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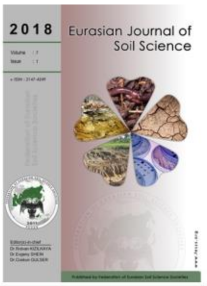

Prediction of infiltration from soil hydraulic properties

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Abstract

Field and laboratory infiltration measurements using infiltrometers have been the only methods of effectively determining the infiltration rates of soils. Infiltration is mainly controlled by soil hydraulic properties, especially the hydraulic conductivity. Due to the ease with which the saturated hydraulic conductivity can be determined, it is often preferred to the unsaturated hydraulic conductivity in hydrological studies. It is well known that, at saturation the steady state infiltrability controls the infiltration process. Thus, it is very clear that the saturated hydraulic conductivity K_s and steady state infiltrability K_o may be closely related in one way or the other, as suggested in some few studies, wherein functions have been developed to relate these two parameters. However, these functions are often site specific and do not always carry out accurately all the time. Determination of K_o can be tedious and time consuming, whereas K_s can be easily determined in the laboratory. The present study aimed to assess the predictability of a modified Philip's equation by substituting K_s for K_o. In this study, field infiltration measurements were conducted in two soil types under three different land use systems with a single ring infiltrometer. Field and laboratory hydraulic and hydrologic experiments were conducted on soils in a turf grass, an arable land and a pastureland in the Kwame Nkrumah University of Science and Technology, Kumasi, Ghana. Goodness-of-fit was used to compare the measured and predicted cumulative infiltration amounts from both K_o and K_s. The results showed that there was a robust relationship between the measured and predicted cumulative infiltration amount values from the Philip's and modified Philip's equations, respectively for all three fields. However, the use of K_s in place of K_o produced the best outcome in all the study areas. Thus, substituting K_s for K_o in the Philip's infiltration equation can better predict cumulative infiltration amount. The proposed modified Philip's infiltration equation and the key parameters (i.e., S_θ and K_s) provide new understanding into the realistic flow processes in soil. Furthermore, the K_s in the new equation is very close to the measured K_o.

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Introduction

"*The important thing in science is not so much to obtain new facts as to discover new ways of thinking about them*" – Sir Lawrence Bragg, the Nobel laureate in physics (Breverton, 2009; Su, 2010). Infiltration studies are necessary in hydrological advancements, such as irrigation design and planning, estimation of water requirements for crops, monitoring of groundwater recharge and prediction of runoff and erosion (Tuffour and Bonsu, 2015). Infiltration measurements in the field are often coupled with complicated apparatus for the hydrological characterization of soils, and also require larger computation times, especially, when steady state flow is required. Since field infiltration measurements are conducted on spot-to-spot basis on a field scale, a large number of determinations is required to assess the magnitude and structure of the variation

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within the field. These measurements have to be repeated at different times, especially in soils where structure varies over time because of natural or anthropogenic factors (Prieksat et al., 1994).

Using small volumes of water, easily transportable equipment and conducting short-duration experiments is desirable to obtain infiltration data at a great number of locations over a large area with the realistic use of resources in terms of time and costs. However, the use of predictive models has been shown to offer a very reliable alternative. In respect of this, infiltration models have gained wide spread usage across the globe in past and recent times (Tuffour et al., 2015). In view of this, several studies, (e.g., Mirzaee et al., 2013; Parhi, 2014; Tuffour and Bonsu, 2015) have highlighted the importance of infiltration modelling as an alternative to field infiltration measurements. As a result, several infiltration models have been developed. According to Tuffour and Bonsu (2015), the purpose of these numerous models is to identify an accurate method for simulating infiltration process for field water management. However, no single model can be expected to best meet all underlying hydrological requirements concurrently. Hence, the selection of a particular model may depend on several factors, such as type of application, desired level of physical-mathematical rigor, and user preference (Clausnitzer et al., 1998). This necessitates the in-depth knowledge of the fundamental assumptions on which a particular model is developed for better application. This has resulted in the widespread adoption of some models such as those of Green and Ampt (1911), Philip (1957a,b,c), Horton (1941) and Kostiakov (1932). Among these, the Philip's equation has been frequently adopted owing to its simplicity and ease of computing its fitting parameters (Mbagwu, 1993).

One key shortcoming identified with the Philip's infiltration equation is the restrictive boundary condition applied by the assumptions of uniform and constant concentration of soil moisture, instantaneous surface ponding of non-infiltrated surface water and saturation of soil at steady state. The assumption that rainfall will cause immediate surface ponding generally is unsubstantiated under field conditions. Even under conditions of relatively high rainfall intensity, the time to surface ponding can be appreciable. Further, the assumption of uniform soil-moisture concentration and soil hydraulic properties rarely is observed under actual field conditions. Under field conditions, the soil is seldom at full saturation even when infiltration approaches steady state, especially due to air entrapment. The objective of this study was to compare infiltration equations in terms of precision and accuracy of estimated parameter confidence intervals using the steady state infiltrability and laboratory column saturated hydraulic conductivity as constants in the Philip's equation.

Theory

When water is applied into a dry soil, initially, most of the water is absorbed by the capillary potential of the soil matrix. The capillary force dominates the initial water infiltration process, however, as infiltration proceeds, the gravitational force dominates. For cumulative infiltration, the general form of the Philip's equation is expressed as:

$$I = S_{\theta} t^{0.5} + K_o t \qquad \text{Eq.1}$$

where,

I = Cumulative infiltration [L]
S_{θ} = Sorptivity [L/T$^{1/2}$]
K_o = Steady state infiltrability
t = Time [T]

The first term of equation (1) is responsible for the uptake of water by capillary forces, and dominates infiltration at small time intervals. The coefficient S_{θ} in the first term, referred to as sorptivity, defined as the ability of the soil to absorb and desorb water by capillarity may also be described in terms of pore-liquid geometry (Philip, 1957b). This parameter is not a directly measurable soil attribute, but may be derived from actual soil properties (Hanks and Ashcroft, 1976). From equation (1), it is clear that as infiltration proceeds with time, the coefficient K_o in the second term, which describes the ability of the soil to transmit water under gravity dominates the infiltration process (Jaynes and Gifford, 1977). Thus, this parameter becomes active at steady flow or at field saturation after very long periods of infiltration measurements. It follows that K_o should be equal to K_s. By this, Philip (1969) reported that for very long time intervals, K_o approaches K_{fs}. According to Swartzendruber and Youngs (1974), this approximation does not introduce any significant error in the computation of cumulative infiltration as a function time. However, Whisler and Bouwer (1970), Smiles and Knight (1976), Skaggs and Khaleel (1982) reported that the assumption of $K_o = K_{fs}$ resulted in over prediction of cumulative infiltration over larger time intervals. Since the determination of K_o requires very long times, Elrick et al. (1995) stated that the use of this approach is highly difficult due to the insufficient information from the measurement of steady state flow in the evaluation of field saturated hydraulic conductivity K_{fs} [L/T] when using the single or double ring infiltrometer. However, since early time measurements of K_s can be achieved under laboratory conditions with reasonable accuracy (Bonsu and Laryea, 1989), this parameter can be adopted as a substitute for both K_o and K_{fs} in order to reduce the measurement times of K_o from long hours to very short minutes, relative to steady flow rate measurements. In this regard, an approximation of $K_{fs} = K_s = K_o$ is assumed at steady state in this study. Hence, equation (1) can be described as:

$$I = S_\theta t^{0.5} + K_s \qquad \text{Eq.2}$$

Material and Methods

Description of study areas

Field hydrological studies were carried out during the dry periods of early September, 2016 to January, 2017 in three different fields with variable soil physical and hydraulic properties. The sites chosen for the measurements were located in a turf grass in the Department of Horticulture (Figure 1a), an arable field in the Plantations section of the Department of Crop and Soil Sciences (Figure 1b) and a pastureland located at the Beef and Dairy Cattle Research Station of the Department of Animal Science (Figure 1c), KNUST. The sites were selected since the occurrence of spatial variability was anticipated because of expected worm activity and the presence of dead root channels. The soils are classified as Ofin series (Stagni-Dystric Gleysol), Kumasi series (Plinthi Ferric Acrisol or Typic Plinthustult) and Asuansi series (Plinthic Acrisol) in the turf grass, arable and pastureland, respectively (FAO-UNESCO, 1988; WRB, 2014). The turf grass site is a grown grassland area with love grass (*Eragrotis curvula*) as the dominant grass species produced for commercial purposes, and has been under different tillage operations. The selected arable land was grown with cowpea (*Vigna unguiculata*) in the previous major season, but was colonized by the regrowth of Guinea grass (*Panicum maximum*). The terrain is generally undulating with average slope of about 5%. The pastureland was a one year cattle-grazed paddock with *Paspalum vaginatum* as the dominant grass. The terrain is undulating with slopes ranging from 1 – 5%.

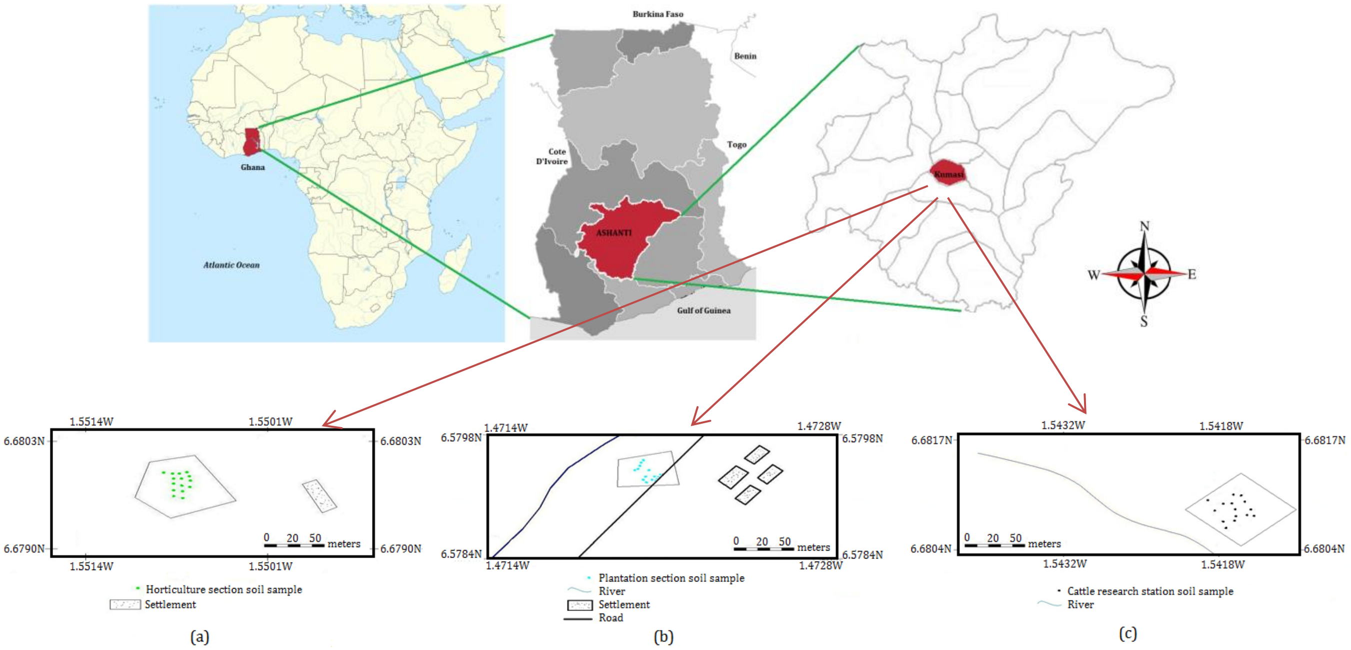

Figure 1. Map showing the outline of the experimental fields (a) turf grass experimental field (b) arable land experimental field (c) pastureland experimental field

Field infiltration measurements

Field infiltration studies were carried out in the selected study sites at fifteen (15) different spots enclosed within 30 cm diameter and 20 high single ring infiltrometers under both early time and saturated conditions. The experiments were designed to test predictions by investigating a range of saturated hydraulic conductivities, and initial and saturated soil water contents. The infiltrometer rings were pushed vertically into the soil to a depth of 10 cm to measure cumulative infiltration amounts and rates. The ponded infiltration experiments were conducted with an inclined plane manometer with angle of inclination β (herein 45°) (Plate 1). A plastic sheet was used to cover the surface of the soil as the water was being added, in order to prevent disturbance of the surface to cause slaking of aggregates and dispersion of clays. Water was gently added to give hydraulic head of 5 cm in the extended cylinder. The plastic sheet was removed and a flexible tubing, which had already been filled with water, was used to connect the surface of the water to a falling head device in the form of a piezometer made of burette connected to the inclined manometer, which allowed measurement of the cumulative volume of infiltration. The fall of the hydraulic head h_o at the soil surface was measured as a function of time t from the inclined water manometer. Early time measurements were conducted at regular time intervals of 10 seconds for two minutes after ponding when infiltration was very fast for the determination of sorptivity. The soil surface was then ponded with water until steady state was reached (approximately 45 minutes), after which the infiltration measurements were resumed at 2 minutes interval for ten minutes for the assessment of steady state flow. The depth of infiltration was computed from the relation:

$$Sin\beta = \frac{h_o}{h_t} \qquad \text{Eq.3}$$

$$h_t = \frac{h_o}{Sin\beta} \qquad \text{Eq.4}$$

where,

h_o = Inclined height [L]
h_t = Vertical height = Infiltrated volume of water [L]
β = Angle of inclination [°]

Cumulative infiltration amount (I) was calculated from the volume of infiltrated water as presented in the relation (Tuffour, 2015):

$$I = \frac{Q}{A} \qquad \text{Eq.5}$$

where,

I = Cumulative volume of infiltrated water [L]
A = πr^2; Surface area of the ring infiltrometer [L^2]
r = $0.5d$; Radius of ring [L]
d = Ring diameter [L]

Sorptivities were estimated from the linear plots of cumulative infiltration amount against the square root of time for the first two minutes of infiltration measurements.

Plate 1. Set up of infiltration apparatus

Laboratory measurements

Saturated hydraulic conductivity was determined from laboratory column studies using the falling-head permeameter (Bonsu and Laryea, 1989). Moisture content was determined by gravimetric method. Particle size analysis was determined by the hydrometer method. The United States Department of Agriculture (USDA) Textural Classification Triangle was used to classify the soils based on the results obtained from the analysis.

Results and Discussion

The results on the soil physical and hydraulic properties of the three experimental fields are summarized in Table 1. Soils were predominantly sandy in texture in the three fields, with mean sand contents ranging from 83 – 89%. The average bulk densities ranged from 1.2 – 1.5 g/cm^3 with average porosities of 43 – 53%. The average initial moisture contents were 4, 24 and 26% at the pastureland, turf grass and arable fields, respectively. Generally, the CVs of the initial soil moisture content were high in all the three fields (34.82 – 61.28%), and this could be a key factor in the high variability observed in the soil hydraulic properties (Table 2). In addition, the results showed that the pastureland recorded the lowest bulk density among the three study areas. In view of the relatively dry soil in the pastureland (θ_v = 4.10%) and the high clay content (7.50%) compared to the other fields, this interesting observation was expected. Clay soils have the ability to crack when dry, which increased the creation of macropores in the pastureland, thereby reducing the bulk density and increasing the total porosity eventually. This observation was also true for the arable field which had a clay content of 7.20%. However, the highest moisture content of 26% recorded in the arable field could be attributable to the presence of the high vegetation cover in the field. The soil particle fractions did not significantly differ among the three fields, indicating that the soils had good scatter of texture and were intrinsically similar among the land use systems (Kelishadi et al., 2013).

Table 1: Soil physical and hydraulic properties of the experimental sites

Soil property	Experimental field		
	Turf grass	Arable	Pastureland
Sand (%)	89.00 (4.42)	86.00 (3.41)	83.00 (3.69)
Silt (%)	5.30 (65.93)	6.70 (32.82)	9.00 (19.82)
Clay (%)	5.30 (13.51)	7.20 (23.51)	7.50 (31.14)
Texture	Sandy loam	Loamy sand	Loamy sand
ρ_b (g cm^{-3})	1.50 (7.82)	1.40 (5.36)	1.20 (10.77)
f (%)	43.00 (10.20)	47.00 (6.13)	53.00 (11.38)
af (%)	24.00 (33.65)	33.00 (27.54)	50.00 (11.53)
θ_v (%)	20.00 (34.82)	26.00 (37.02)	4.10 (61.28)
K_s (cm min^{-1})	0.25 (81.87)	0.81 (42.81)	1.20 (49.59)
S_θ (cm min$^{-1/2}$)	0.75 (88.26)	2.60 (51.89)	3.40 (49.19)
K_o (cm min^{-1})	0.20 (88.07)	0.58 (42.88)	0.76 (51.08)
i (cm min^{-1})	0.16 (83.90)	0.57 (42.96)	0.73 (50.62)
I (cm)	9.60 (81.11)	34.00 (47.02)	44.00 (61.48)

ρ_b = Bulk density; f = Total porosity; af = Air-filled porosity; θ_v = Initial volumetric water content; K_s = saturated hydraulic conductivity, K_o = steady state infiltrability, S_θ = Sorptivity, I = Cumulative infiltration amount, i = Infiltration rate; () = Coefficient of variation (%)

From Table 1, the coefficients of variation of the soil hydraulic properties were greater than 36%, revealing very high spatial variability as described by Wilding (1985) and Tuffour et al. (2013; 2016). The greatest values of CV of the soil hydraulic properties were noted in the turf grass, with the highest being S_θ (88.26%) and the least I (81.11%). The high observed high CVs could be attributed to the heterogeneity of large-sized soil pores (Kelishadi et al., 2013). Consistent with the report by Kelishadi et al. (2013), the soil hydraulic properties were highly variable as evidenced by their CV values. An interesting trend observed was that the soil hydraulic properties (K_s, S_θ, K_o, i and I) decreased with increasing sand content. The corresponding CVs, however, increased with increasing sand content. This shows a low frequency of macropores in the soils at the turf grass site, which recorded the highest percentage of sand. The high values of the soil hydraulic properties recorded in the pastureland was as a result of the relatively high clay content, with increased macropores due to cracking. These cracks served as pathways through which water quickly entered the soil. Further, the low initial moisture content of the soil could have resulted in an increased affinity of the soil to water due to high matric forces as evidenced by the high S_θ value of 3.4 cm min$^{-1/2}$ in Table 2. In contrast, Tuffour et al. (2014) observed severe reductions in soil hydraulic parameters in pastureland, due to soil compaction resulting from structural damage and destruction of macropores due to grazing. Hence, the soils in the pastureland could be described as resilient, and are highly recommended for pastureland establishment (Tuffour et al., 2014). Additionally, the results showed that the averages of soil hydraulic properties were significantly affected by soil textural class and land use system.

In this study, the goodness-of-fit of the proposed modification of the Philip's equation and its ability to predict cumulative infiltration amount was evaluated using the root mean square error (RMSE) and the coefficient of determination (R^2). The R^2 values were high and ranged from 0.97 – 1.00. Similarly, the predictability of the Philip's equation was tested using the RMSE and R^2. The R^2 values were also high, ranging from 0.76 – 0.99. Values of the RMSE showed that the predicted cumulative infiltration amounts from both equations were closer to the measured ones. Thus, the predicted cumulative infiltration amount from K_s showed no disparity with that from K_o, even though the predictability was better with K_s than K_o (Table 2; Figures 2). The linear relationships between the measured and predicted cumulative infiltration amounts (Table 2) indicate the appropriateness of predicting infiltration form these simple soil hydraulic properties (i.e. sorptivity and laboratory-measured saturated hydraulic conductivity).

Table 2. Predictability of cumulative infiltration amount from steady state infiltrability and saturated hydraulic conductivity

Experimental field	Interactions	Prediction index			
		R^2	Slope	Intercept	RMSE
Turf grass	I_m vs I_{K_o}	0.97	0.58	0.34	0.0043
	I_m vs I_{K_s}	0.99	0.38	-0.059	0.0021
Arable	I_m vs I_{K_o}	0.76	0.60	3.80	0.053
	I_m vs I_{K_s}	1.0	0.39	-0.058	0.0012
Pastureland	I_m vs I_{K_o}	0.99	0.39	0.39	0.005
	I_m vs I_{K_s}	0.99	0.49	-0.57	0.003

R^2 = Coefficient of determination; I_m = Measured infiltration amount; I_{K_o} = Predicted infiltration amount from steady state infiltrability; I_{K_s} = Predicted infiltration amount from saturated hydraulic conductivity; RMSE = Root mean square error

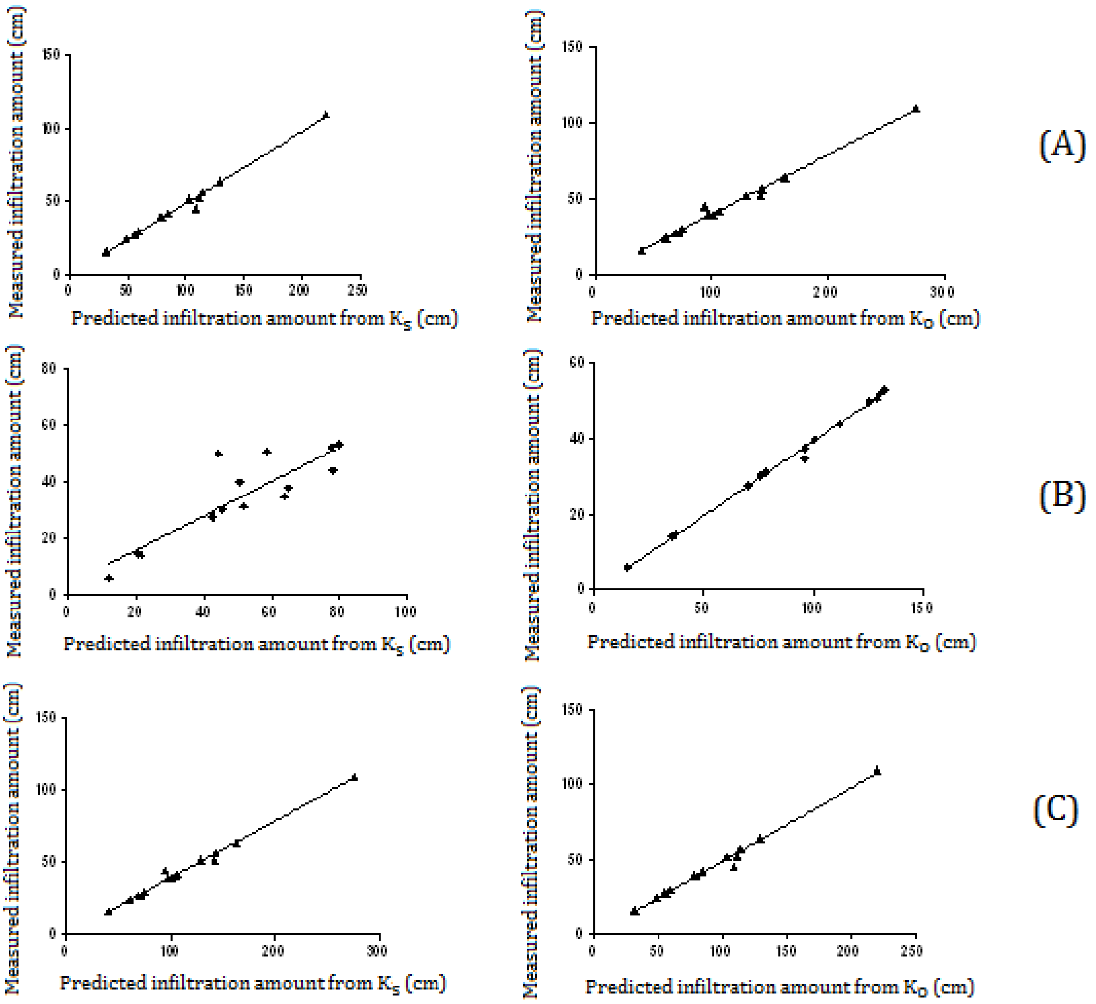

Figure 2. Goodness-of-fit of measured and predicted cumulative infiltration amount from K_o and K_s for soils (a) arable field (b) pastureland (c) turf grass

Overall, the lowest RMSE values were obtained with the modified equation. Thus, even though both forms of the equation gave very good predictions, the performance of the modified equation was found to be better in all the study sites. The differences in the RMSE values for the two equations at the different locations could be attributed to the variations in site conditions, such as soil particle size distribution (Haghighi et al., 2010) and soil structure due to their high influence on infiltration. Thus, the suitability of the two equations for the prediction of infiltration can be site-specific. This implies that in this study, the impact of spatial variation within relatively short distances and the occurrence of preferential flow through the macropores created by cracking of clay significantly affected the data and the model parameters. Hence, the predictability of infiltration models should be validated under different soil conditions (Haghighi et al., 2010). In this study, the low predictive ability of the Philip's equation for predicting the final infiltration amount could be due to the longer time taken to approach steady state infiltrability, owing to low initial soil moisture contents, especially in the pastureland and high soil porosities observed in all three fields.

Comparisons on correlation between K_s – and K_o – related parameters were carried out in the study using classical regression technique. Significant correlations were observed between K_o and K_s, as well as cumulative infiltration amounts predicted from these two parameters (Table 3; Figures 3). The results as shown in Table 3 is a clear evidence that the performance of equation (2) was better than that of equation (1). This confirms the reports by Philip (1957b), Youngs (1968) and Skaggs et al. (1969) that the approximation made in equation (1) is not physically consistent, and hence, predicts low infiltration values for long time periods. Curve fitting method has also been used to accurately relate the Philip's equation to measured infiltration data. For instance, Whisler and Bouwer (1970) obtained close agreement with experimental values when the parameters were determined by curve fitting, but the physical significance of the parameters was laid off. Similarly, Smiles and Knight (1976) suggested that the appropriateness of infiltration data to the 2-parameter Philip equation can be determined by plotting $It^{\frac{1}{2}}$ as a function of $t^{\frac{1}{2}}$.

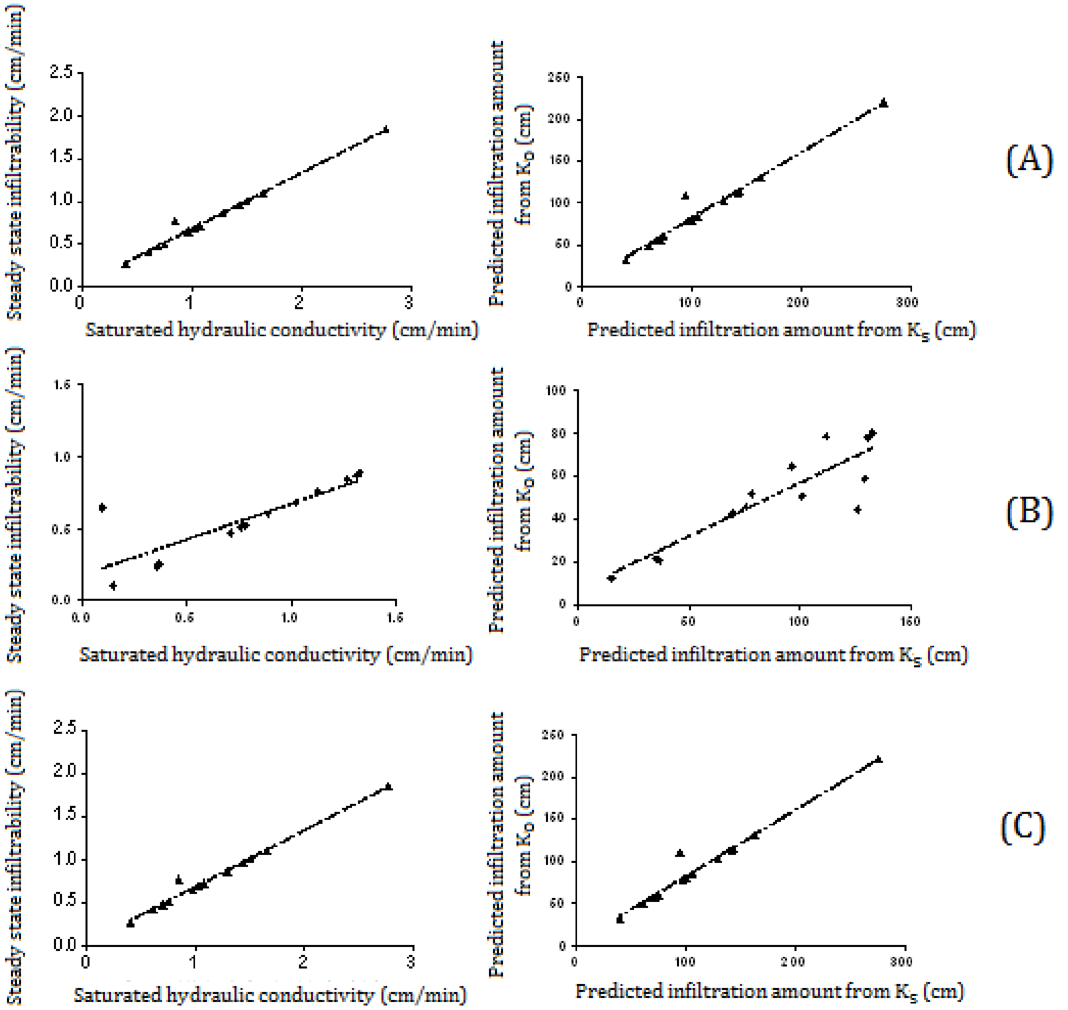

Figure 3. Goodness-of-fit of $K_o$and K_s and their predicted cumulative infiltration amounts for soils (a) arable field (b) pastureland (c) turf grass

Table 3. Summary of correlation analysis

Experimental field	Interaction	Correlation index		
		r	Confidence interval (95%)	
			Lower limit	Upper limit
Turf grass	I_{K_o} vs I_{K_s}	0.99	0.98	1.00
	K_o vs K_s	1.00	1.00	1.00
Arable	I_{K_o} vs I_{K_s}	0.88	0.67	0.96
	K_o vs K_s	0.85	0.59	0.95
Pastureland	I_{K_o} vs I_{K_s}	0.98	0.94	0.99
	K_o vs K_s	0.99	0.97	1.00

r = Correlation coefficient; K_o = Steady state infiltrability; K_s = Saturated hydraulic conductivity

Conclusion

This study evaluated the acceptability and applicability of substituting K_s for K_o in the Philip's equation. The Modified Philip's infiltration model was more suitable for predicting water infiltration into the soils than the Philip's equation. Consequently, the Modified Philip's model is recommended for use in coarse textured soils. This could be of immense importance in the design and planning of irrigation projects. For instance, once the values of the infiltration rate are constant, the basic infiltration rate has been reached and the established curve can be used to determine how long it will take to infiltrate a certain amount of water. This information is important for irrigation water management. The proposed new infiltration equation and the key parameters (i.e., S_θ and K_s) provide new understanding into the realistic flow processes in soil. The new equation not only fits the data very well; it also has considered K_s to imply that infiltration into soils at steady state occurs under full saturation of the topsoil. Furthermore, the K_s in the new equation is very close to the measured K_o.

Soil hydraulic properties were highly variable among the different soil types and land use systems. On the average, the soil hydraulic properties were significantly affected to a large extent by soil structure and management practices, but not by the soil textural class. Land use systems significantly affected the soil hydraulic parameters (hydraulic conductivity, steady-state infiltrability and sorptivity). Soil hydraulic conductivity was higher in the pastureland soils as compared to the other cultivated soils, which is related to the higher clay content and higher degree of cracking of the pastureland soil.

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