Saxton and Rawls 2 (2006)	2.08	-1.00	-14.0	0.92	0.39	5.0	7.38	5.19	11.0	9.89	-7.75	-11.0

fully identify the parameter to be optimized (Hopmans and Šimůnek, 2009).

The results from the performed evaluations suggest the need to obtain values from the parameters of the Green-Ampt equation that are suited to the characteristics of soils in Mexico, so as to reach more accurate estimations of the infiltration. According to the results found in this study, the water retention curve must be used to obtain parameter ψ_f, as was done in the retention curve method, and this curve could be generated taking into consideration the physical properties of the soils, as was done by Rajkai *et al.* (2004), considering the sand, clay and organic matter contents, and the bulk density from the soils representative of the country to minimize the costs of the studies. Another alternative could be the study of empirical functional relations to obtain ψ_f directly as a function of sand and clay contents and the porosity of the soil; these equations have to be specific for soil uses to improve the representativeness of their characteristics (Rawls *et al.*, 1989; King *et al.*, 1999).

Conclusions

It is a challenge to obtain the adequate values of the parameters of the Green-Ampt equation, especially the wetting front capillary pressure head, because of the field and laboratory studies demands, and due to the analysis of information and costs implied. The parameters of the wetting front capillary pressure head and the saturated hydraulic conductivity from the Green-Ampt equations were determined with different procedures in Mexican agricultural soils of six textural classes, and their representativeness evaluated through the comparison of the estimated infiltration depths compared to those obtained in the field with a double ring infiltrometer. The mean values found by Rawls *et al.* (1983) by texture class, and recommended for soils in Mexico, turned out to be inadequate, with a drastic underestimation of the measured infiltration depths, while the most representative values were those obtained from the water retention curve in the case of the wetting front capillary pressure head and with the constant head permeameter for the saturated hydraulic conductivity.

Finally, obtaining the parameters from the Green-Ampt equation from agricultural soils in Mexico is recommended, and the adaptation of the Brooks and Corey method that was made in this study is suggested to obtain the wetting front capillary pressure head.

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EVALUACIÓN DE LA ECUACIÓN DE INFILTRACIÓN DE GREEN Y AMPT EN ALGUNOS SUELOS AGRÍCOLAS DE MÉXICO, USANDO INFORMACIÓN DEL USDA Y UN MÉTODO MODIFICADO DE BROOKS Y COREY

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RESUMEN

Una representación adecuada del proceso de infiltración del agua en el suelo permite mejorar la eficiencia de aplicación y la uniformidad en riego por gravedad. Se sabe que el modelo de Green y Ampt representa adecuadamente el proceso de infiltración, por lo que investigadores del Departamento de Agricultura de Estados Unidos (USDA) determinaron los valores de sus parámetros para suelos de los EEUU, los que son expuestos en cuadros o expresados mediante relaciones funcionales. Esa información se utiliza como referencia en varias partes del mundo, pero no hay certeza de que sean representativos de los suelos locales, como es el caso de México. El objetivo de este estudio fue determinar y evaluar los parámetros de la ecuación de Green y Ampt en algunos suelos de importancia agrícola en México. Los parámetros se obtuvieron de cuatro formas: una de ellas aplicó una metodología adaptada de Brooks y Corey para cuantificar la presión capilar en el frente húmedo y usó la conductividad hidráulica a saturación obtenida con un infiltrómetro de carga constante, y los otras tres consistieron en tomarlos de tres investigaciones reportadas por el USDA. Los valores de los parámetros sugeridos en México subestimaron drásticamente los resultados con errores relativos (RE) en un rango de -49,0 a -94,0% y los más representativos fueron los obtenidos con la metodología propuesta en esta investigación, con un RE de -15,0 a 6,0%.

AVALIAÇÃO DA EQUAÇÃO DE INFILTRAÇÃO DE GREEN-AMPT EM ALGUNS SOLOS AGRÍCOLAS DO MÉXICO, USANDO INFORMAÇÃO DO USDA E UM MÉTODO MODIFICADO DE BROOKS E COREY

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RESUMO

Uma representação adequada do processo de infiltração da água no solo permite melhorar a eficiência na aplicação e na uniformidade em irrigação por gravidade. Sabe-se que o modelo de Green-Ampt representa adequadamente o processo de infiltração, assim os investigadores do Departamento de Agricultura de Estados Unidos (USDA) determinaram os valores de seus parâmetros para solos dos EEUU, os que são expostos em quadros ou expressados mediante relações funcionais. Essa informação se utiliza como referência em várias partes do mundo, mas não há certeza de que sejam representativos dos solos locais, como é o caso de México. O objetivo deste estudo foi determinar e avaliar os parâmetros da equação de Green-Ampt em alguns solos de importância agrícola no México. Os parâmetros foram obtidos de quatro formas: uma delas aplicou uma metodologia adaptada de Brooks e Corey para quantificar a pressão capilar na frente úmida e usou a condutividade hidráulica a saturação obtida com um infiltrômetro de carga constante, e os outros três consistiram em tomá-los de três investigações relatadas pelo USDA. Os valores dos parâmetros sugeridos no México subestimaram drasticamente os resultados com erros relativos (RE) em uma faixa de -49,0 a -94,0% e os mais representativos foram os obtidos com a metodologia proposta nesta investigação, com um RE de -15,0 a 6,0%.