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A. Keynote Speakers

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1st Topic: Sustainable Agriculture, Agricultural Productivity, and Modern Technologies

Field Evaluation of Infiltration Models under Oil Palm Plantation: Stemflow and Throughfall Areas

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ABSTRACT

Although the performance of infiltration models has been well tested for subtropical areas, only a few is given to tropical areas especially those for stemflow and throughfall areas underneath oil palm plantation. Distinguishing both areas are attributed not only by their behavior in distributing rainfall into soil surface, but also characterized by different organic content and soil compaction. Experiments were carried out at both areas of an oil palm tree with a tension disc infiltrometer. Cumulative infiltrations from the tension disc infiltrometer were used to define the objective function to be minimized during optimization of the parameters of the ten infiltration models. The performances of the models were evaluated with consideration of root mean square error and paired student's t-test of the selected model error. All infiltration models performed well for oil palm plantation on sandy loam soil. The two areas exhibited contrasting hydraulic properties as indicated by saturated hydraulic conductivity. On average, values of this parameter for the stemflow area of an oil palm tree were five times higher compared to those of the throughfall area. Green-Ampt model, Smith model, Mezencev model, and Philip model performed better than the other infiltration models among their categories. The research also indicated that two-parameter Philip infiltration model is recommended as the best description of the relationship between cumulative infiltration and time at two areas underneath oil palm plantation over the least square method.

***Index Terms*—infiltration models, oil palm, stemflow, throughfall.**

Introduction

Infiltration is affected by rainfall intensity [1] and the physical properties of soils, such as initial soil water content and saturated hydraulic conductivity [2]; soil texture and structure [3], [4], [5]; vegetation cover, and plant root density. Generally, cumulative infiltration is higher with high initial soil water content, and higher with higher soil saturated hydraulic conductivity. Existing soil organic matter produced by trees increases the friability of stiff, tight soils, and makes the soil crumbly to accelerate soil structural development then increase infiltration capacity [6], [7]. Existing tree root will improve soil structure and thus infiltration [8], [9].

Previous studies have paid attention to the effects of stemflow as a main source of tree induced infiltration and soil water movement ([9], [10], [11], [12], [13]). For the last five years, [14] observed that for a heavy storm event, the cumulative stemflow per infiltration area along the downslope sides of the tree trunk was 18.9 times the cumulative open-area rainfall. In addition, [15] evaluated that the amount of stemflow under the banana stem was up to six times higher than in the row of downstream area. Moreover, several studies have modeled flow under stemflow and throughfall areas of different vegetations such as olive tree [13], banana plant [15], [16], tall stewartia [17], and ponderosa pine [18]. Malaysia and Indonesia are the two largest producer of palm oil in the world. Oil palm covers 5 million ha or 15% of Malaysia's total land area [19]. The expansion area dominantly originates from land conversion of rubber. Even though Malaysia receives between 2000 to 3000 mm of annual rainfall, about 41 to 51% of gross rainfall was intercepted by its canopy [20], [21]. In addition, the use of harvesting machine could compact the soil and reduce the infiltration.

A number of infiltration models were systematically and extensively reviewed, presented, and summarized by [22], and [2]. Although many researchers have taken efforts to successfully compare and evaluate those infiltration models in different scenarios under field conditions [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], most of that research was conducted in agricultural fields. An evaluation of those infiltration models under field condition at stemflow and throughfall areas underneath oil palm plantation is still lack.

Therefore, the objectives of present study are (1) to summarize and choose appropriate infiltration models used for soil underneath oil palm plantation, (2) to estimate and assess those parameters involved with those infiltration models, and (3) to evaluate the prediction ability of those infiltration models for the soil underlying oil palm plantation.

The Models

Models to estimate cumulative infiltration rates used in this study are summarized in Table 1.

TABLE 1: SUMMARY OF INFILTRATION MODELS

Models	Descriptions
Green-Ampt	Homogenous, uniform initial moisture content, good prediction [23], [33]
Kostiakov	Simplest model, basic infiltration rate of soil not accounted [23]
Horton	Based on work-energy principle, ponding is assumed [23]
Philip	Moisture content represented by an infinite series [23]
Smith	Suitable for uniform initial moisture content profile before redistribution, homogeneous soil [22]
Mezencev	Flexible model, basic infiltration rate of soil is considered [23]. Due to limitation of Kostiakov's equation to explain the infiltration at longer time [34]
Parlange	For estimating cumulative infiltration with constant surface water content, uniform initial water content and homogeneous soil [22]
Collis-George	Due to limitation of Green-Ampt model which do not mimic the observed behavior of simple soils at long times and the Horton model did not at short times [35]
Brutsaert	Applied for uniform antecedent water content, homogeneous soil, and describe water ponded into a semi-infinite [22]
Swartzendruber & Clague	For estimating cumulative infiltration with constant surface water content, uniform initial water content and homogeneous soil [22]

The equation of each infiltration models (Table 1) are listed in Table 2.

TABLE 2: INFILTRATION MODEL EQUATIONS

Models	Equation
Green-Ampt	$\frac{K_s}{\theta_s-\theta_i}t = L_f-\left(h_o-h_f\right)\ln\left(1+\frac{L_f}{\left(h_o-h_f\right)}\right)$ $F = L_f \Delta\theta$
Kostiakov	$F = \frac{\alpha}{1-\beta}t^{1-\beta}$
Horton	$F = f_c t + \frac{1}{k}\left(f_0 - f_c\right)\left(1-e^{-kt}\right)$
Philip	$F = S t^{\frac{1}{2}} + C t$

Smith	$F = f_c t + \frac{A(t-t_o)^{1-b}}{1-b}$
Mezencev	$F = f_c t + \frac{\alpha}{1-\beta} t^{(1-\beta)}$
Parlange	$F = K_s t + \frac{1}{2}\frac{S^2}{K_s}\left[1-\exp\left(-2\left(\frac{K_s{}^2 t}{S^2}\right)\right)\right]$
Collis-George	$F = K_s t + \frac{1}{N}\frac{S^2}{K_s}\left[\tanh\left(N^2\left(\frac{K_s{}^2 t}{S^2}\right)\right)\right]^{1/2}$
Brutsaert	$F = K_s t + \frac{S^2}{K_s}\left[\frac{K_s t^{1/2}/S}{\left(1+\alpha\left(K_s t^{1/2}/S\right)\right)}\right]$
Swartzendruber & Clague	$F = K_s t + \frac{1}{\alpha}\frac{S^2}{K_s}\left[1-\exp\left(-\alpha\left(\frac{K_s t^{1/2}}{S}\right)\right)\right]$

F = cumulative infiltration, L_f = length of wetting front, θ_s = saturated moisture content, θ_i = initial moisture content, t = time, K_s = saturated hydraulic conductivity, h_0 = pressure head at surface, h_f = pressure head at wetting front, f_0 = initial infiltration rate, f_c = final infiltration rate, k = infiltration decay factor, α; β, N = constants, S = sorptivity, C = parameter depend on soil diffusivity and moisture retention characteristics, A; b = parameters depends on soil characteristic, t_0 = initial time when runoff start.

Methodology

The field experiments were carried out at an oil palm plantation in Johor Darul Takzim, Malaysia (at 01°33'50.1" E and 103°36'09.6" N). The plantation was established around 18 years ago.

A tension disc infiltrometer was used to conduct field infiltration experiments underneath and between oil palm trees to obtain soil hydraulic properties for stemflow (SA) and throughfall (TA) areas, respectively. Three successive tensions of -5, -2, and 0 cm H_2O were applied in all disc infiltrometer experiments. The disc infiltrometer had a diameter of 20 cm and was made of the nylon mesh. To get good contact between the disc and the soil, a thin layer of sand of ~ 2 mm was placed at the top of the soil. The sand layer was moistened immediately before placing the disc membrane on the soil in order to prevent air entry into the disc.

Having finished the field experiments, laboratory measurements were carried out to determine initial water contents, bulk densities, porosities and root density of the undisturbed soil taken from stemflow and throughfall areas before field experiment started.

The infiltration models were categorized into 4 groups by taking into account the number of unknown parameters. The parameters of the models were then optimized by minimizing the objective function which is the sum of squares error between observed and estimated cumulative infiltration for the tension of 0 cm H_2O.

The performances of the models were evaluated within each group by considering its root mean square error (RMSE). The comparison of the best model between each group was carried out using paired student's t-test based on the prediction accuracy (error) of each selected model.

Results and Discussion

Laboratory experiment

Table 3 below summarized the laboratory measurements of the soil physical properties.

TABLE 3: LABORATORY MEASUREMENTS.

Location	Initial moisture (cm^3 cm^{-3})	Bulk density (g/cm^3)	Porosity (%)	Organic content (g/cm^3)
Stemflow area	0.430	0.63	76.1	0.024
Throughfall area	0.434	1.29	51.2	0.006

Based on the USDA soil classification, the soil at the plantation is sandy loam (76.6% of sand, 13.0% of clay, and 10. 3% of silt).

Based on laboratory measurements, the stemflow area has a high porosity and a high organic content (see Table 3). The occurrence of higher soil organic matter not only will strengthen the soil aggregates but also enhance soil capacity in holding and storing water. This is because soil organic matters minimizes soil compaction, provide pores, and is able to store a quantity of water which corresponds to a multiple of the organic matters weight [36].

E. Field measurement

From the field infiltration measurement using the tension disc infiltrometer, we obtained cumulative infiltrations for stemflow and throughfall areas. Figure 1 shows cumulative infiltrations for both areas. Notice the three different slopes represent pressure heads (h = -5, -2 and 0 cm H_2O). The steepest slope attributed 0 cm H_2O and the gentlest slope indicated -5 cm H_2O. Stemflow area required 70 minutes to allow water infiltrate 800 cm into the soil. However, the throughfall area needed 130 minute to penetrate water 500 cm into the soil.

The results from cumulative infiltration curves show that the infiltration rate for stemflow area is faster rather than throughfall area. This is due to effect of the organic content (see Table 3). As explained by [6] and [7], existing soil organic matter produced by trees increases the friability of stiff, tight soils, and makes the soil crumbly to accelerate soil structural development then increase infiltration capacity.

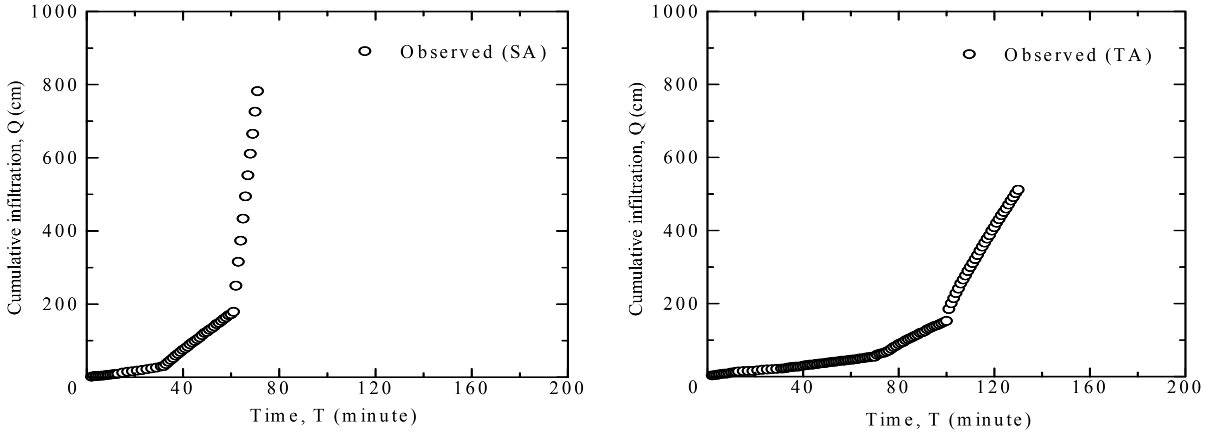

Figure 1: Cumulative infiltration rate for stemflow (top) and throughfall (bottom) areas for three consecutive pressure head (h = -5, -2 and 0 cm H_2O).

F. Model parameters

The models were categorized into 4 groups which is five unknown parameters based model (Green-Ampt), four unknown parameters based model (Smith), three unknown parameters based model (Horton, Mezencev, Collis-George, Brutsaert, and Swartzendruber & Clague), and two unknown parameters based model (Kostiakov, Philip, and Parlange).

The optimized parameter values for the ten infiltration models for both areas are listed in Table 4 - Table 11. Those were optimized by minimizing the objective function which is the sum of squares error between observed and estimated cumulative infiltration for the tension of 0 cm H_2O.

TABLE 4: THE OPTIMIZED PARAMETERS OF GREEN-AMPT INFILTRATION MODEL FOR SANDY LOAM SOIL UNDERNEATH OIL PALM PLANTATION

Model	Green-Ampt				
	K_S	θ_S	θi	h_0	h_f
Stemflow area	0.18	0.751	0.430	0.0	-0.07
Throughfall area	0.03	0.512	0.434	0.0	-1.27

K_s = saturated hydraulic conductivity (cm/min), θ_s = saturated moisture content (cm^3/cm^3), θ_i = initial moisture content (cm^3/cm^3), h_0 = pressure head at surface (cm H_2O), h_f = pressure head at wetting front (cm H_2O).

TABLE 5: THE OPTIMIZED PARAMETERS OF SMITH INFILTRATION MODEL FOR SANDY LOAM SOIL UNDERNEATH OIL PALM PLANTATION

Model	Smith			
	f_C (cm/min)	A	B	t_0 (min)
Stemflow area	0.17	0.029	0.560	0.38
Throughfall area	0.03	0.030	0.589	0.01

TABLE 6: THE OPTIMIZED PARAMETERS OF HORTON INFILTRATION MODEL FOR SANDY LOAM SOIL UNDERNEATH OIL PALM PLANTATION

Model	Horton		
	f_C (cm/min)	f_0 (cm/min)	k
Stemflow area	0.18	0.24	0.710
Throughfall area	0.03	0.09	0.422

TABLE 7: THE OPTIMIZED PARAMETERS OF MEZENCEV INFILTRATION MODEL FOR SANDY LOAM SOIL UNDERNEATH OIL PALM PLANTATION

Model	Mezencev		
	□□	□	f_C (cm/min)
Stemflow area	0.043	0.354	0.16
Throughfall area	0.030	0.587	0.03

TABLE 8: THE OPTIMIZED PARAMETERS OF COLLIS-GEORGE INFILTRATION MODEL FOR SANDY LOAM SOIL UNDERNEATH OIL PALM PLANTATION

Model	Collis-George		
	S ($cm/min^{0.5}$)	K_S (cm/min)	N
Stemflow area	0.02	0.18	0.034
Throughfall area	0.03	0.03	0.135

TABLE 9: THE OPTIMIZED PARAMETERS OF BRUTSAERT INFILTRATION MODEL FOR SANDY LOAM SOIL UNDERNEATH OIL PALM PLANTATION

Model	Brutsaert		
	S ($cm/min^{0.5}$)	□	K_S (cm/min)
Stemflow area	0.06	0.001	0.17
Throughfall area	0.08	0.423	0.03

TABLE 10: THE OPTIMIZED PARAMETERS OF SWARTZENDRUBER & CLAGUE INFILTRATION MODEL FOR SANDY LOAM SOIL UNDERNEATH OIL PALM PLANTATION

Model	Swartzendruber & Clague		
	S ($cm/min^{0.5}$)	K_S (cm/min)	□□
Stemflow area	0.06	0.17	0.001
Throughfall area	0.08	0.03	0.741

TABLE 11: THE OPTIMIZED PARAMETERS OF KOSTIAKOV, PHILIP, AND PARLANGE INFILTRATION MODELS FOR SANDY LOAM SOIL UNDERNEATH OIL PALM PLANTATION

Models	Kostiakov		Philip		Parlange	
	□□	□	S	C	S	K_S
Stemflow area	0.21	0.07	0.06	0.17	0.15	0.19
Throughfall area	0.06	0.21	0.07	0.03	0.10	0.03

S = sorptivity ($cm/min^{0.5}$), C = parameter depend on soil diffusivity and moisture retention characteristics (cm/min), K_s = saturated hydraulic conductivity (cm/min).

From Table 4 - Table 11, the two areas exhibited contrasting hydraulic properties as indicated by saturated hydraulic conductivity (K_s). Notice final infiltration rate (f_c) of Smith model, Horton model and Mezencev model attributed similar magnitude with saturated hydraulic conductivity as well as α of Kostiakov model and C of Philip model. The characteristic of saturated hydraulic conductivity for stemflow area ranges from 0.16 - 0.21 cm/min with average value of 0.18 cm/min meanwhile those for throughfall area ranges from 0.03-0.06 cm/min with average value of 0.03 cm/min. Notice, on average, values of the properties for the stemflow area were about five times higher compared to those for the throughfall area. This may be caused by the physical properties of both areas. Notice, high percentage of organic content contributes significant difference on this matter as well as the effect of the bulk density. The values agreed well with those obtained from inverse estimation using Hydrus 2D/3D which is 0.034 cm/min and 0.179 cm/min for throughfall and stemflow areas, respectively [37].

G. Model performance

The values of the root mean square error (RMSE) for those ten infiltration models for both areas are listed in Table 12. Mezencev model as the modified Kostiakov model had the lowest RMSE among three unknown parameters based model (Horton, Mezencev, Collis-George, Brutsaert, and Swartzendruber &

Clague) followed by Brutsaert model, Swartzendruber & Clague model, Horton model, and Collis-George model. As compared to the original Kostiakov model, Mezencev model performed better. The additional term $f_c t$ contributes positive effect into the ability of the model to fit observed data. Similar to the result presented by [27] and [38] for silt loam, sandy clay loam and sand soil textures, among three-parameters model, Mezencev model was found to be best in fitting measured infiltration and in prediction ability for cumulative infiltration.

Among two unknown parameters based model (Kostiakov, Philip, and Parlange), the theoretically based Philip model was found to have the lowest RMSE. On the other word, it was found to be the best, among two parameters model, in fitting measured infiltration and in prediction ability for cumulative infiltration. As one of the theoretically based soil infiltration models, Philip model was regarded as one of the most predictive models [31].

Among the most predictive models (Green-Ampt, Smith, Mezencev, and Philip), rank 1st in Table 12, Smith model had the lowest RMSE compared to Mezencev model, Philip model and Green-Ampt model. However, having conducted paired student's t-test based on the prediction accuracy (error) of those models, notice there is no statistically significant difference among them. With the hypothesized mean difference of the prediction accuracy (error) between the models equals to zero, and the alpha level equals to 0.05, it was found that probability (T<=t) for two-tail is always more than the alpha level. It means that we accepted the hypothesized mean difference of the prediction accuracy (error) between the models equals to zero. On the other word, there was no statistically significant difference among Green-Ampt model, Smith model, Mezencev model, and Philip model. Nevertheless, in the present study, by considering number of parameters (two unknown parameters), Philip model was regarded as one of the most predictive models among others.

TABLE 12: RMSE OF THE TEN INFILTRATION MODELS FOR SANDY LOAM SOIL UNDERNEATH OIL PALM PLANTATION

Models	Root Mean Square Error			
	Stemflow area	Throughfall area	Mean	Rank
Green-Ampt	5.26E-03	2.03E-03	3.64E-03	1[a]
Smith	3.79E-03	1.92E-03	2.85E-03	1[a]
Mezencev	3.83E-03	1.92E-03	2.87E-03	1[a]
Brutsaert	4.12E-03	1.98E-03	3.05E-03	2
Swartzendruber & Clague	4.12E-03	2.01E-03	3.07E-03	3
Horton	4.12E-03	4.59E-03	4.35E-03	4
Collis-George	8.04E-03	1.07E-02	9.37E-03	5
Philip	4.12E-03	2.85E-03	3.48E-03	1[a]
Kostiakov	4.71E-03	8.63E-03	6.67E-03	2
Parlange	7.84E-03	1.11E-02	9.49E-03	3

Superscript a attributed that probability (T<=t) for two tail is always more than the alpha level (0.05). Same superscript means there is no statistically significant difference among the models.

Conclusion

The present study was conducted to evaluate the performance of ten classical infiltration models at stemflow and throughfall areas underneath oil palm plantation. The infiltration models investigated and compared included Green-Ampt model, Kostiakov model, Horton model, Philip model, Smith model, Mezencev model, Parlange model, Collis-George model, Brutsaert model, and Swartzendruber & Clague model. Mezencev model performed better among others with consideration to root mean square error. Paired student's t-test indicated that two-parameters Philip model performed as good as

Mezencev model and Smith model in describing the relationship between cumulative infiltration and infiltration time for the researched oil palm plantation underlined by sandy loam soil.

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