Water Infiltration into Homogeneous and Heterogeneous Soils at Saturation Level

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Abstract. Water supply either by rainfall or irrigation wets the soil. Water infiltration brings water to soil depth beneath the soil surface. Water in contact with the soil is known as soil moisture content, and it is accessible to plant roots absorption. Soil texture is crucial in determining soil infiltrability by water. In this study, we compared three parameters of water infiltration between homogeneous and heterogeneous soils. The parameters were the time for soil water to reach a certain designated depth of observation (0.15, 0.46, 0.61 m), water infiltration rate, and infiltrated water height. The study uses the Richards equation to govern water diffusion and gravitational fluxes in the soil. The equation was discretized into algebra equations using the cell-centered finite difference method and solved implicitly in FORTRAN language. In the study, a few selected soil series (Lubok Kiat, Jerangau, Rudua, Tasik, Batu Hitam) in Terengganu state were investigated. Results showed an apparent difference in these parameters when compared between homogeneous and heterogeneous soils. The Jerangau and Tasik soil series were largely affected by soil heterogeneity, but to a lesser influence was exhibited by Rudua and Batu Hitam. The most negligible impact was found in Lubok Kiat. The research identifies three significant findings that: (1) a similar soil texture at all soil depths of concern would exhibit similar water infiltration properties; (2) the clay subsoil layer, Jerangau series, overlaid by higher hydraulic conductive soil (sandy clay) significantly increases water infiltration time due to matric suction interaction between soil layer; and (3) some soil series properties can be assumed homogeneous, for example, Lubok Kiat and Rudua though appeared to have heterogeneous soil layers, but the water infiltration properties indicate they were comparable to homogenous soil.

Keywords: Richards' equation, water flux, soil layers, water distribution

I. INTRODUCTION

Rainfall is one of the processes in the hydrological cycle [1]. Rainwater that hits the ground is subsequently going through evaporation from the soil water surface [2], infiltration into the soil

[3], and surface runoff for excess water [4]. Water in the soil could infiltrate deeper by percolation to form groundwater [5]. The mechanisms involved are diffusion and gravitational pull on the water [6]. Another water supply method in the soil is the dew formation and fog attachment on the soil surface [7]–[9]. However, the method is limited in quantity to sustain the demand for plant water requirements. The sustainable water supply to meet the plant needs in the field is mainly supported by a water irrigation system [10].

Water attached to the soil is better known as soil moisture content [11]. The soil moisture content could vary between residual water content and saturated water content [12]. The soil residual water content is the minimum water remaining in the soil after draining. In contrast, saturated water content refers to the maximum water storage in the soil achieved by unlimited water supply by rainfall, irrigation, or any water supply methods. The soil moisture content represents the water volume over the total soil volume, including the pore space, that is, with air and water, between the soil particles [13].

Soil texture determined the soil's ability to retain water [14]. In general, soil texture could be classified into twelve textural classes, for example, the USDA soil textural triangle [15]. A soil textural class, for instance, clay soil, has unique parameters' value for water retention function and unsaturated hydraulic conductivity [16]. The former relates soil moisture content with the suction pressure in the soil. The latter describes the soil's ability to conduct water at different water saturation levels. Also, each soil texture has its unique profile of water distribution and infiltration [17].

Furthermore, soil horizons are rarely homogeneous [18]. Homogenous soil means a single soil texture for the entire soil depth. However, soil horizons consist of soil layers with different textures [19-21], which is known as heterogeneous soil. Depending on the scale of concern soil depths, soil in kilometers of depth would generally be of interest in water resources like groundwater engineering [22], [23]. In forestry, soil depth up to 1.5 km would be of concern [24]. In agriculture, soil down to centimeter depths where plant roots penetrate and grow would be a matter of concern [10]. This study focuses on the centimeter from the soil surface to depths where plant roots hold.

In Malaysia, there are over a hundred soil series [25]. Terengganu itself accounts for fifteen soil series. About eight out of those soil series are heterogeneous. The layer in heterogeneous soil could be as small as 5 cm depth to over 100 cm soil depth. The smallest 5 cm soil could be limited by field sampling instrumentation. Hence, a substantially smaller soil depth layer could be left unnoticed. Although, in theory, soil heterogeneity may influence soil water infiltration properties, the hypothesis has not been tested, particularly on Terengganu soil. Water infiltration in the soil is indicative of the water travel distance with time; it has crucial implications in water irrigation management in terms of water supply, storage and distribution system, which ultimately relates to cost management. Hence, it motivates the current studies.

The water infiltration rate could be different when comparing homogeneous and heterogeneous soil horizons. The current work aim is to study the effect of soil heterogeneity on (1) the time needed for water to reach specifically designated depths, (2) the water infiltration rate, and (3) the quantity of water (in water height) given by water volume over a unit of land area.

II. MATERIALS AND METHODS

Over the years, many soil series were found in different states by the Department of Agriculture (DoA), Malaysia [26]–[28]. Terengganu state, in particular, many past research works were mainly focused on sandy soil [29]–[31]. Similarly, focus discussion on homogeneous soil horizon was observed in the work of Ishaq and co-workers in Terengganu [32], [33]. Rather than being limited to a single homogeneous soil series, the current study Terengganu soil series includes Batu Hitam, Tasik, Jerangau, Rudua, and Lubok Kiat (Table 1). Among all soil series in Terengganu, they have the most distinguished variation in soil texture layers (heterogeneous). Hence, the effect of heterogeneous soil layers compared to homogenous soil can be studied on water infiltration.

The soil series information was obtained from the DoA [25]. The soil series were classified into homogenous and heterogeneous soil textures. Out of simplicity, the soil is generally characterized as homogenous, leaving the critical information of soil heterogeneity behind. The soil texture of the homogenous soil was estimated from soil particle distribution using a soil texture calculator [34]. A similar method was used to estimate the heterogeneous soil texture. Both the homogenous and heterogenous soil depths were subjected to water infiltration study. In this study, the soil depths of concern were 0.15, 0.46, and 0.61 m. Water travel time, water infiltration rate, and the height of the water column infiltrated into the soil at the specific soil depths were estimated.

TABLE 1. A few soil series of Terengganu state soil. The soil depths and soil series information were retrieved from the Malaysia Department of Agriculture [25].

Soil Series	Heterogeneous soil texture	Homogeneous soil texture
Jerangau	Sandy clay (0-5 cm) Clay (5-150 cm)	Clay
Batu Hitam	Silty clay (0-33 cm) Clay (33-122 cm)	Silty Clay
Lubok Kiat	Clay (0-60 cm) Clay loam (60-85 cm) Clay (85-105 cm)	Clay
Rudua	Loamy sand (0-70 cm) Candy loam (70-150 cm)	Loamy Sand
Tasik	Clay loam (0-110 cm) Clay (110-160 cm)	Clay

Richards' equation [35] was used to study water infiltration at saturation in the soil surface. The governing equation is as follows,

$$\frac{\partial \theta_L}{\partial t} = \frac{\partial}{\partial z}\left[K\left(\frac{\partial \psi_m}{\partial \theta_L}\right)\frac{\partial \theta_L}{\partial z} - K \right] \tag{1}$$

Two constitutive functions used in the Richards’ equation were given by van Genuchten equations [12] as below,

$$\theta_L\left(\psi_m\right)=\theta_r+\frac{\theta_s-\theta_r}{\left[1+\left(\alpha\psi_m\right)^n\right]^{1-1/n}} \tag{2}$$

$$K\left(\theta_L\right)=K_s\left(\frac{\theta_L-\theta_r}{\theta_s-\theta_r}\right)^L\left\{1-\left[1-\left(\frac{\theta_L-\theta_r}{\theta_s-\theta_r}\right)^{1/m}\right]^m\right\}^2 \tag{3}$$

Equation 1 was solved using the finite difference method [36]. The algebraic equations were implemented in FORTRAN 2008 programming language [37]. Further explanation on the scheme was provided in Goh and Noborio [38]. Below is the algebraic equation used in the current study,

$$\begin{aligned}\frac{\theta_{L(k)}^{\ \ n+1}}{\Delta t}-\frac{\theta_{L(k)}^{\ \ n}}{\Delta t}=&\frac{K_{k+1/2}\left(\partial\psi_m/\partial\theta_L\right)_{k+1/2}\theta_{L(k+1)}^{\ \ n+1}}{\left(\Delta z\right)^2}-\frac{K_{k+1/2}\left(\partial\psi_m/\partial\theta_L\right)_{k+1/2}\theta_{L(k)}^{\ \ n+1}}{\left(\Delta z\right)^2}\\&-\frac{K_{k-1/2}\left(\partial\psi_m/\partial\theta_L\right)_{k-1/2}\theta_{L(k)}^{\ \ n+1}}{\left(\Delta z\right)^2}+\frac{K_{k-1/2}\left(\partial\psi_m/\partial\theta_L\right)_{k-1/2}\theta_{L(k-1)}^{\ \ n+1}}{\left(\Delta z\right)^2}-\frac{K_{k+1/2}\vec{k}}{\Delta z}+\frac{K_{k-1/2}\vec{k}}{\Delta z}\end{aligned} \tag{4}$$

III. RESULTS AND DISCUSSION

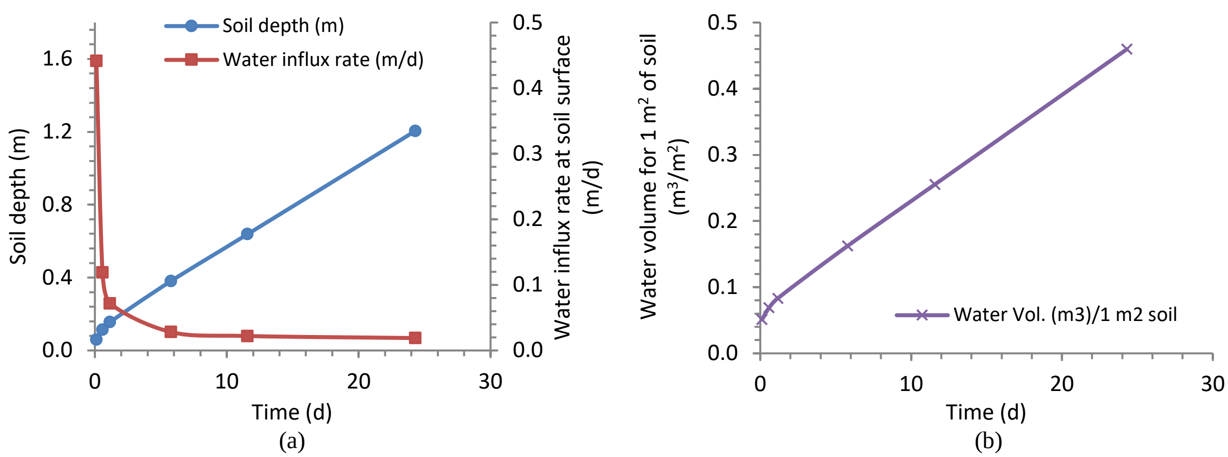


FIGURE 1. Information derived from Tasik soil series water infiltration study. (a) The relation of water infiltrated into soil depths (meter), water infiltration rate (meter height of water per day), and simulation time in days. (b) The relation between the infiltrated water height (meter) and time (days).

As part of crop management, soil moisture is necessary for plant growth [39]. Furthermore, there are three critical parameters to monitor. First is the time needed for water to reach a particular soil depth, that is, 0.15, 0.46, and 0.61 m. The second is the rate of water infiltration. The third is the water volume needed to irrigate a unit area of the soil. The three soil depths were chosen in this study because they represent the importance of plant-effective root depths. For instance, the effective root zone to absorb soil water at 0.15 m is essential for lettuce, onion, radish, spinach. At 0.46 m, it is crucial for broccoli, cabbage, carrots, cauliflower, cucumber, eggplant. Furthermore, at 0.61 m, it is for corn, melons, pumpkins, tomatoes, and watermelons plant roots [40].

Figure 1(a) shows the Tasik soil series for soil depth penetration rate by water was rapid at an early stage of infiltration, and gradually the penetration rate reduced and became constant. Initially, the water influx into the soil dominates by the water diffusion mechanism. After the soil surface saturates fully with water, the gravitational pull becomes prominent in the rest of the infiltration process. The diffusion mechanism governs by the soil water pressure gradient. The conventional pressure gradient is by pressure force pushing from high to low pressure, but in the case studies we had on the soil, the water infiltration process depends on suction pressure force that attracts soil water from the surrounding low suction pressure region. Also, the gravitational pull on water relies on the soil's hydraulic conductivity, increasing at high water content and vice versa [41]. Figure 1(b) observation was in line with the theoretical description that the water column penetration increased faster initially before stabilizing at a constant rate. Similarly, Batu Hitam, Jerangau, Rudua, and Lubok Kiat soil series exhibit a similar trend (data not shown).

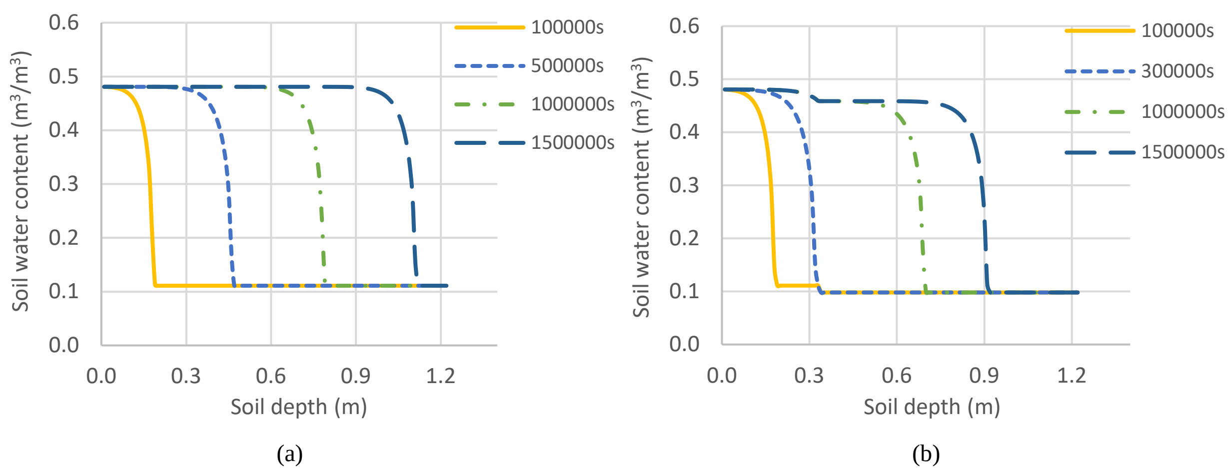


FIGURE 2. Water infiltration profile on Batu Hitam soil series. (a) Homogeneous soil. Single soil texture (Silty clay: 0-122 cm). (b) Heterogeneous soil. Dual soil texture (Silty clay: 0-33 cm, Clay: 33-122 cm).

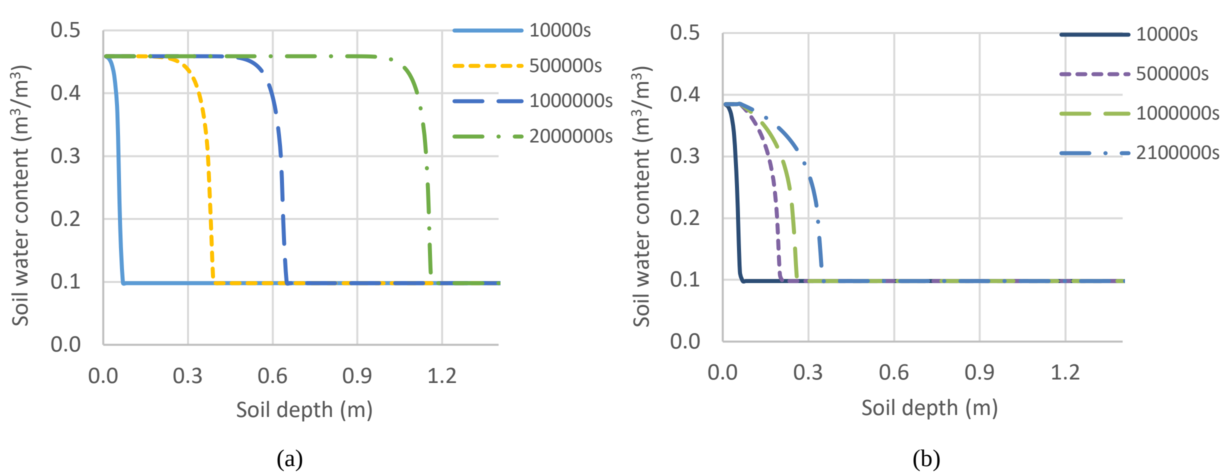


FIGURE 3. Water infiltration profile on Jerangau soil series. (a) Homogeneous soil. Single soil texture (Clay: 0-150 cm). (b) Heterogeneous soil. Dual soil texture (Sandy clay: 0-5 cm, Clay: 5-150 cm).

The water infiltration process in heterogeneous soil may deviate from that observed in the homogeneous soil. Figure 2 compares heterogeneous and homogenous soil series (Batu Hitam) refers to the time needed for soil water to reach specific soil depths. Batu Hitam heterogeneous soil appeared to have slowed down the water infiltration. At equal water infiltration time, the soil waterfront has reached 1.1 m on homogeneous soil, whereas only 0.9 m on heterogeneous soil. The second layer (Clay texture) in the Batu Hitam heterogeneous soil retards the water movement. This is because clay texture, which underlays the silty clay layer, has a lower hydraulic conductivity (that is to say, a slower water movement) than the upper soil layer (silty clay). The Jerangau soil series, however, the top 5 cm layer of sandy clay as upper layer soil reduces the subsequent water infiltration into the clay layer by a significant amount, refer to Figure 3. The soil matric suction of sandy clay at the top reduces the matric suction effect in the second layer (clay), a soil layer in a homogenous state that would reduce the time needed for water to infiltrate into the soil depth. The waterfront reduces from 1.8 (homogeneous) to 0.37 m (heterogeneous) soil depth at an equivalent time.

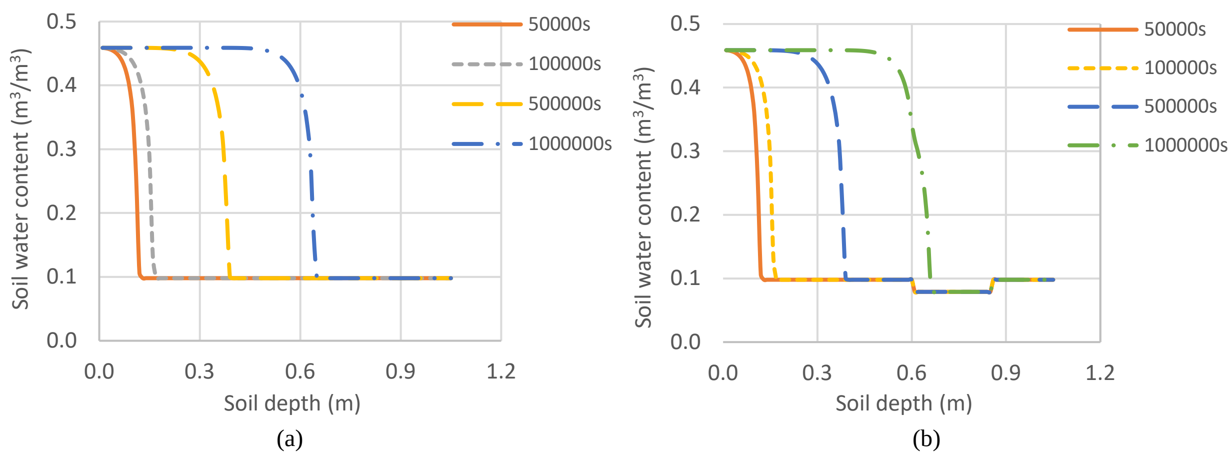
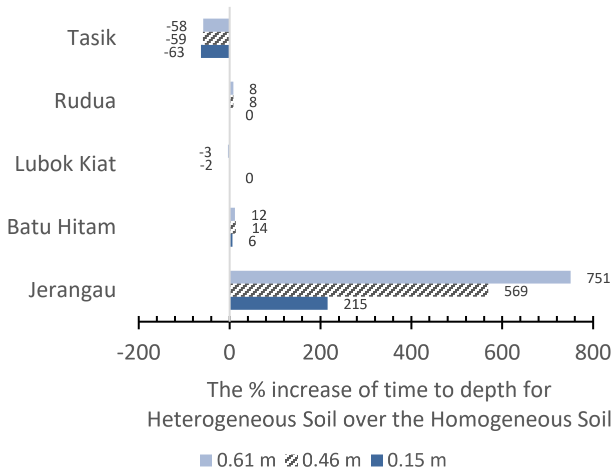


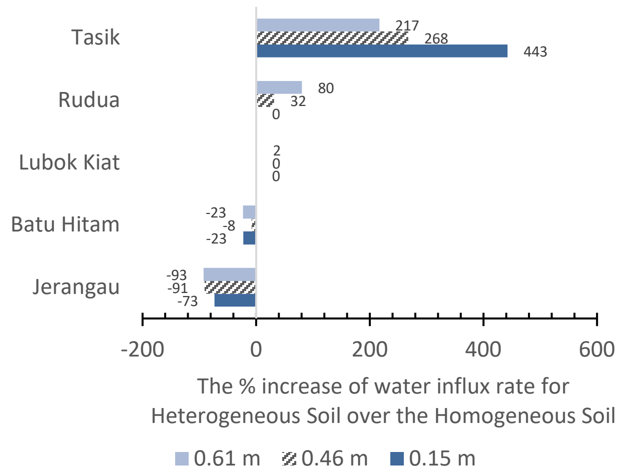
FIGURE 4. Water infiltration profile on Lubok Kiat soil series. (a) Homogeneous soil. Single soil texture (Clay: 0-105 cm). (b) Heterogeneous soil. Triple soil texture (Clay: 0-60 cm, Clay loam: 60-85 cm, Clay: 85-105 cm).

In contrast to Batu Hitam and Jerangau, Figure 4 on the Lubok Kiat soil series appeared to speed up the water infiltration in an insignificant amount. However, it was not apparent that the water infiltration front slightly increased from 0.65 m (homogeneous) to 0.67 m (heterogeneous) soil depth. A complete summary that estimates the percentage increment of time to soil depth from heterogeneous over homogeneous soil at different soil depths (0.15, 0.46, 0.61 m) observes in Figure 5(a). Consistent with the observation in Figures 2 to 4, the water travel time to soil depth observed was Batu Hitam (+14% at 0.46 m), Jerangau (+750% at 0.61 m), Lubok Kiat (-3% at 0.61 m). Furthermore, the soil series of Tasik (-63% at 0.15 m) and Rudua (+8% at 0.61 m).

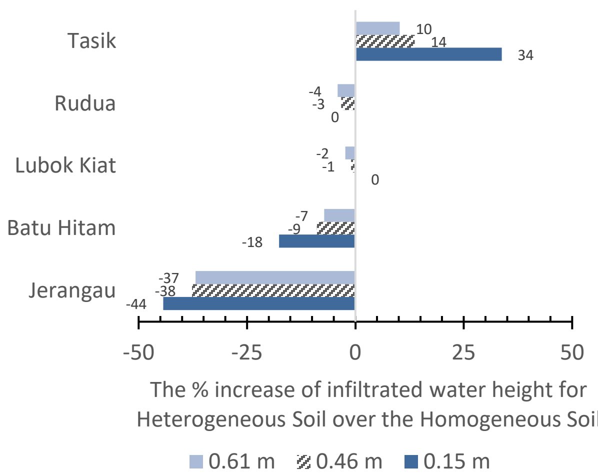
Moreover, soil heterogeneity influences the water infiltration rate, Figure 5(b), and the infiltrated water height, Figure 5(c). Water infiltration rate increased in the increasing sequence, Lubok Kiat (+2%), Rudua (+80%), and Tasik (+443%). In contrast, it decreases in Jerangau (-93%) and Batu Hitam (-23%). The infiltrated water height increases in Tasik (+34%), but it reduces in Jerangau (-44%), Batu Hitam (-18%), Rudua (-4%), and Lubok Kiat (-2%). The water infiltration process in Jerangau, Batu Hitam, and Tasik soil series appeared sensitive to soil heterogeneity horizon, whereas Lubok Kiat and Rudua were least sensitive, and they can be treated as homogeneous soil.



(a)



(b)



(c)

FIGURE 5. Percentage increment of parameter for heterogeneous soil over the homogeneous soil at 0.15, 0.46, 0.61 m. (a) Water travel time to soil depth. (b) Water influx rate. (c) Water volume over 1 m^2 area of land is equivalent to water height.

IV. CONCLUSIONS

Soil heterogeneity on water infiltration parameters was quantified based on three concerned soil depths related to agricultural water irrigation management. The parameters were the time for water to reach the soil depths, water infiltration rate, and infiltrated water height. The soil heterogeneity at Lubok Kiat does not appear to influence the parameters that percentages of variation were well within 3% at most. This implies that a similar soil texture at the concerned depth on both homogeneous and heterogeneous soil layers has a limited effect on water infiltration parameters. The Batu Hitam appears to be moderately affected by soil heterogeneity. It was an excellent case to demonstrate a soil underlay by a less permeable soil; for example, the clay would increase water infiltration time and influence the other two infiltration parameters. At

Tasik and Jerangau, soil heterogeneity has the most significant influence on the parameters. A large increase in time in Jerangau heterogeneous soil showed the importance of a thin layer of soil to as low as 5 cm on water infiltration. Out of the five heterogeneous soils, two soils could be assumed homogeneous; they are Lubok Kiat and Rudua, hence, simplifying modeling set in the investigation of water irrigation management.

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NOMENCLATURE

$\theta_L(\psi_m)$	soil moisture content (θ_L, $m^3 \cdot m^{-3}$) with soil matric suction (ψ_m) that is reported in negative pressure
L	an empirical constant relating to pore tortuosity or connectivity
z	either upward or downward length in meter
θ_s	the soil moisture content at full saturation ($m^3 \cdot m^{-3}$)
K_s	saturated hydraulic conductivity ($m \cdot s^{-1}$)
$K(\theta_L)$	unsaturated hydraulic conductivity (K) as a function of soil water content
α, n	equation fitting parameters
θ_r	the soil moisture content at the minimum level ($m^3 \cdot m^{-3}$)
m	equation constant that $m = 1 - 1/n$
t	simulation time in second
k	the center of the cell, which is oriented in the vertical direction
$k + 1/2$	the interface of a cell that is located in between cell k and $k+1$
$k - 1/2$	the interface of the cell that is located in between cell $k-1$ and k.
n, $n+1$	the existing and the new iterated variables, respectively.
Δt	time step size
Δz	spatial size

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