

Evaluation of some infiltration models and hydraulic parameters

F. Haghghi*, M. Gorji, M. Shorafa, F. Sarmadian and M. H. Mohammadi

Soil Science Department. University of Tehran. Karaj. Iran

Abstract

The evaluation of infiltration characteristics and some parameters of infiltration models such as sorptivity and final steady infiltration rate in soils are important in agriculture. The aim of this study was to evaluate some of the most common models used to estimate final soil infiltration rate. The equality of final infiltration rate with saturated hydraulic conductivity (K_s) was also tested. Moreover, values of the estimated sorptivity from the Philip's model were compared to estimates by selected pedotransfer functions (PTFs). The infiltration experiments used the double-ring method on soils with two different land uses in the Taleghan watershed of Tehran province, Iran, from September to October, 2007. The infiltration models of Kostiakov-Lewis, Philip two-term and Horton were fitted to observed infiltration data. Some parameters of the models and the coefficient of determination goodness of fit were estimated using MATLAB software. The results showed that, based on comparing measured and model-estimated infiltration rate using root mean squared error (RMSE), Horton's model gave the best prediction of final infiltration rate in the experimental area. Laboratory measured K_s values gave significant differences and higher values than estimated final infiltration rates from the selected models. The estimated final infiltration rate was not equal to laboratory measured K_s values in the study area. Moreover, the estimated sorptivity factor by Philip's model was significantly different to those estimated by selected PTFs. It is suggested that the applicability of PTFs is limited to specific, similar conditions.

Additional key words: final infiltration rate, saturated hydraulic conductivity, sorptivity.

Resumen

Evaluación de algunos modelos de infiltración y de algunos parámetros hidráulicos

En la agricultura es importante evaluar las características de la infiltración y de algunos parámetros de los modelos de infiltración, como sortividad y tasa de infiltración constante final de los suelos. El objetivo de este estudio fue evaluar algunos de los modelos utilizados más frecuentemente para estimar la tasa de infiltración final del agua en el suelo, así como estudiar la relación de la tasa de infiltración final con la conductividad hidráulica saturada (K_s) y comparar los valores estimados de la sortividad según el modelo de Philip con los estimados según funciones seleccionadas de edafotransferencia (PTFs). Se realizaron unos experimentos de infiltración en la cuenca de drenaje Taleghan, Teherán, Iran, desde septiembre a octubre de 2007, mediante el método del doble anillo, en suelos con dos diferentes usos. Se ajustaron los modelos de infiltración de Kostiakov-Lewis, el de dos términos de Philip y el de Horton a los datos de infiltración observados. Se estimó la bondad del ajuste de algunos parámetros de los modelos y el coeficiente de determinación mediante el software MATLAB. Al comparar la tasa de infiltración medida y estimada según los modelos, utilizando la raíz del cuadrado medio del error (RMSE), los resultados mostraron que el modelo de Horton predijo mejor la tasa de infiltración final. Los valores K_s medidos en laboratorio fueron más altos y significativamente diferentes que las tasas de infiltración finales estimadas según los modelos seleccionados. La tasa de infiltración final estimada no fue igual a los valores K_s medidos en laboratorio. Además, el factor de sortividad estimado según el modelo Philip fue significativamente diferente de aquellos estimados según PTFs seleccionados. Se sugiere que la aplicabilidad de los PTFs se limite a condiciones específicas y similares.

Palabras clave adicionales: conductividad hidráulica saturada, sortividad, tasa de infiltración final.

* Corresponding author: haghghi634@gmail.com

Received: 17-03-09; Accepted: 29-01-10.

Abbreviations used: EC (electrical conductivity), K_s (saturated hydraulic conductivity), PTFs (pedotransfer functions), RMSE (root mean squared error).

Introduction

Infiltration is the term applied to the process of water entry into soil (Hillel, 1980). Evaluation of soil infiltration characteristics and determination of the final steady infiltration rate are required for increased irrigation water use efficiency, the design of irrigation systems, and decreased water and soil losses which are important factors in agriculture. The final steady infiltration rate of a soil is the minimum rate that water enters into the soil (Mbagwu, 1993). Since measuring the final infiltration rate is time consuming, several models have been proposed to determine this parameter. Empirical models such as those of Kostiakov (1932) and Horton (1940), and physical models such as that of Philip (1957) are the most commonly models to estimate final infiltration rate. Singh (1992) stated that the various models can estimate different values of the final soil infiltration rate which seems incorrect as the parameter is soil-dependent. The ability of the models to estimate infiltration rate has been examined by many researchers. Gifford (1976) observed that among the Horton, Kostiakov and Philip's models, the Horton model gave the best fit of infiltration data in mostly semi-arid range lands in Australia, but only under specific conditions. Roohian *et al.* (2005) suggested that Horton's model gives an acceptable estimate of final infiltration rate under given soil texture conditions. However, complicated factors that influence the final infiltration rate are a major reason for the different applicability of the models. Machiwal *et al.* (2006) observed infiltration was well described by the Philip's model in wasteland in Kharagpur, India. Navar and Synnott (2000) evaluated the infiltration rates of soils under four land uses in north-eastern Mexico. Among the infiltration models of Horton, Philip, a modified Kostiakov and Green-Ampt, the modified Kostiakov model gave the best fit. Hajabbasi (2006) evaluated the Kostiakov, Horton, and Philip's infiltration models under different tillage and rotations in a clay-loam in North-west Iran and reported that the Horton's model gave the best prediction of infiltration rate in that region.

Soil hydraulic parameters, such as saturated hydraulic conductivity (K_s) and sorptivity (S) are important factors that govern the soil infiltration rate. Several workers have evaluated the Philip's model parameters, transmissivity (A) and sorptivity factors in their experiments (Sutikto *et al.*, 1993; Mohammadi and Refahi, 2006). The A factor in the Philip's model, may approximate to K_s for long periods (Swartzendruber and Youngs,

1974; Rawls, 1992). The fit of measured infiltration data to the Philip's model leads to $A = K_s$, as time approaches infinity (Philip, 1969). In Horton's model, the infiltration capacity approximates to a constant minimum (non-zero) rate of i_c , as time approaches infinity (Horton, 1940; Hillel, 1998) that can be equal to K_s . Mishra *et al.* (2003) showed that A varied from 50 to 75% of K_s values. Mbagwu (1995) also showed that values of the final infiltration rate and K_s were not equal over long periods.

Sorptivity is function of soil suction which is important for knowing soil hydraulic properties. This parameter is defined as a physical quantity that shows the capacity of a porous medium for capillary uptake and release of water into soil (Philip, 1957). This parameter can be estimated by defined PTFs as the relationship between soil hydraulic and other more available measured properties (Bouma, 1989) which can be used to estimate hydraulic parameters such as S factor.

The aim of this work was to evaluate the most common models used to estimate the final infiltration rate of soils, and compare values of the estimated final infiltration rate with laboratory measured K_s on undisturbed soil columns, and finally, to compare values of the S factor estimated by the Philip's model and PTFs.

Material and methods

Characteristics of the research area

The study was conducted on part of the Taleghan watershed in Iran. Eight points were selected at two sites ($36^{\circ} 08' 10.8''$ N, $50^{\circ} 40' 40.6''$ E, at 2,236 m asl and $36^{\circ} 08' 58.6''$ N, $50^{\circ} 43' 12.6''$ E, at 1,453 m asl, respectively) so the sites had the least difference in soil properties in the area studied. These sites were in rangelands with similar soil surface conditions and homogeneous soils. Soil depth and plant cover at points 1, 2, 3, and 4 were slightly greater than at points 5, 6, 7, and 8. The history of these rangelands showed that they were cropped for several years in the last century at points 3, 4, 7, and 8 using animal tillage. According to the Taleghan watershed study report (1993) the soils are calcareous and are classified as Typic Xerorthents. The depth of the Ap and C horizons were mostly 15 and 30 cm respectively and the boundary between horizons was smooth. The soil structure was massive in the soils studied. Soil texture in this area varied from clay-loam to silty clay loam. Minimum and maximum

daily temperatures were approximately -5.6 and 17°C, respectively. Mean annual rainfall varied from 464 to 796 mm and the land had a slope of about 15%.

Soil sampling and analysis

Soil properties were determined by sampling at 0-15 and 15-30 cm soil depths. At each site, 48 undisturbed soil sample cores of 5 cm height and diameter and 98.12 cm³ volume were taken (four replicates). They were used to measure the saturated hydraulic conductivity (K_s) using the constant head method (Klute and Dirksen, 1986), total porosity (by measuring saturated water content), and initial moisture content (gravimetrically). Darcy's equation was used to calculate the K_s value. Additionally, 24 composite soil samples were collected for measurement of soil chemical properties. Organic matter and particle size distribution were measured by the modified Walkley-Black wet oxidation method (Allison and Moodie, 1965) and the Bouyoucos hydrometer procedure (Gee and Bauder, 1986). Dry bulk density was determined by the core method (Davies *et al.*, 1973). Infiltration was measured using a double-ring infiltrometer (Bouwer *et al.*, 1999), with 25 cm inner diameter and 60 cm outer diameter rings (four replicates at each site) installed in the soil. Grass was carefully cut at the soil surface with shears in the inner and outer rings. A constant water head of approximately 15 cm was kept in both rings and amount of the water drop and the depth of added water were recorded for two hours. The EC of the water used was 0.49 dS m⁻¹, and sodium (Na) content was 20 mg L⁻¹. The data were fitted to three chosen infiltration models and the best-fit model selected. The soil Na (in a soil saturation extract) and calcium carbonate content (CaCO₃) were measured by flame emission and a volumetric method (Allison and Moodie, 1965), respectively. Soil pH and electrical conductivity (EC) were determined in soil saturation extract using the procedures of Page *et al.* (1982).

Estimation of infiltration model parameters

In this study, a few commonly used infiltration models, such as Kostiakov-Lewis, Philip two-term, and Horton's model were fitted to the infiltration data. The model-estimated final infiltration rate and sorptivity factor were determined using MATLAB software. The values of the measured final field infiltration rate with the

measured K_s in the laboratory and estimated S factor, by the Philip's model and PTFs were compared using a t-test (SAS/STAT, 1985).

Kostiakov-Lewis model

The modified Kostiakov model for long time periods is:

$$i(t) = at^{-b} + i_c \quad [1]$$

where a and b are the equation's parameters ($a > 0$ and $0 < b < 1$); $i(t)$ and i_c are the infiltration rate and presumed final infiltration rate in cm min⁻¹ at time t in min, respectively.

Horton's model

The Horton's infiltration model (Horton, 1940) is:

$$i(t) = (i_0 - i_c)e^{-kt} + i_c \quad [2]$$

where i_0 is the initial infiltration rate in cm min⁻¹; t is time; and k is the infiltration decay factor.

Philip two-parameter model

The Philip two-term model (Philip, 1957) is:

$$i(t) = \frac{1}{2} St^{-0.5} + A \quad [3]$$

where A is a transmissivity factor in cm min⁻¹ as a function of soil properties and water content; S is sorptivity which is a function of soil matric potential (cm min^{-0.5}).

Estimation of sorptivity factor by pedotransfer functions

Sorptivity factor was estimated using Youngs' equation (Youngs, 1964), based on some measured soil properties:

$$S = \sqrt{2(\phi - \theta_i) K_s S_f} \quad [4]$$

where ϕ , θ_i and K_s are porosity, volumetric initial moisture (cm³ cm⁻³), and saturated hydraulic conductivity (cm h⁻¹) respectively, which were measured in the laboratory (Table 1). The wetting front suction is S_f (cm), which was estimated using the Brooks-Corey

Table 1. Physical and chemical soil properties of the eight points studied

Point	Soil depth (cm)	Sand (%)	Silt (%)	Clay (%)	Bulk density (g cm ⁻³)	Initial moisture (%)	Total porosity (%)	CaCO ₃ (%)	OM ^a (%)	Na (meq L ⁻¹)	EC ^b (dS m ⁻¹)	pH
1	0-15	27.2	45.8	27.0	1.14	12	56.9	11.4	2.05	0.267	0.56	7.9
	15-30	28.4	39.6	32.0	1.16		56.2	14.2	1.64	0.180	0.40	7.8
2	0-15	20.4	47.6	32.0	1.25	12	52.8	11.8	2.49	0.887	0.56	8.0
	15-30	19.2	46.3	34.5	1.27		52.0	12.0	2.06	0.354	0.39	7.8
3	0-15	35.1	38.1	26.8	1.41	15	46.8	6.8	1.68	0.306	0.39	7.9
	15-30	32.5	38.5	29.0	1.59		40.0	7.2	1.50	0.214	0.42	7.8
4	0-15	36.5	34.3	29.2	1.22	9	53.9	4.4	1.83	0.245	0.53	7.9
	15-30	34.2	36.8	29.0	1.51		43.0	7.7	1.36	0.362	0.35	7.8
5	0-15	22.7	46.5	30.8	1.40	6	47.1	19.4	2.30	0.284	0.51	7.8
	15-30	18.1	45.9	36.0	1.43		46.0	22.7	1.55	0.375	0.24	7.7
6	0-15	22.4	49.2	28.4	1.38	6	47.9	26.6	2.39	0.267	0.58	7.8
	15-30	18.0	42.8	39.2	1.48		44.1	30.8	1.41	0.115	0.23	7.8
7	0-15	14.0	51.4	34.6	1.41	7	46.8	18.1	1.31	0.250	0.44	7.8
	15-30	13.7	45.7	40.6	1.50		43.3	18.3	0.46	0.128	0.24	7.9
8	0-15	13.5	49.9	36.6	1.22	7	53.9	18.8	1.45	0.206	0.43	7.9
	15-30	11.0	47.4	42.6	1.31		50.5	26.4	0.46	0.123	0.23	7.8

^a Organic matter. ^b Electrical conductivity.

(Brooks and Corey, 1964) and Rawls and Brakensiek (Rawls, 1992) functions. They are expressed as equations [5] and [6], respectively:

$$Sf = \frac{2+3\lambda}{1+3\lambda} \cdot \frac{h_b}{2} \quad [5]$$

where λ and h_b are the Brooks-Corey pore-size distribution index and bubbling pressure head (cm). These parameters are defined based on clay and sand %, and porosity (cm³ cm⁻³).

$$\begin{aligned} Sf = & \exp[6.53 - 7.326(\phi) + 0.00158(C^2) + 3.809(\phi^2) + \\ & + 0.000344(S)(C) - 0.04989(S)(\phi) + \\ & + 0.0016(S^2)(\phi^2) + 0.0016(C^2)(\phi^2) - \\ & - 0.0000136(S^2)(C) - 0.00348(C^2)(\phi) + \\ & + 0.000799(S^2)(\phi)] \end{aligned} \quad [6]$$

where S, C, and ϕ are sand, clay %, and porosity (cm³ cm⁻³), respectively (Rawls, 1992).

Results

Selection of best-fit infiltration model

The results of the soil analyses are shown in Table 1. As expected, the soil analysis results showed that soil texture varied from clay-loam to silty clay loam, the soil

pH from 7.7 to 8.0 and the EC from 0.23 to 0.58 dS m⁻¹ at soil depths of 0-15 and 15-30 cm. Thus, there was no salinity or sodicity in soils of the area studied. Table 1 shows there were no notable differences among the soil properties studied. In this study, the goodness of fit of the selected models and their ability to estimate the final soil infiltration rate was evaluated using root mean squared error (RMSE). The R values were high (0.99) and equal for all points. Values of RMSE and i_c showed that estimated infiltration rates by the Horton's model, were closer to the measured ones (Table 2). Comparing observed values with estimated final infiltration rate, is shown in Table 2. The results showed that the Kostiakov-Lewis model could not estimate the final steady infiltration rate at point 4 and the estimated values of this parameter using this model underestimated the observed ones at all points and had the greatest errors. Comparing measured values with estimated final infiltration rates, showed that the Philip two-term model estimated the final infiltration rate as well as the Horton's model, but had more values of RMSE than this model (Table 2). Overall, the lowest RMSE values were obtained with the Horton's model. The lowest estimated i_c by the Philip and Kostiakov-Lewis model was at P4. The highest sorptivity and lowest A values obtained from the Philip's model were observed at P4.

Table 2. Values of estimated and observed final infiltration rate, measured K_s , and root mean squared errors (RMSE) for the eight sample points

Point	Kostiakov-Lewis model		Philip two-term model		Horton's model		Observed final infiltration rate (cm min ⁻¹)	Saturated hydraulic conductivity (K_s) (cm min ⁻¹)
	i_c	RMSE	A	RMSE	i_c	RMSE		
1	0.2052	0.4202	0.2232	0.3175	0.2998	0.3648	0.2803	0.6083
2	2.22 × 10⁻¹⁴	0.623	0.2354	0.9557	0.1902	0.2257	0.2441	0.5850
3	0.0585	0.5275	0.1619	0.5784	0.2576	0.7348	0.2347	0.4516
4	0	0.6667	0.0184	0.6837	0.2005	0.2409	0.1863	0.4433
5	0.0870	0.3166	0.1274	0.3266	0.1828	0.4679	0.1613	0.2516
6	5.13 × 10⁻¹⁴	0.1025	0.2079	0.243	0.2247	0.1122	0.2285	0.2316
7	1.37 × 10⁻¹²	0.2932	0.1189	0.4016	0.1205	0.2788	0.1098	0.2050
8	0.0452	0.0589	0.0730	0.08246	0.0888	0.0926	0.0869	0.2250

Bold values show the lowest values of estimated final infiltration rate and the highest RMSE values for the points studied.

Final infiltration rate and K_s

The results showed that the saturated hydraulic conductivity, measured in the laboratory, was positively related to the observed final infiltration rate ($R = 0.612$) (Table 2, Fig. 1). The results showed that measured

values of the saturated hydraulic conductivity were significantly higher than the observed final infiltration rate in the field at all 8 points, ($P > F = 0.0299$, $P = 0.05$) (Table 2). Measured K_s was approximately 2-3 times the observed final infiltration rate at most sample points.

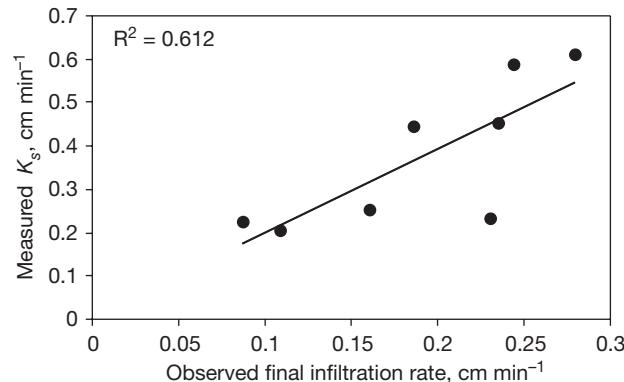


Figure 1. Correlation between saturated hydraulic conductivity (K_s) and final infiltration rate.

Estimated sorptivity factor

The sorptivity factor, in the Philip's model, changed from 0.315 to 2.984 among the different sample points (Table 3, Fig. 2). Statistical analysis at $p < 0.01$ (SAS/STAT, 1985) showed significant differences between the sorptivity factor from the Philip's model and the one estimated by PTFs. From Figure 2 it can be seen that sorptivity values estimated by PTFs had high deviations from the Philip's sorptivity factor. Further, the correlation between parameters of the Philip's model (S and A) was poor and the relationship between them was not significant ($R = 0.127$) (Fig. 3).

Table 3. Estimated sorptivity factor (cm min^{-0.5}) by the Philip's model and pedotransfer functions (PTFs)

Point	Estimated sorptivity factor by the Phillip's model	Estimated sorptivity factor by PTFs	
		Brooks-Corey	Rawls-Brakensiek
1	1.217	0.3669	0.5282
2	1.322	0.4015	0.4867
3	1.741	0.3561	0.5726
4	2.984	0.3144	0.5739
5	0.970	0.3405	0.4155
6	0.543	0.3893	0.4761
7	0.592	0.4290	0.4371
8	0.315	0.4307	0.4518

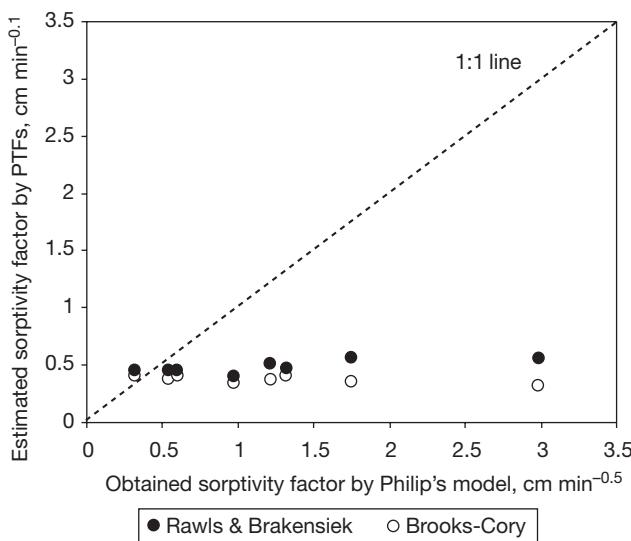


Figure 2. Relationship between sorptivity factor obtained by Philip's and one estimated by pedotransfer functions (PTFs).

Discussion

In this study, the Horton's model gave the best fit of the results for all sample points. The different values of RMSE, for each model, at the different points is probably due to changed conditions at the points such as soil particle size distribution (Table 1), because of a high dependency of infiltration rate on soil texture (Rawls, 1992; Mohammadi and Refahi, 2006). The suitability of the Kostiakov and Philip's models for estimation of the infiltration rate can be site-specific (Mbagwu, 1993). In addition, complicated conditions and regional soil variation can significantly affect measured and estimated values. Thus, spatial variations

in short distances and probable preferential flow at some points such as P4 can affect the data set obtained and consequently the model parameters. The result of this study agrees with the earlier result of Hajabbasi (2006), who found that the Horton's model is applicable in a clay loam soil of northwest Iran. Thus, the applicability of infiltration models should be tested under different conditions, because the various models can suppose different final infiltration rate values for a soil, which is not correct, while the final infiltration rate is generally a soil-dependent parameter (Singh, 1992; Mishra *et al.*, 2003). In this study, the low predictive ability of the Kostiakov-Lewis model for estimating the final infiltration rate could be because it takes longer to obtain a steady infiltration rate because of a low initial soil moisture content (Navar and Synnott, 2000). It also seems that a longer time duration, more than 2 hours, may be required for application of the Philip's model (Philip, 1969; Mbagwu, 1993). Also, the Philip's two-term model sometimes can not accurately describe the measured field data (Gosh, 1983).

Significant difference between the Philip's sorptivity factor in P4 compared to other sample points may be due to the impossibility of accurately determining the value of the final infiltration rate using the Philip's model. Overall, spatial soil variability is important in infiltration modelling. Significant differences between the observed final infiltration rate and K_s can be attributed to the effect of trapped air under field conditions (Radcliffe and Rasmussen, 2000) or disturbed core samples producing preferential flow in the laboratory (Maheshwari, 1996; Mohammadi and Refahi, 2006). Thus, complicated conditions in the field, differences between laboratory and field conditions, and spatial soil variability can be good reasons for the observed results (*i.e.* Taleghan watershed). Differences between K_s and the final infiltration rate (in Table 2) were similar to those of Mohammadi and Refahi (2006).

In this study, the variation in the sorptivity parameter showed no clear pattern in the study region. This agrees with the results of Machiwal *et al.* (2006). Soils in the field are more heterogeneous than laboratory soil cores and this is a possible reason for the differences. Thus, PTFs should be developed for hydrologic parameters of models on a larger scale than soil core. Also, PTFs derived from one database, in a particular region and condition, is not applicable under all conditions (Kern, 1995; Wösten *et al.*, 2001). Thus, PTFs should be applied to similar conditions to the soils investigated. Moreover, soil pore size distribution is an important factor in

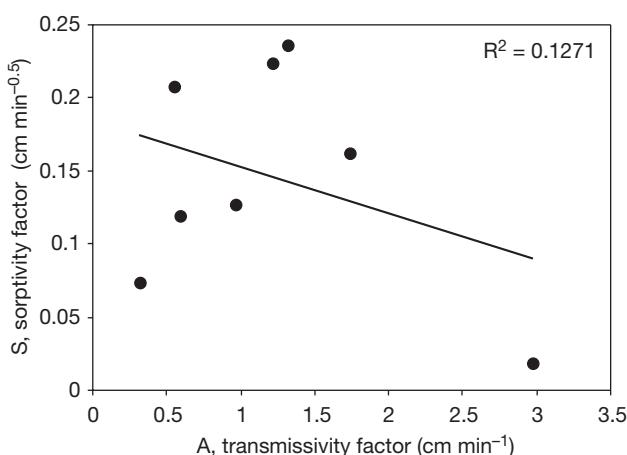


Figure 3. The correlation between Philip's sorptivity and transmissivity parameters.

spatial variation of Philip's sorptivity parameter (Sharma *et al.*, 1980; Machiwal *et al.*, 2006), whereas total porosity was considered in selected PTFs in this study. Other possible reasons for the difference could be due to variation in soil effective porosity, pore size distribution (Sharma *et al.*, 1980), matric properties, and probable preferential flow. These can be possible reasons for differences between estimated values of sorptivity factor by Philip's equation and PTFs. However, the relationship between the sorptivity factor and effective porosity needs to be evaluated in more detail. Wide variation in model parameters can also be due to non-uniform initial soil moisture. The poor correlation between parameters of Philip's model (S and A) observed in this study, is confirmed by the findings of Talsma (1969).

In conclusion, in this work infiltration models were evaluated. The results showed that Horton's model can be used for estimating final soil infiltration rate. Only, one or some of the infiltration models are better and appropriate for a specific study site. This investigation showed that Horton's model was better than the Kostiakov-Lewis and Philip's model at most sample points in the Taleghan watershed in Iran. Thus, infiltration models should be tested for their ability to estimate the final infiltration rate of each location and it should be documented at each site. It was found that the observed final infiltration rate has no equal concept to the measured saturated hydraulic conductivity for all conditions and sites. Moreover, the determined sorptivity factor is a variable parameter under field conditions and estimated values of this factor by PTFs were significantly different compared with the values obtained for Philip's sorptivity factor. Thus, the use of various models and PTFs is restricted and this problem needs to be considered in these sorts of studies. It is suggested that in the future there is a need to evaluate the parameters of infiltration models and the relationship among them, accurately and for the calibration of PTFs and infiltration models under different conditions. Soil spatial variability has an appreciable effect on infiltration properties and hydraulic parameters that need to be evaluated in more detail.

Acknowledgements

The authors would like to thank the Tehran University Research Fund, Faculty of Agriculture and Natural Resources, for financial support.

References

- ALLISON L.E., MOODIE C.D., 1965. Carbonate. In: Methods of soil analysis (Black C.A. *et al.*, eds). Part 2. Agron. Monogr. 9. ASA and SSSA, Madison, WI. pp. 1379-1396.
- BOUMA J., 1989. Using soil survey data for quantitative land evaluation. *Adv Soil Sci* 9, 177-213.
- BOUWER H., BACK J.T., OLIVER J.M., 1999. Predicting infiltration and ground-water mounds for artificial recharge. *J Hydrol Eng* 4(4), 350-357.
- BROOKS R.H., COREY A.T., 1964. Hydraulic properties of porous media. *Hydrology paper* 3. Colorado St Univ, Fort Collins, USA.
- DAVIES B.D., FINNEY J.B., RICHARDSON S.J., 1973. Relative effect of tractor weight and wheel-slip in causing soil compaction. *J Soil Sci* 24, 399-409.
- GEE G.W., BAUDER J.W., 1986. Particle size analysis. In: Methods of soil analysis (Klute A., ed), Part 1, 2nd ed. Agronomy No. 9. Am. Soc. Agron., Madison, WI. pp. 825-844.
- GIFFORD G.F., 1976. Applicability of some infiltration formula to rangeland infiltrometer data. *J Hydrol* 28, 1-11.
- GOSH R.K., 1983. A note on the infiltration equation. *J Soil Sci* 136, 333-338.
- HAJABBASI M.A., 2006. Evaluation of Kostiakov, Horton and Philip's infiltration equations as affected by tillage and rotation systems in a clay-loam soil of Northwest Iran. 18th World Congress of Soil Science, Pennsylvania, USA, 13 July.
- HILLEL D., 1980. Applications of soil physics. Academic Press Inc, NY.
- HILLEL D., 1998. Environmental soil physics. Academic Press Inc, New York, USA.
- HORTON R.E., 1940. An approach toward a physical interpretation of infiltration capacity. *Soil Sci Soc Am J* 5, 339-417.
- KERN J.S., 1995. Evaluation of soil water retention models based on basic soil physical properties. *Soil Sci Soc Am J* 59, 1134-1141.
- KLUTE A., DIRKSEN C., 1986. Hydraulic conductivity and diffusivity. In: Methods of soil analysis (Klute A., ed). Part 1. Physical and mineralogical methods, 2nd ed. Agronomy monographs, 9. ASA-SSA, Madison, WI. pp. 687-734.
- KOSTIAKOV A.N., 1932. On the dynamics of the coefficient of water percolation in soils and on the necessity of studying it from a dynamic point of view for the purposes of amelioration. *Transactions 6th Congress of International Society of Soil Science*, Moscow. Russian Part A. pp. 17-21.
- MACHIWAL D., MADAN KUMAR J.H.A., MAL B.C., 2006. Modelling infiltration and quantifying spatial soil variability in a watershed of Kharagpur, India. *Biosyst Eng* 95, 569-582.
- MAHESHWARI B.L., 1996. Correlations and interactions among hydraulic parameters of non-cracking soils. ASAE Annual International Meeting. Paper no 962105.
- MBAGWU J.S.C., 1993. Testing the goodness of fit of selected infiltration models on soils with different land

- use histories. International Atomic Energy Agency and UN Educational Scientific and Cultural Organization, IC/93/290.
- MBAGWU J.S.C., 1995. Testing the goodness of fit of infiltration models for highly permeable soils under different tropical soil management systems. *J Soil Sci* 34, 199-205.
- MISHRA S.K., TYAGI J.V., SINGH V.P., 2003. Comparison of infiltration models. *Hydrol Process* 17, 2629-2652.
- MOHAMMADI M.H., REFAHI H.G., 2006. Estimation of infiltration through soil physical characteristics. *J Iranian Agr Sci* 36, 1391-1398.
- NAVAR J., SYNNOTT T.J., 2000. Soil infiltration and land use in Linares, NL, Mexico. *Terra Latinoamericana* 18, 255-262.
- PAGE A.L., MILLER R.H., KEENEY D.R., 1982. Method of soil analysis. Part 2. Chemical and microbiological properties, 2nd ed. *Agronomy monographs*, ASA-SSA, Madison, WI, USA.
- PHILIP J.R., 1957. The theory of infiltration: 4. Sorptivity and algebraic infiltration equations. *J Soil Sci* 84, 257-264.
- PHILIP J.R., 1969. The theory of infiltration. *Adv Hydro Sci* 5, 215-296.
- RADCLIFFE D.E., RASMUSSEN T.C., 2000. Soil water movement. In: *Handbook of soil science* (Sumner M.E.). Chapter 4. University of Georgia.
- RAWLS W.J., 1992. Infiltration and soil water movement. In: *Handbook of Hydrology*, Chapter 5 (Madmen D.R.), McGraw-Hill, Inc, USA.
- ROOHIAN M.H., MIRING U.A., SAGHAFIAN B., DELAFKAR H., 2005. Horton's infiltration model calibration in Nimrod watershed, Firoozkooh, Tehran province, 3rd Erosion & Sediment National Conference, Tehran.
- SAS/STAT, 1985. User's guide: Basics. SAS Institute Inc Cary, NC, USA.
- SHARMA M.L., GANDER G.A., HUNT C.G., 1980. Spatial variability of infiltration in a watershed. *J Hydrol* 45, 101-122.
- SINGH V.P., 1992. Elementary hydrology. Prentice Hall: Englewood Cliffs, NJ, USA.
- SUTIKTO T., CHIKAMORI K., 1993. Evaluation of Philip's infiltration equation for cultivated upland terraces in Indonesia. *J Hydrol* 143, 279-295.
- SWARTZENDRUBER D., YOUNGS E.G., 1974. A comparison of physically-based infiltration equations. *T ASAE* 12, 822-828.
- TALSMAN T., 1969. *In situ* measurement of sorptivity. *Aust J Soil Res* 7, 269-276.
- TEHRAN UNIVERSITY, 1993. Comprehensive watershed management study of Taleghan watershed report. Irrigation Engineering Department, Tehran, Iran.
- WÖSTEN J.H.M., PACHEPSKY Y.A., RAWLS W.J., 2001. Pedotransfer functions: bridging the gap between available basic soil data and missing soil hydraulic characteristics. *J Hydrol* 251, 123-150.
- YOUNGS E.G., 1964. An infiltration method measuring the hydraulic conductivity of unsaturated porous materials. *J Soil Sci* 97, 307-311.