Modelling Infiltration in A Large Scale Paddy Field in Malaysia

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ABSTRACT

A number of models are available to measure infiltration in agricultural fields; however, their applicability is site specific. It is not easy to choose an adequate model to estimate infiltration at a particular agricultural field. In this study, ten different infiltration models have been used for the estimation of infiltration rate in data scarce Muda Irrigation Scheme, the largest paddy field in Malaysia. The model parameters are estimated from soil characteristics, secondary data and literature. The estimated infiltration rates by the models are compared with the measured infiltration rates in order to assess the suitability of the models in the paddy field of Malaysia. The results show that the infiltration rate estimated by physically based Smith-Parlange nonlinear model is very close to the observed rate. Mean monthly infiltration rate estimated by Smith-Parlange model is 0.098mm with a maximum 0.227mm during December to March and a minimum 0.005mm in May and August. All other methods are found to overestimate the infiltration rate. Though the performance of the models is assessed based on results obtained using limited data and secondary information, it is expected that the research will help select the right model to estimate infiltration, which is highly important for irrigation management especially in paddy fields.

Keywords: Infiltration Model, Infiltration Rate, Muda Irrigation Scheme, Malaysia, Paddy Field.

1.0 INTRODUCTION

Infiltration is the process of water entry from the ground surface into the soil from rainfall, snowmelt, and irrigation (Houser, 2005). Infiltration and soil water movement play a key role in surface runoff (Wood *et al.,* 1986; Winchell *et al.,* 1998), groundwater recharge (Shanafield and Cook, 2014), evapotranspiration (Cordova and Bras, 1981; Kirchner *et al.,* 2008), soil erosion (Yu *et al.,* 2003), and transport of chemicals in surface and subsurface water (Govindaraju, 1996). The ability to quantify infiltration is of great importance in watershed management (Zolfaghari *et al.,* 2012). Accurate estimation of infiltration is required to improve runoff estimation, using hydrologic models or pollution leaching or solute transport through sub-surface media (Rumynin, 2011). By understanding the variation of infiltration rates along with the variation in surface conditions, measures can be taken to increase infiltration rates, which help, for example, reduce erosion and flooding caused by overland flow (EPA, 1992).

Quantification of infiltration is also necessary to assess the availability of water for crop growth and to estimate the amount of additional water needed from irrigation (Brouwer *et al.,* 1989). If water is ponded on the surface, the infiltration occurs at the potential infiltration rate (Wilkie, 1999). Therefore, infiltration rate in paddy fields is high due to ponding of water on the surface (Wilkie, 1999).

Because of the fundamental role of infiltration in surface and subsurface hydrology, irrigation and agriculture, infiltration has received a great deal of attention from soil and water scientists, and a large number of models for its computation have been developed. Infiltration models can be classified, in general, into three groups, namely, (i) physically based, (ii) semi-empirical, and (iii) empirical. Obviously, there are a large number of infiltration models but their suitability in real life problems is not obvious. The downward flow rate of water through soil is governed by the saturated conductivity of the soil layer (Liu *et al.,* 2001; Huang *et al.,* 2012). The rate of infiltration is affected by soil characteristics (soil texture, structure and temperature), land cover (vegetation types and cover), storage capacity, rainfall intensity and transmission rate through the soil. Hence, the suitability of a model under given condition is not always evident. Some comparative studies have indicated that the Green-Ampt type models perform better than the curve-number model in predicting infiltration from catchment runoff volumes (Chahinian *et al.,* 2005; Van Mullem, 1991). Mishra *et al.,* (2003) compared the performance of fourteen physically based, semi-empirical, and empirical infiltration models, including the Green-Ampt and Horton models and concluded that the Horton model performs significantly better than the Green-Ampt model. The above studies pointed out that determining the suitability of infiltration models require testing with field data.

In the present study ten infiltration models have been used for the estimation of infiltration in the Muda Irrigation Scheme, which is considered as the largest paddy field of Malaysia. The models used in this study are due to Green and Ampt (1911), Soil Conservation Service (SCS, 1972), Horton (1940), Holtan (1961), Philip (1957), Singh and Yu (1990), Mishra and Singh (2002), Smith and Parlange (1978) Linear and Nonlinear, and Morel-Seytoux (1978). Many of these models distinguish between the actual infiltration rate, f, and the potential infiltration rate, f_p, which is equal to the infiltration rate when water is ponded at the ground surface. Thus, the aims of this study are to (i) use various infiltration models to estimate infiltration rate as a part of irrigation water management the Muda Irrigation Scheme of Malaysia and (ii) compare the performance of various infiltration models in order to propose the suited model(s) for the area. The Muda Irrigation Scheme accounts for about 40% of total rice production in the country (Tukimat *et al.,* 2012). Accurate estimation of infiltration is very essential for water resources planning and management in the scheme.

The agricultural catchments of Malaysia are poorly gauged. In most of the cases, enough information is rarely available for hydrological model calibration. This is especially true for the Muda Irrigation Scheme, where enough data were not available for model calibration. Hence, the objective of the present study was to test rather simple uncalibrated models in estimating hourly infiltration rate in the area. The model parameters were estimated from physical characteristics of soil and literature.

In the following sections of the paper, a brief description of the study area and the data used for the study are given. This follows the methodology section where all the ten models used in the study are described. The application of the models to the Muda Irrigation Scheme to estimate infiltration rate is discussed thereafter. The obtained results are then compared to identify the most suitable model(s) for measuring infiltration rate in the study area. Finally, some conclusions are drawn based on the findings of the study.

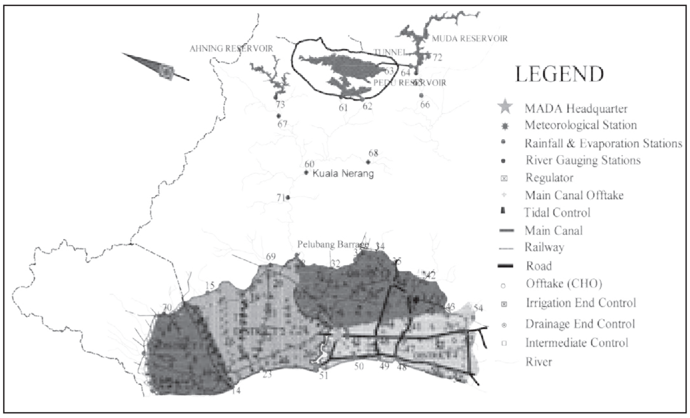

Figure 1: GIS Digitized Muda Irrigation Scheme in Kedah, Malaysia

2.0 STUDY AREA AND DATA

The Muda Irrigation Scheme covers a total gross area of 126,000 ha, out of which about 97,000 ha is under the double cultivation of paddy (MADA, 1977). It is the largest double cropping area in Malaysia. The map of the area is shown in Figure 1. The area is located at about $5^{0}45^{\prime}$ ~$6^{0}30^{\prime}$ N latitude and $100^{0}10^{\prime}$ ~$100^{0}30^{\prime}$ E longitude in the vast alluvial Kedah-Perlis Plain of about 20km wide and 65km long between the foothills of the Central Range and the Straits of Malacca. The area is generally flat with slopes varying from 1 in 5000 to 1 in 10000. The altitude varies between 4.5 m in the inland fringe and 1.5 m above mean sea level in the coastal area (MADA, 1977).

The soil in the Kedah-Perlis of Malaysia consists of heavy clay. The majority of their parent materials consist of marine sediments deposited during the rise in sea level. While the land efflorescence carried to the sea had been deposited on the sea-bed, these sediments were replenished with base and silicic acid, and are rich in mineral and chemical substances (Furukawa, 1976). The soils become very hard and compact during the non-irrigation period, and they crack markedly. When saturated with water, the cracks are filled up due to swelling and slaking phenomena and their permeability decreases rapidly.

Table 1: Step-by-Step Procedure of Calculating Infiltration Using Green-Ampt Model.

Parameter	**Month**											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
*Rainfall, P (mm month^{-1})	20.6	52.4	102.1	184.0	236.7	169.3	210.3	237.5	310.5	287.5	197.8	77.7
*Elementary area, ω (%)	9.01	34.75	49.78	84.26	100.00	77.18	97.86	100.00	91.79	97.65	98.32	43.78
**Rainfall Intensity (cm h^{-1})	2.033	2.033	2.033	2.033	2.033	2.033	2.033	2.033	2.033	2.033	2.033	2.033
Hydraulic Conductivity, K (cm h^{-1})	0.0288	0.0208	0.0161	0.0053	0.0004	0.0075	0.0010	0.0004	0.0029	0.0011	0.0009	0.0179
Porosity, η	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46
ψ (cm)	156.62	156.62	156.62	156.62	156.62	156.62	156.62	156.62	156.62	156.62	156.62	156.62
Time step, t = 1 h	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
θ_e	0.371	0.371	0.371	0.371	0.371	0.371	0.371	0.371	0.371	0.371	0.371	0.371
$\theta r = \eta - \theta_e$	0.090	0.090	0.090	0.090	0.090	0.090	0.090	0.090	0.090	0.090	0.090	0.090
S_e $(0 \leq s_e \leq 1)$	0.090	0.090	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.738
$\Delta\theta = (1 \leq s_e)\ \theta_e$	0.3378	0.3378	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0973
CRC	0.71	0.71	0.71	0.71	0.71	0.711	0.71	0.71	0.71	0.71	0.71	0.71
F (t), cm	1.490	1.260	0.045	0.023	0.006	0.030	0.010	0.006	0.020	0.010	0.009	0.630
Infiltration rate, f (mm h^{-1})	7.481	6.348	0.262	0.133	0.027	0.157	0.050	0.027	0.081	0.053	0.047	3.214

**** Observed Data (Source: Muda Agricultural Development Authority, Alor Setar, Kedah, Malaysia)***
***** Rainfall Intensity (Al-Mamun and Hashim, 2004)***

The soil in the area is generally heavy marine clay type and the coefficient of permeability varies from 1x10^{-7} to 8x10^{-5}cm s^{-1}. The physio-chemical properties of subsoils of the Muda plain for Chengai soil series type used in this study were: 62% clay, 27% silt, 0.3% carbon, 0.05% nitrogen, 10.7% sand, and 0.28 CEC (ratio of cation-exchange capacity of clay to percent clay) (Paramananthan, 1989). The annual rainfall in the study area is comparatively high, but not evenly distributed throughout the year because of the tropical monsoon climate.

The long-term (1971-97) mean monthly observed rainfall from 53 rainfall stations located in and around the study area were used in this study. The observed total existing water from the time period 1991-97 in each infinitesimal area for dry (February-July) and wet (August-January) crop seasons was converted to moisture content (%) and averaged. The values were then used as input to the models used in this study. The probable maximum soil moisture content in the study area is 85mm for 100% soil saturation (Kitamura, 1987).

The irrigation scheme was divided into 172 irrigation blocks. Kitamura (1990) measured seepage and percolation loss at an irrigation block named SCRBD5b (central canal right bank drain 5b) situated in the south-western part of the Muda Irrigation Scheme area. This data has been used in the present study as the observed data. Kitamura (1987; 1990) observed the average seepage and percolation loss during paddy growth stage in the area as 0.9 mm d^{-1}. MADA (1977) and Teoh and Chua (1989) measured the average seepage and percolation loss during paddy growth stage as 1 mm d^{-1}. To measure percolation, the 'quick percolation measuring apparatus' was used. The rainfall intensity and the other data used in this study are given in Table 1.

3.0 MODELING APPROACH

Ten infiltration models, namely, Green and Ampt, SCS, Horton, Holtan, Philip, Singh-Yu, Mishra-Singh, linear Smith-Parlange, nonlinear Smith-Parlange and Morel-Seytoux models were used in the present study to assess their performance in estimating the surface runoff in the Muda Irrigation Scheme. The models used in the present study can be classified into three classes: physically based model (e.g., Green and Ampt, 1911; Morel-Seytoux, 1978; Philip, 1957; Smith and Parlange, 1978), semi-empirical models (e.g., Mishra and Singh, 2002; and Singh and Yu, 1990), and empirical models (e.g., Holtan, 1961; Horton, 1940; SCS, 1972). A brief description of each model is provided below.

3.1 General Hydrologic Budget

The general hydrologic budget with all the components is shown in Eq. (1). When all other variables except the infiltration are known, then the infiltration rate can be computed using the following equation:

$$\begin{aligned} W(t+\Delta t) = W(t) + P(t,t+\Delta t) - ET_p(t,t+\Delta t) - R(t,t+\Delta t) - F(t,t+\Delta t) \\ -S_l(t,t+\Delta t) + IR(t,t+\Delta t) \end{aligned} \qquad [1]$$

where, $W(t+\Delta t)$ is the soil moisture content at time $t+\Delta t$; $W(t)$ is the soil moisture content at time t; $P(t, t+\Delta t)$ is the aerial precipitation; $ETp(t, t+\Delta t)$ is the potential evapotranspiration; $R(t, t+\Delta t)$ is the runoff; $F(t,t+\Delta t)$ is the infiltration loss to groundwater; $S_l(t,t+\Delta t)$ is the seepage loss; and $IR(t, t+\Delta t)$ is the irrigation amount supplied between t and $t+\Delta t$, respectively.

3.2 Green-Ampt Model

The Green and Ampt model (1911) is an approximate theory-based infiltration model utilizing Darcy's law. The Green-Ampt equation for cumulative infiltration F can be obtained as

$$F(t) - \psi\Delta\theta \ln\left(1 + \frac{F(t)}{\psi\Delta\theta}\right) = Kt \qquad [2]$$

where, Ψ is the Green-Ampt wetting front suction parameter, K is the hydraulic conductivity of soil, $\Delta\theta$ is the change in moisture content.

Once F is found from Eq. (2), the infiltration rate, $f = dF/dt$, can be obtained from

$$f(t) = K\left(\frac{\psi\Delta\theta}{F(t)} + 1\right) \qquad [3]$$

After laboratory tests of many soil samples, Brooks and Corey (1964) concluded that ψ can be expressed as a logarithmic function of an effective saturation, S_e. If the residual moisture content of the soil after it has been thoroughly drained is denoted by θ_r, the effective saturation is the ratio of the available moisture $\theta-\theta_r$ to the maximum possible available moisture content $\eta-\theta_r$:

$$s_e = \frac{\theta-\theta_r}{\eta-\theta_r} \qquad [4]$$

where, η is the total porosity and θ is moisture content. The effective saturation has the range $0 \le s_e \le 1.0$, provided that $\theta_r \le \theta \le \eta$. For the initial condition, when $\theta = \theta_i$, cross-multiplying Eq. (4) gives $\theta_i - \theta_r = S_e\theta_e$, and the change in the moisture content when the wetting front passes is $\Delta\theta = \eta - \theta_i = \eta - (S_e\theta_e + \theta_r)$; therefore

$$\Delta\theta = (1 - s_e)\theta_e \qquad [5]$$

The soil porosity (total volume occupied by pores per unit volume of soil) is computed from bulk density and particle density (normally assumed to be equal to 2.65 g cm-^{3}) as follows:

$$\eta = 1 - \frac{BD}{PD} \qquad [6]$$

where, BD is the soil bulk density (g cm-^{3}), and PD is the particle density (g cm-^{3}). If the cation-exchange capacity of the clay (an indicator of the shrink-swell capacity of the clay) is available, the bulk density at the water content for 33 kPa tension can be estimated as

$$BD = 1.51 + 0.0025(S) - 0.0013(S)(OM) - 0.0006(C)(OM) - 0.0048(C)(CEC) \qquad [7]$$

where, S is the percent sand, C is the percent clay, OM is the percent organic matter [1.7 (percent organic carbon)], and CEC ranges from 0.1-0.9.

The ψ value can be obtained from the soil properties by the following equation (Rawls and Brakensiek, 1983):

$$\psi = \exp\begin{bmatrix} 6.53 - 7.326(\eta) + 0.00158(C^2) + 3.809(\eta^2) + 0.000344(S)(C) - 0.04989(S)(\eta) \\ +0.0016(S^2)(\eta^2) + 0.0016(C^2)(\eta^2) - 0.0000136(S^2)(C) - 0.00348(C^2)(\eta) \\ -0.000799(S^2)(\eta) \end{bmatrix} \qquad [8]$$

The Brooks-Corey residual water content θ_r can be estimated from

$$\begin{aligned} \theta_r &= -0.0182482 + 0.00087269(S) + 0.00513488(C) + 0.02939286(\eta) \\ &- 0.00015395(C^2) - 0.0010827(S)(\eta) - 0.00018233(C^2)(\eta^2) \\ &+ 0.00030703(C^2)(\eta) - 0.0023584(\eta^2)(C) \end{aligned} \qquad [9]$$

The area, bare outside canopy, was assumed to be crusted and the effective hydraulic conductivity was considered equal to the saturated hydraulic conductivity K_s times a crust factor CRC. Rawls *et al.,* (1990) developed the following relationship for the crust factor:

$$CRC = \frac{SC}{1+\left(\Psi_i / L\right)} \qquad [10]$$

where, SC = correction factor for partial saturation of the soil = 0.736 + 0.0019S; ψ_i = matric potential drop at the crust-subcrust interface = 45.19 – 46.68 (SC), cm; and L = wetting front depth in cm.

The cumulative infiltration at the ponding time t_p is given by F_P, where i is the constant intensity of rainfall (cm h-^{1}); and the infiltration rate by $f = i$; substituting into Eq. (3),

$$t_p = \frac{K\Psi\Delta\theta}{i(i-K)}, \qquad i > K \qquad [11]$$

The Green-Ampt equations are developed for homogeneous soils. The approach can be extended to describe infiltration into layered soils, when the hydraulic conductivity of the successive layers is known. As long as the wetting front is in the top layer, the equations remain the same. After the wetting front enters the second layer, the effective hydraulic conductivity K is set equal to the harmonic mean $K_h = \sqrt{K_1 K_2}$ for wetted depths of the first and second layers, and the capillary head is set equal to ψ of the second layer. This principle is then carried out through the third and succeeding layers.

3.3 Horton Model

A three-parameter empirical infiltration model was presented by Horton (1940) and it has been widely used in hydrologic modelling (Eq (12)). According to this approach the infiltration starts at a constant rate, f_0, and decreases exponentially with time, $\boldsymbol{t}$. After some time when the soil saturation level reaches a certain value, the rate of infiltration will level off to the rate f_c.

$$f_t = f_c + \left(f_0 - f_c\right)e^{-kt} \qquad [12]$$

where, f_t is the infiltration rate at time $\boldsymbol{t}$; f_0 is the initial infiltration rate (also the maximum infiltration rate); f_c is the equilibrium infiltration rate after the soil has been saturated (also the minimum infiltration rate); k is the decay constant specific to the soil (T^{-1}).

Horton's equation can also be used to find the total volume of infiltration, F, after time $\boldsymbol{t}$.

$$F_t = f_c t + \frac{\left(f_0 - f_c\right)}{k}\left(1 - e^{-kt}\right) \qquad [13]$$

Alternatively, Eqs (12) and (13) can be combined to yield the following direct relationship between F and f_t.

$$F(t) = \left[\frac{f_c}{k}\ln\left(f_0 - f_c\right) + \frac{f_0}{k}\right] - \frac{f_c}{k}\ln\left(f_t - f_c\right) - \frac{f_t}{k} \qquad [14]$$

3.4 SCS Model

The SCS curve-number model is the most widely used model for estimating rainfall excess. According to SCS model, the total infiltration, F, for a rainfall event, P, can be estimated as,

$$F = \frac{\left(P - 0.2S_p\right)S_p}{P + 0.8S_p}, \qquad P > 0.2S_p \qquad [15]$$

where, S_p is the soil storage capacity. The infiltration rate, f, can be derived from Eq. (15) by differentiation,

$$f = \frac{dF}{dt} = \frac{{S_p}^2 i}{\left(P + 0.8S_p\right)^2} \qquad [16]$$

Instead of specifying S_p directly, a curve number, CN, is usually specified where CN is related to S_p by

$$CN = \frac{1000}{10 + 0.0394S_p} \qquad [17]$$

where, S_p is in mm. Clearly, in the absence of available storage (S_p = 0, impervious surface) the curve number is equal to 100, and for an infinite amount of storage the curve number is equal to zero.

3.5 Philip Model

Philip's Two-Term equation (Philips, 1957) is a truncated power series solution that could be used as an infiltration model. The equation is

$$f = \frac{1}{2}S_v t^{-1/2} + \frac{2}{3}K_s \qquad [18]$$

where, f is in cm h^{-1}, t is time for ponding (h), S_v is the sorptivity (LT$^{-0.5}$), K_s is in cm h^{-1}), and S_v can be approximated using the following equation developed by Youngs (1964):

$$S_v = \sqrt{2\left(\eta - \theta_i\right)K\Psi} \qquad [19]$$

The K_s can be estimated from (Brooks and Corey, 1964):

$$\frac{K(\theta)}{K_s} = \left(\frac{\theta - \theta_r}{\eta - \theta_r}\right)^n = \left(s_e\right)^n \qquad [20]$$

where n= 3 + 2 / λ, and the Brooks-Corey pore-size distribution index, λ can be estimated from

$$\lambda = \exp\begin{bmatrix} -0.7842831 + 0.0177544(S) - 1.062498(\eta) - 0.00005304(S^2) \\ -0.00273493(C^2) + 1.11134946(\eta^2) - 0.03088295(S)(\eta) \\ +0.00026587(S^2)(\eta^2) - 0.00610522(C^2)(\eta^2) \\ -0.00000235(S^2)(C) + 0.00798746(C^2)(\eta) - 0.00674491(\eta^2)(C) \end{bmatrix} \qquad [21]$$

3.6 Singh-Yu Model

Singh and Yu (1990) derived a model based on two postulates, namely, (i) the rate of infiltration in excess of the final infiltration rate, called excess infiltration, at any time is directly proportional to the mth power of the available storage space in the soil column at that time, and (ii) the rate of excess infiltration is inversely proportional to the nth power of the cumulative infiltration up to that time. This model is expressed mathematically as,

$$f(t) = f_c + \frac{a\left[S(t)\right]^m}{\left[S_0 - S(t)\right]^n} \qquad [22]$$

where, $f(t)$ is the infiltration rate (LT^{-1}) at time $\boldsymbol{t}$, f_c is the final infiltration rate (LT^{-1}), $S(t)$ is the available storage for water retention in the soil column at time $\boldsymbol{t}$ (L), S_0 is the potential storage space available for moisture retention in soil column at the beginning (L), and a, m, and n are the coefficient and exponents of the variables $S(t)$ and $(S_0$ - $S(t))$, respectively. The cumulative infiltration F is equal to $(S_0$ - $S(t))$.

3.7 Holtan Model

Holtan (1961) developed an empirical equation on the premise that soil moisture storage, surface-connected porosity, and the effect of root paths are the dominant factors influencing the infiltration capacity. Holtan and Lopez (1971) modified the equation as

$$f = GI\ AS_a^{1.4} + f_c \qquad [23]$$

where, f is the infiltration rate (in h^{-1}); GI is the growth index of crop in percent maturity varying from 0.1 to 1.0 during the season; A is the infiltration capacity (in h^{-1}) per (in) of available storage and is an index representing surface-connected porosity and the density of plant roots which affect infiltration, considered 0.10 for fallow and row crops type land use with poor condition (Frere *et al.,* 1975); S_a is the available storage in the surface layer (in), and f_c is the constant infiltration rate (in h^{-1}) when the infiltration rate curve reaches asymptote (steady infiltration rate).

3.8 Mishra–Singh Model

By expressing the SCS model in the form of the Horton method Mishra and Singh (2002) developed an infiltration equation by assuming a linear variation of the cumulative precipitation with time or with constant rainfall intensity:

$$f = f_c + \frac{S_p k}{(1 + kt)^2} \qquad [24]$$

where, S_p is the potential maximum retention capacity of the catchment used in the SCS model; a general model parameter S_0, identical to the model of Singh–Yu (1990), and k is the decay coefficient identical to the decay parameter used in the Horton model. The mathematical expression of Eq. (24) is a specific form of the retention model proposed by van Genuchten (1980) relating θ with Ψ.

3.9 Smith-Parlange Linear and Nonlinear Models

Smith and Parlange (1978) derived an infiltration model expressed as:

$$f = K_s\left(\frac{C}{K_s F} + 1\right) \qquad [25]$$

where, C is a parameter related to the soil sorptivity and varies linearly with the initial soil moisture. It also depends on the amount and pattern of rainfall intensity. Parameters C and K_s can either be determined graphically or by using a regression approach utilizing infiltration data. The parameter C in the Green-Ampt equation is

$$C \approx -\Psi_{avg}(\theta_s - \theta_i)K_s \qquad [26]$$

where, Ψ_{avg} is average capillary tension across the wetting front. Mein and Larson (1973) proposed a relation

$$\Psi_{avg} = -\frac{1}{K_s}\int_{K_i}^{K_s} \Psi\, dK_s \qquad [27]$$

Later, Smith and Parlange (1978) derived a nonlinear infiltration model expressed as:

$$f = K_s \frac{e^{(FK_s/C)}}{e^{(FK_s/C)-1}} \qquad [28]$$

3.10 Morel-Seytoux Model

Morel-Seytoux (1978) model is a modification of Green and Ampt (1911) model. The model is based on the ponding time concept: runoff cannot occur as long as the soil surface retention potential is not met. Therefore, at every time stem, the model needs to determine whether the ponding time (*tp*) has been reached. For $t>t_p$ the cumulative infiltration $F(t)$ at time t, is calculated from

$$F(t) - F_p - \left[S_f + F_p\left(1 - \frac{1}{\beta}\right)\right]\ln\left[\frac{S_f + F(t)}{S_f + F_p}\right] = \frac{K_s(t - t_p)}{\beta} \qquad [29]$$

where, F_p [L] is the cumulative infiltration when ponding occurs; β is a new viscous correction parameter introduced by Morel-Seytoux and Khanji (1974), the value of which varies usually between 1 and 1.7 and is generally fixed at 1.3; and S_f [L] is a storage and suction factor that can be expressed as a function of the soil hydraulic properties

$$S_f = (\theta_s - \theta_i)H_c\left[1 - \frac{1}{3}\left(\frac{\theta_i - \theta_r}{\theta_s - \theta_r}\right)^6\right] \qquad [30]$$

where, H_c [L] is the capillary height.

3.11 Evaluation of Models Performance

Due to the limitation of good quality field data, calibration of any or all of the above mentioned models is a challenge for many agricultural fields around the world. For the Muda irrigation scheme the limitation of the field data does not allow a comprehensive calibration of models mentioned above. Calibration increases model accuracy and reduces uncertainty of model predictions. If measured data is not available, studies on uncertainty assessment or sensitivity analysis of model parameters may not be carried out. In this regard, the IAHS initiative of Prediction in Ungauged Basins regarding modelling ungauged catchments is noteworthy. The main recommendation of leading hydrologists around the world who participated in this initiative (Sivapalan *et al.,* 2003; Sivapalan, 2006) about simulating ungauged basin was on using a model, with limited calibration and on improving the understanding of the processes with modelled results to compensate for the limitation of calibration. Furthermore, they recommended to use new data points, which may appear in future, to compare the model results and if needed to update the model parameters.

Several statistical measures, namely, correlation coefficient, coefficient of determination (R^2), variance, relative mean absolute error, Nash and Sutcliffe efficiency, etc., are available to evaluate the performance of a model. The relative mean absolute error (RMAE), which incorporates both systematic and random errors, is used in this study to assess the model performance. The relative mean absolute error (RMAE) can be expressed as

$$RMAE = \left(\frac{1}{n}\sum_{i=1}^{n}|y_i - x_i|\right)/\,\overline{x}$$

where, x_i = ith observation of the observed data, y_i = ith observation of the model data,

$$\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \ = \text{mean of } x \text{, and } n = \text{sample size.} \qquad [31]$$

4.0 RESULTS AND DISCUSSION

The models used in this study can be considered site specific rather than universally applicable. Thus, the estimated model

Table 2: Observed Infiltration and Models Infiltration Rates for Different Months in the Study Area.

Observed Data	Month											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
*Mean Monthly Rainfall, P (mm)	20.6	52.4	102.1	184.0	236.7	169.3	210.3	237.5	310.5	287.5	197.8	77.7
*Daily Cumulative Infiltration (mm)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
**Infiltration Rate (mm h^{-1})	0.079	0.079	0.079	0.079	0.079	0.079	0.079	0.079	0.079	0.079	0.079	0.079
Model	**Monthly Infiltration Rate (mm h^{-1})**											
Smith-Parlange (Nonlinear)	0.227	0.227	0.227	0.075	0.005	0.106	0.015	0.005	0.041	0.015	0.013	0.227
Holtan	0.254	0.254	0.254	0.254	0.254	0.254	0.254	0.254	0.254	0.254	0.254	0.254
Singh-Yu	0.321	0.321	0.321	0.321	0.321	0.321	0.321	0.321	0.321	0.321	0.321	0.321
Morel-Seytoux	0.211	0.159	0.114	1.030	0.995	0.965	0.859	0.995	1.030	0.993	0.997	0.129
Horton	0.831	0.831	0.831	0.831	0.831	0.831	0.831	0.831	0.831	0.831	0.831	0.831
SCS	7.369	2.267	0.789	0.281	0.177	0.327	0.220	0.176	0.107	0.123	0.246	1.236
Green-Ampt	7.481	6.348	0.262	0.133	0.027	0.157	0.050	0.027	0.081	0.053	0.047	3.214
Philip	3.858	3.283	2.895	1.646	0.426	1.965	0.722	0.426	1.222	0.745	0.670	3.056
Mishra-Singh	5.504	5.504	5.504	5.504	5.504	5.504	5.504	5.504	5.504	5.504	5.504	5.504
Smith-Parlange (Linear)	11.534	5.125	53.777	10.833	0.016	17.095	0.657	0.016	3.596	0.769	0.493	6.088

**** Observed Data (Source: Muda Agricultural Development Authority, Alor Setar, Kedah, Malaysia)***
***** Calculated infiltration rate from observed daily cumulative infiltration of 1 mm***

parameter values as well as the model outputs may vary from location to location. In this study, the cumulative infiltration and the infiltration rates were estimated using the ten models mentioned above. Due to the scarcity of the observed data the models were not calibrated. Limited available observed data together with secondary information about the study area from literature were used in this study. Further descriptions are provided in the following sections.

4.1 Green-Ampt Model

In order to apply the Green-Ampt model (Eq (3)), the effective hydraulic conductivity K, the wetting front suction head Ψ, the porosity η and the effective porosity θ_e need to be measured or estimated. Generally, K varies along with Ψ, so the values of Ψ and K should be considered as typical representative values that may allow some variability in applications. Using the soil properties reported by Paramananthan (1989), the porosity, residual moisture content, the effective porosity and soil suction head were estimated.

The hydraulic conductivity of sandy loam soil decreases more rapidly with the decrease in the ponding depth than that of the clayey soil, such that at lower ponding depth values (or at higher suctions) the hydraulic conductivity of the clayey soil is higher. The soil in the study area is of heavy clay type (Chengai series) with the coefficient of permeability ranging from $1\text{x}10^{-7}$ to $8\text{x}10^{-6}$ cm s^{-1} (Kitamura, 1990). The coefficient of permeability is allowed to vary in different months as a function of moisture content in each month, considering the highest value (i.e., $8\text{x}10^{-6}$ cm s^{-1}) for dry soil during dry season and vice-versa. The area which is bare/outside of the canopy was assumed to be crusted and the effective hydraulic conductivity was considered equal to the saturated hydraulic conductivity K_s times a computed crust factor CRC (Eq (10)) of 0.71. The step-by-step procedure of calculating hourly cumulative infiltration and infiltration rate in each month using this model is shown in Table 1. The mean infiltration rate was found to be 1.490 mm h^{-1} by this model (Table 2).

4.2 Horton Model

By considering the USDA soil texture of type clay, an f_c value of 0.5mm h^{-1} was estimated using Eq (12). Following the recommendation of Singh (1992) to maintain the radio f_0/f_c of the order of 5 and using the value of the decay constant, k = 0.03 min^{-1} the mean value of f_t was estimated to be 0.831mm h^{-1} (Table 2). The variability of the infiltration parameters in the Horton model is due to the reasons that infiltration depends upon several factors that are not explicitly accounted for in finding f_c values for different soil types and vegetation covers. For example, the initial moisture content and organic content of the soil, vegetative cover, and season are not explicitly accounted for in the Horton model (Linsley *et al.,* 1982). Moreover, the USDA soil types do not match exactly with the soil types in the study area. Thus, an experimental study is required to estimate the values of f_0, f_c and k to find much more reliable infiltration rate in the study area.

4.3 SCS Model

The soil in the study area can typically be considered as a combination of fallow cover type and row cover type, comprising of *CN* for hydrologic soil group *D* (soils that swell significantly when wet, heavy plastic clay and saline soil). Therefore, the resulting *CN* was chosen based on the bare soil, crop residue cover and row crops (straight row with poor and good conditions only), and was considered to be the average of the curve numbers for these soil types. By referring to the CN Table of the SCS method the curve number was computed as: $CN = (94+93+90+91+89)/5 = 91.4$. Assuming an average rainfall intensity of 1-day duration, the probable maximum precipitation (PMP) was measured at an airport station closed to the study area (Al-Mamun and Hashim, 2004). The storage value was found to be 23.88mm. The infiltration rate (mm h^{-1}) in each month was estimated and the mean infiltration rate was found to be 1.110 mm h^{-1} (Table 2).

4.4 Philip Model

The inputs to this model are mainly the physio-chemical properties of soil and moisture content. In calculating K_s (Eq (18)) for different months, the effective saturation values for different months were taken from the Green-Ampt model. The value of K_s during December to February was considered to be equal to the maximum value obtained in March, because the computed values of K_s were found to be comparatively higher than the soil hydraulic conductivity during December to February. The hourly cumulative infiltration and infiltration rate were calculated, and the mean infiltration rate was found to be 1.743mm h^{-1} (Table 2).

4.5 Singh-Yu Model

Since the soil in the study area is heavy plastic clay, the minimum values of *a, m,* and *n* are taken from literature (Mishra *et al.,* 2003) as such values are not available in the study area, to achieve more realistic results. The hourly cumulative infiltration was taken from the Green-Ampt model (1911). The potential storage space available for moisture retention in soil column S_0 (Eq (22)) was considered equal to S_p of the SCS model (Eq (16)). Musgrave (1955) reported that the potential infiltration rate fc was varied from 0.0 to 0.13cm h^{-1} for the hydrologic soil group *D*. Accordingly, an average value of (0.0+0.13)/2, i.e., 0.065 (cm h^{-1}) was considered for the potential infiltration rate f_c. MADA (1977) and Teoh and Chua (1989) reported measured daily seepage and percolation loss of only 1mm for the Muda soil type. Following the recommendation of Singh (1992), the authors considered $f_0/f_c = 5$ and by further considering that the infiltration rate f must be higher than fc, the resulting hourly infiltration rate was estimated. The resulting mean infiltration rate from this model was estimated to be 0.321mm h^{-1} (Table 2).

4.6 Holtan Model

The storage S_a (mm) value (Eq (23)) was taken from the SCS model and converted to inches in order to comply with the system of units used in the Holtan model. The average value of the vegetation parameter *A* in the Holtan model for land use type 'fallow and row' crops with poor condition was considered as 0.1 (Frere *et al.,* 1975). Musgrave (1955) reported that the final infiltration rate fc varied from 0.0 to 0.13cm h^{-1} for the hydrologic soil group *D*. Accordingly, an average value of $f_c = (0.0+0.13)/2$, i.e., 0.065cm h-1 was considered in Eq (23). The authors refer once again to MADA (1977) and Teoh and Chua (1989) for the measured daily infiltration and percolation loss of only 1mm d^{-1} for the Muda soil type. Accordingly, it was assumed that the f_c value would be less than 1mm d^{-1}. Following the recommendation of Singh (1992) for f_0/f_c ratio to be about 5 and considering that the infiltration rate *f* must be higher than f_c, the infiltration rate was estimated considering the value of f_c at 0.5mm d^{-1} in absence of reliable data. Consequently, the mean infiltration rate from this model is found to be 0.254 mm h^{-1} (Table 2).

4.7 Mishra-Singh Model

In calculating the infiltration rate f using the Mishra-Singh model, the S_p, f_c and *k* values of Eq (24) were obtained from the SCS, Holtan, and Horton models, respectively. The estimated mean infiltration rate using this model was found to be 5.504 mm h^{-1} (Table 2). Considering typical values of S_p, f_c and *k* for the Narsinghpur Clay (NC) (Mishra *et al.,* 2003), the estimated infiltration rate was found to be very high (5.504mm h^{-1}) as shown in Table 2.

4.8 Smith-Parlange Linear and Nonlinear Models

In calculating f (mm h^{-1}) by Smith-Parlange nonlinear model (Eq 25), the following considerations were undertaken: (i) the values of the cumulative infiltration *F* were obtained from the Green-Ampt model, (ii) the K_s values were obtained from the Philip model, (iii) the value of K_i was assumed equal to *K* value, (iv) ψ value was taken from the Green-Ampt model to calculate $\psi_{avg.}$, (v) the initial water content θ_i for each month was assumed to be the respective moisture content θ in each month, and (vi) the θ values were considered 99.9% in May and August instead of 100% in order not to get zero value of *C* as zero value of *C* results FK_s/C infinity and produces an unrealistic result. The hourly infiltration rates and the corresponding cumulative infiltration amounts for each month were calculated, and the resulting mean infiltration rates from the linear and nonlinear Smith-Parlange models were found to be 9.167mm h^{-1} and 0.098mm h^{-1}, respectively (Table 2).

4.9 Morel-Seytoux Model

In calculating the values of hourly cumulative infiltration *F(t)* and the infiltration rate *f(t)* ((Eq 29)), the following considerations were made: (i) the value of the saturated hydraulic conductivity K_s was obtained from the Philip model, (ii) the ψ value was obtained from the Green-Ampt model and set identical to H_c value, (iii) the value of t_p was obtained from rainfall intensity *i*, which was assumed to be an average rainfall intensity of probable maximum precipitation of 1-day duration measured at Airport Station close to the study area, Kedah, Malaysia (Al-Mamun and Hashim, 2004), (iv) the initial water content θ_i was assumed to be the respective moisture content θ in each month, and (v) the value of β was fixed at 1.3. The resulting hourly cumulative infiltration *F(t)* and the corresponding infiltration rate *f(t)* were estimated, and the mean monthly infiltration rate using Eq. (3) was found to be 0.706mm h^{-1} (Table 2).

4.10 Evaluation of Models Performance

The models used in this study differ by their mathematical structures and therefore, their parameters are required to be calibrated, even when the input hydrologic data are from the same site. Predictions from uncalibrated models are uncertain.

The observed total existing water from 1991-97 in each infinitesimal area for dry (February-July) and wet (August-January) crop seasons were converted to moisture content and averaged, and used as an input to the models used in this study (Kitamura, 1987). The available observed data, together with secondary information about the study area literature were used to estimate the infiltration rate.

The observed cumulative infiltration $F(t)$ of 1mm was converted to the infiltration rate $f(t)$ (mm h^{-1}) for comparison purpose. Using the Green-Ampt Model (Eq (2)), the corresponding hydraulic conductivity K value was found to be 0.0705cm d^{-1} against an observed daily cumulative infiltration and percolation loss of 1mm, keeping the other parameters of Eq (2) the same as the parameters of the Green-Ampt model. Using Eq (3), the corresponding converted observed infiltration rate of 0.0786mm h^{-1} was achieved against the observed daily cumulative infiltration and percolation loss of 1mm in order to compare the models results with the observed infiltration rate, i.e., to fulfil the comparison requirement.

The performance of the models was evaluated based on the relative mean absolute error (RMAE) criterion. The RMAE values for the 10 models were computed and the models were ranked according to the increasing RMAE values to identify the most suitable model for the study area. Within the selected modelling framework, the performance evaluation of the models suggests that the Smith-Parlange nonlinear model performed the best compared to other models. The second best suited model was found to be the Holtan model. The suitability of the other models in descending order can be found according to the ascending order of RMAE values and ranks, given in Table 3.

Table 3: Performance of Different Models in Estimation of the Infiltration Rate.

Model	Mean Monthly Model Infiltration Rate (mm h^{-1})	RMAE	Rank
Smith-Parlange (Nonlinear)	0.098	0.253	1
Holtan	0.254	2.230	2
Singh-Yu	0.321	3.083	3
Morel-Seytoux	0.706	7.990	4
Horton	0.831	9.570	5
SCS	1.110	13.126	6
Green-Ampt	1.490	17.961	7
Philip	1.743	21.180	8
Mishra-Singh	5.504	69.040	9
Smith-Parlange (Linear)	9.167	115.652	10

However, the applications of the other available models and/or the use of individual storm events and much more precise field data might alter this suitability for the study area. Therefore, a detailed experimental study can be undertaken to run the models with more readily and to develop a new model for the heavy marine clay type soils in the study area.

The practical benefits of this study are to estimate the modelled cumulative infiltration quantity and infiltration rates in different months to allow irrigation scheduling and estimating water loss and in turn to compute the surface runoff from the scheme to design drainage channels.

5.0 CONCLUSIONS

Infiltration models were used in the present study to calculate cumulative infiltration and infiltration rates using uncalibrated models. Available observed data and information about the study area from literature were used in estimating infiltration rates. Using the soil properties reported by Paramananthan (1989), the porosity, residual moisture content, the effective porosity and soil suction head were computed. The soils in the study area is heavy clay type (Chengai series), with the coefficient of permeability ranging from to $1x10^{-7}$ to $8x10^{-6}$ cm s^{-1} (Kitamura, 1990). The coefficient of permeability was allowed to vary as a function of moisture content in different months, considering the highest value for the dry soil and vice-versa. The performance of the models was evaluated based on the RMAE criterion. Within the selected modelling framework, the evaluation of performance of the models is helpful in identifying models, which might be used to estimate the infiltration rate in the study area. It has been found that compared to other models the infiltration rate estimated by the physically based Smith-Parlange nonlinear model (1978) was closest to the observed rate. The suitability of the other models can respectively be regarded as the Holtan, Singh-Yu, Morel-Seytoux, Horton, SCS, Green-Ampt, Philip, Mishra-Singh, and Smith-Parlange (linear) model (Table 2).

The models used in this study are site specific and not as such universal. Thus, their performance may vary from site to site. The performance of the models is based on the results obtained using limited data and secondary information. Thus, a detailed experimental study can be undertaken to run these models satisfactorily in the near future. Finally, based on the available data and information, it can be concluded that the Smith-Parlange nonlinear model is considered to be the most suitable model for estimating infiltration in the study area. It is expected that this study will be used as a guideline in model selection and estimation of infiltration rates in the agricultural field of Malaysia, which in turn will help in irrigation water management, soil erosion control, irrigation efficiency improvement and agricultural pollution assessment.

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PROFILES

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