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Modelling Water Consumption Efficiency Based on Perlis State Soil Series

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ABSTRACT

Water is a limited resource for Perlis state. Domestically, meeting the water supply in the state requires improving the current supply facility and repairing water leakages in the supply system. However, an even more important aspect of water resources management is the water consumption from agricultural activities such as the over-irrigation in the crop field. This study identifies the soil series of Perlis state, determines its soil textures, estimates the field capacity, permanent wilting point, and plant available water. Additionally, the water infiltration studies were carried out. Results showed there were ten soil series present in the state, and this soil can be categorized by four soil textures that the clay soil texture dominates in seven soil series. Fully saturated soil in the Perlis state potentially losses 27-56% of its soil moisture content drains by gravity, which is unavailable to crop consumption, hence, wastage. An estimated 1.7×10^{-4} to 2.1×10^{-3} m/s water infiltration rate over the soil depths from 0.15-1.5 m. Knowing the soil surface area for the crop field allows the estimate of water volume needed in a unit time needed for storage tank estimation and distribution system designs. The water requirement increases by including the water evaporation rate into the water infiltration rate.

Keywords:
Crop plantation; water conservation; water-saving; water irrigation; Perlis cropland

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1. Introduction

The domestic water demand in Perlis state depends on its ability to expand the water treatment facility to increase its water supply capability and resolve the water supply system efficiency such as water leakage [1]. Water withdrawal directly from groundwater and water sources such as lakes or rivers contributes largely (approximately 70%) to agricultural activities [2]. Efficiency in water

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consumption on crop fields translates to significant water-saving for future generations and other socioeconomic developmental needs [3]. Water consumption efficiency views as crop production concerning minimal water consumed [4].

The current practice of over-irrigation on crop fields contradicts the desirable water consumption efficiency approach [5]. Over-irrigation on crop fields by farmers protected the high-value crop over a relatively cheap water supply. Additionally, over-irrigation potential in water ponding [6] on soil surface increases water evaporation, and deeper water penetration to the soil contributes to groundwater resources [7]. Moreover, over-irrigation could lead to landslide, especially in the sloppy area [8]. The water penetration into deeper ground potentially carries chemicals such as herbicides, pesticides, or soluble fertilizers to pollute the existing pristine groundwater [9]. Hence, supplying adequate water to the soil for crop growth while not polluting aquifer storage is the way forward. The ability to sense the amount of water in the soil would be beneficial [10], however, it comes with additional operational cost.

Water variability in the soil has an important implication between soil water availability and crop consumption. A tiny amount of water adhering to the soil creates a permanent wilting point (PWP) that water is unavailable to crop root absorption [11]. While filled soil pores result in eventual water drainage by gravitational pull until a new state forms known as field capacity (FC) [12], [13]. Efficient water supply to the crop field raises the soil moisture content to FC only because water supply over this level results in water lost by gravity. The soil moisture content ranged between FC and PWP is known as plant available water (PAW). It is plant available because it remains stationary and only mobile to plant root absorption or evaporation [14], [15].

In crop fields, water supplies penetrating the soil are only essential to meet the crop water demand. Depending on crops, roots depth in the soil varies with crop types. There are oil palm, rubber, tobacco, fruits, vegetables, flowers, and industrial crops such as areca nut, coconut, nipah, coffee, roselle, sago, sugar cane, and tea, in Perlis state [5]. Other than that, there are paddy, mushroom, and herbal [1], [16]. The crops covered a wide range of soil depths, such as paddy root depth of 0.15 m, pepper at 0.45 m, lemon at 0.6 m, and pineapple at 1.5 m [17]. The purpose of irrigation is to deliver infiltrated water into those soil depths.

The current study aims to investigate the Perlis state soil series wetness to meet crop water demand efficiently. The Perlis state soil series were identified and characterized, then, the FC, PWP and PAW were estimated. Further work includes the study of water infiltration to determine the time required for water to reach the plant root depth of concern, the amount of water that has infiltrated into the soil to reach the concern soil depth, and estimate the rate of cumulative water penetration into the soil. Current studies extend the work of Goh and Fadhli [18] to include the water infiltration into the soil.

2. Methodology

2.1 Soil Series Identification and Characterization

Soil series from Perlis state were determined from the Department of Agriculture, Malaysia [19]. The composition of sand, silt, and clay for each soil series was determined. The soil composition was used to determine the soil texture [20] that can be used to estimate the soil-water characteristic curve [21]. The characteristic curve parameters govern the relation of soil moisture content, and the soil suction head was represented by the van Genuchten equation [22].

The FC soil moisture content was determined at the soil suction pressure of -3.3 m, while PWP soil moisture content was identified at -150 m [23]. The difference in value given FC minus PWP provides the PAW [13] indicates the amount of water available in the soil to meet the crop demand for growth and yield.

2.2 Theory of Water Flux in the Soil

Water flux in the soil refers to the following equation [24],

$$m_L = -\rho K \frac{dh_m}{dz} + \rho K \tag{1}$$

where m_L represents the mass flux rate over a unit area (kg/m^2/s), the water has a density (ρ, kg/m^3), K is the saturated hydraulic conductivity (m/s), and dh_m/dz is the vertical spatial derivative of soil matric suction head (dimensionless).

Equation (1) was oriented downward positive. For upward orientation, the term ρK would become $-\rho K$. The first term on the right-hand side of Eq. (1) refers to water diffusion that is the movement of water from low pressure suction region to high pressure suction region. The second term on the right-hand side of the equation indicates the flow of water due to gravitational pull, hence, it presents in vertical coordinate direction. Exclude the gravitational pull when water flows in horizontal axis. Water flux by diffusion could either moving upward or downward, but gravity flow on water always directed downward.

A mass conservation equation over a unit volume of soil has the following relation [25],

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(K \frac{\partial h_m}{\partial z} - K \right) \tag{2}$$

where it has time t in s, and θ is the volume of water over a unit volume of soil (m^3/m^3). Equation (2) models the soil moisture content variation in space and time. The left side of Eq. (1) represents the rate of rising or falling of soil moisture content in a volume of soil, whereas the right side of Eq. (2) governs the flux of water mass in or out of the soil volume. A greater water influx than the outflux results in rising moisture content the left side of the equation, and vice versa. To model water dynamics or distribution in the soil, a soil depth discretized into vertical cells that each cell represents:

$$\frac{\theta_i^{n+1} - \theta_i^n}{t_{i2} - t_{i1}} = \frac{\left(K \frac{\partial h_m}{\partial z} - K \right)_{i+\frac{1}{2}} - \left(K \frac{\partial h_m}{\partial z} - K \right)_{i-\frac{1}{2}}}{\Delta z_i} \tag{3}$$

where i is the cell under investigation, θ_i^n is at time t_{i1}, θ_i^{n+1} is at time t_{i2}, $\left(K \frac{\partial h_m}{\partial z} - K \right)_{i+\frac{1}{2}}$ is the water mass flux on the right side of the cell, and $\left(K \frac{\partial h_m}{\partial z} - K \right)_{i+\frac{1}{2}}$ is the water mass flux on the left side of the cell. Equation (3) was programmed in FORTRAN 2018.

2.3 Water Infiltration into the Soil

Equation (1) was discretized and programmed to model water infiltration into the various soil series [26]. The parameter governs the water infiltration process given by the van Genuchten equation. Water infiltrated the soil top at FC, and the bottom of the medium was permeable to water flux [27]. As water infiltrate into the soil at FC, the rise of soil moisture content in the soil was observed. The time needed for water to penetrate 0.15, 0.45, 0.6, and 1.5 m soil depths were monitored for each soil series.

3. Results

3.1 Field Capacity, Permanent Wilting Point, and Plant Available Water of Soil Series

Ten soil series were found for Perlis state, and they were Chengai, Kangar, Hutan, Sogomana, Gajah Mati, Kundor, Tualang, Harimau, Telemong and Holyrood. The Gajah Mati has laterite gravel and stone that constitutes 60-80% all over the soil depth. The first seven soil series were clay soil textures. The Harimau soil series was sandy clay, while Holyrood and Telemong were sandy clay loam and sandy loam, respectively. The Holyrood has endopedon argillic that results in low clay content.

Table 1
Field capacity (FC), permanent wilting point (PWP), plant available water (PAW), and percentage of water available to plant

Parameters	Chengai, Kangar, Hutan, Sogomana, Gajah Mati*, Kundor, Tualang	Harimau	Holyrood	Telemong
FC (m^3/m^3)	0.33	0.28	0.23	0.17
PWP (m^3/m^3)	0.19	0.19	0.11	0.06
PAW (m^3/m^3)	0.14	0.09	0.12	0.11
FC/θ_s (%)	73	72	60	44

* The soil series contained laterite gravel and stone that constitutes 60-80% all over the soil depth. Hence, the FC, PWP, PAW, and FC/θ_s could appear less than that of a fully clayey soil.

The Chengai, Kangar, Hutan, Sogomana, Gajah Mati, Kundor, and Tualang have FC (0.33 m^3/m^3), PWP (0.19 m^3/m^3) and PAW (0.14 m^3/m^3) greater than Harimau, Telemong, and Holyrood (Table 1). The high PAW implies the soil's ability to store a large amount of water for plant absorption. Nonetheless, the FC, PWP, and PAW of Harimau, Telemong, and Holyrood remain comparably close to that of the former seven soil series.

Also, the FC/θ_s values of Harimau, Telemong, and Holyrood were lower than the previous seven soil series. The FC/θ_s percentage implies the pore space in the soil available to store water; hence Perlis soil series pore space could retain moisture from 44 to 73% of total pore space and be available for crop use. Accordingly, if all the soil space fills with irrigation water, 27-56% of the other pore space will empty by gravitational drainage. The ultimate purpose of irrigation was to supply the water to the soil depth to meet the crop root absorption.

3.2 Water Infiltration Study

A step further in this investigation was to conduct a water infiltration study. The infiltration study relates the time of water infiltration with the soil depth that has penetrated by the water. Estimating the amount of water that has infiltrated the soil, an additional estimation would be possible, which is the water infiltration rate. The water infiltration rate implies the amount of water required to supply to the field, which has important implication on the water storage tank, water sourcing, and distribution system. The water infiltration study investigates the water penetration rate at the soil surface after the water has penetrated to the soil depths of 0.15, 0.45, 0.6, and 1.5 m which has direct implication on the Perlis state crop's root depths (Figure 1). The figure does not indicate the rate at which water move, but it relates the water infiltration rate (m/s) and the depth at which water column penetrated the soil. Whereas Figure 3 showed the water infiltration rate over time, which imply the amount of water entering the soil surface reduces over time.

Telemong, Holyrood, and Harimau soil series allow water to penetrate the soil depth faster than the other soil series because the former have coarser soil textures than the latter (Table 2). Water penetration time increases across different soil series with soil depth, and the time gradient is more significant at deeper soil depth. Although Chengai, Kangar, Hutan, Sogomana, Gajah Mati, Kundor, and Tualang soil series stored more water, they take longer water penetration time than other soil series. The volume of water entering the soil, on the other hand, was increasing linearly with soil depth (Figure 2). Therefore, the water rate entering the soil surface decreases as water infiltration front reaches a deeper soil (Figure 3).

In an early state of dry soil, a greater increase in soil matric suction (-m), over a unit of increment in soil moisture content (m^3/m^3), than in higher moisture content, i.e. wet soil. Equation (1), the first term on the right-hand side, shows soil matric suction gradient (dh_m/dz) drives soil water diffusion; hence, a greater $dh_m/d\theta$ at early state on the soil surface drives a more significant water infiltration rate than in already wetted soil condition.

Table 2
The time (days) needed for water to infiltrate the soil depth

Soil series	Soil depth (m)			
	0.15	0.45	0.6	1.5
Chengai, Kangar, Hutan, Sogomana, Gajah Mati*, Kundor, Tualang	17	147	259	1562
Harimau	12	109	192	1176
Holyrood	9	78	136	810
Telemong	7	59	103	612

Note: the time is in a unit day. * The soil series contained laterite gravel and stone that constitutes 60-80% all over the soil depth. Hence, it could reduce the time to appear less than that of a fully clayey soil.

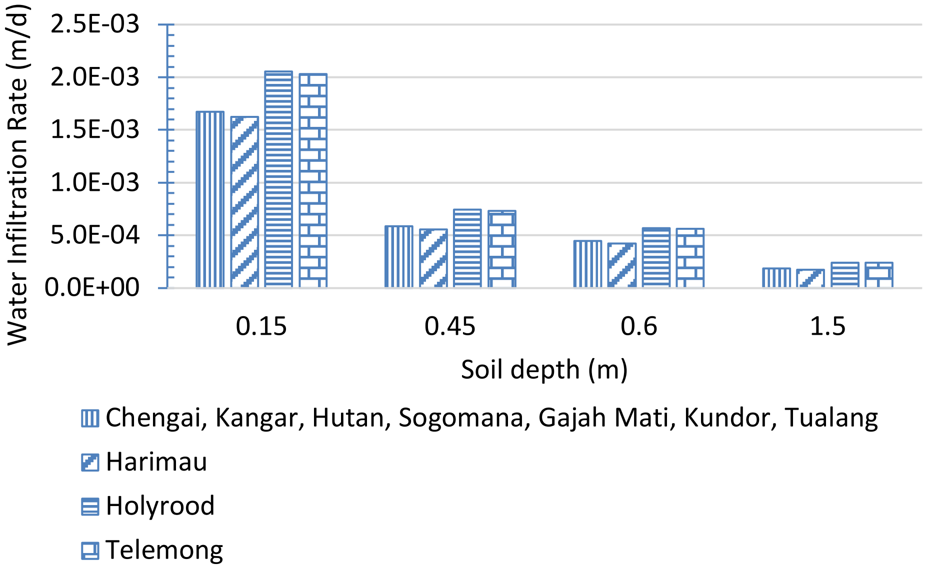

Fig. 1. Water penetration rate at the soil surface when the water from has reached a specific soil depths of 0.15, 0.45, 0.6, and 1.5 m. Note that Gajah Mati soil series contained laterite gravel and stone that constitutes 60-80% all over the soil depth. Hence, it could increase the water infiltration rate than that of a fully clayey soil

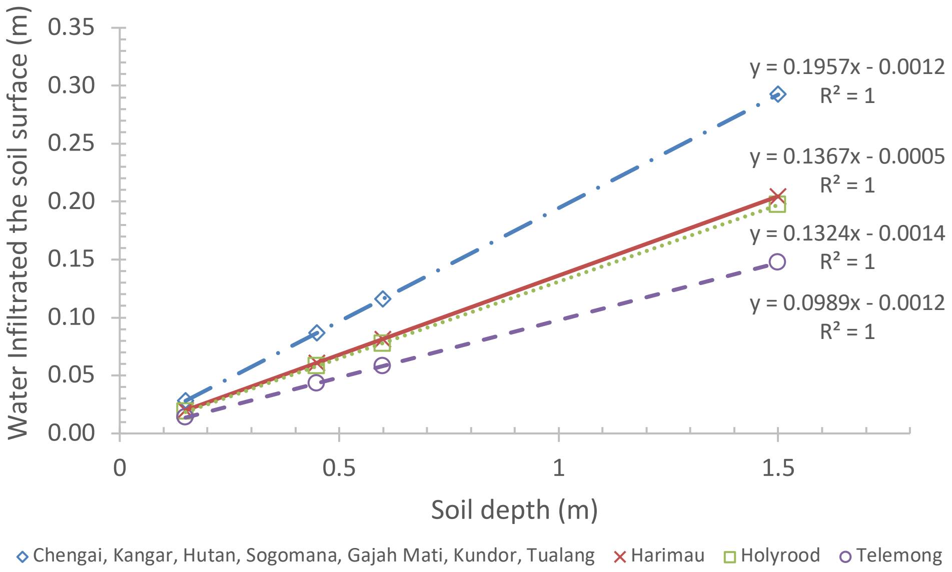

Fig. 2. The amount of water in height infiltrated into the soil surface after the water has reached the soil depths of 0.15, 0.45, 0.6, and 1.5 m, for different soil series

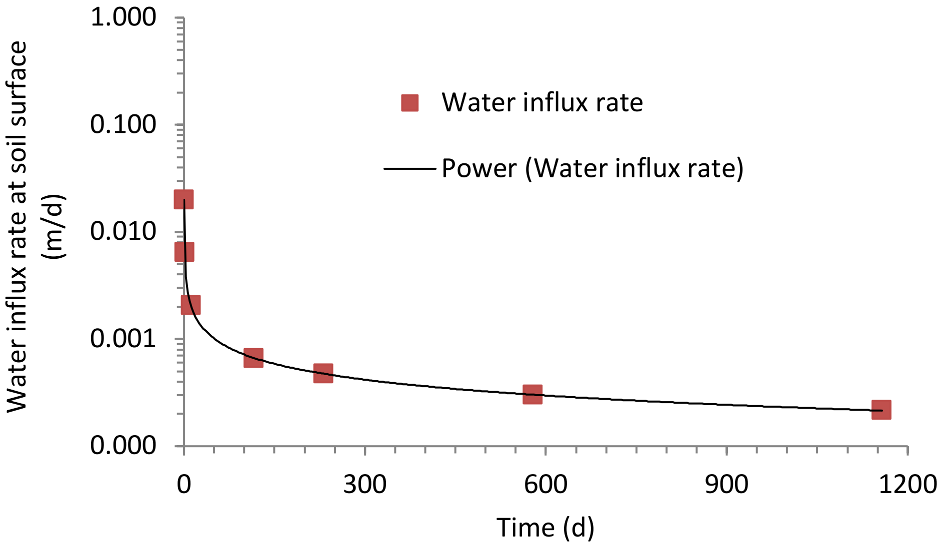

Fig. 3. Water infiltration rate at the soil surface at different times on Chengai, Kangar, Hutan, Sogomana, Gajah Mati, Kundor, and Tualang soil series

The current study excludes the contribution of rainfall. Also, evaporation was excluded from the estimation. The rainfall and evaporation contribution can be easily accounted for by taking the rate at which it enters the soil and leaving the soil in water meter depth per second, respectively.

Moreover, the effect of preferential flow was not considered because considering a common practice in agriculture to conduct tillage before seeding or planting, hence, the soil can be assumed to achieve a more homogeneous and freer from the effect of preferential flow.

The study also excludes the contribution from vapor flux and heat flux in the soil. The effect of dual-porosity can be considered under preferential flow, but dual-porosity is important only when considering solute transport.

4. Conclusions

Perlis state consists of ten soil series. The soil series divides into four soil textures, mostly in clay domination. The FC, PWP, and PAW show Chengai, Kangar, Hutan, Sogomana, Gajah Mati, Kundor, and Tualang store more water than the other soil series. However, these values were not significantly different from one another.

The ratio of soil moisture content's field capacity and soil porosity demonstrates 27-56% of the water used to fill the soils to saturation would be drained by gravity. The water was considered unavailable to plant consumption because the water retention time was shorter than the soil moisture content range between FC and PWP. Hence, the over-irrigation practice would indeed be a waste of water.

The current studies relate the magnitude of water infiltration rate to the water volume needed to supply to the crop fields in a unit of time that is useful to estimate water storage tank size and the potential water supply system. Also, the study reveals the falling water infiltration rate as water continues to infiltrate the soil from an initially dry state that signifies a huge capacity of soil to absorb water in dry state before it stabilizes as water continues to infiltrate deeper into the soil, when it achieves a constant water infiltration profile. Although the rate of water infiltration was gradually decline with time, the amount of water infiltrated the soil, in terms of water height, was linearly and positively correlated with the soil depth at which water has infiltrated the soil. Hence, by maintaining a constant soil moisture content at the soil surface was able to supply sufficient water to the soil depth but come at the cost of reducing water infiltration rate over time. An optimize or increasing water infiltration rate in reducing water penetration time is an important area of investigation for future study.

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