Vol. 12, No. 1 (2023) : 162 - 173 DOI : http://dx.doi.org/10.23960/jtep-l.v12i1.162-173

JURNAL TEKNIK PERTANIAN LAMPUNG

ISSN 2302-559X (print) / 2549-0818 (online)
Journal homepage : https://jurnal.fp.unila.ac.id/index.php/JTP

Infiltration Model of Mediterranean Soil with Clay Texture

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Article History :

Received : 24 October 2022
Received in revised form : 8 December 2022
Accepted : 3 January 2023

Keywords :
Horton model,
Philip model,
Infiltrometer,
Kostiakov model,
Tillage

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ABSTRACT

Infiltration plays an essential role in increasing the soil water content as a part of the hydrological cycle. Infiltration affects surface runoff and soil conservation. It also determines the sustainability of the groundwater system. Heavy rain intensity exceeding the infiltration capacity will result in surface runoff, and excessive surface runoff will cause soil erosion. This study aims to investigate the suitable infiltration rate model in the Mediterranean soil of clay textured with various soil conditions. Infiltration rate measurement employed a double-ring infiltrometer in soil without and with tillage. The applied infiltration rate model was an empirical model and the function of time, which includes the Kostiakov, Horton, and Philip Models. The results demonstrated that the Mediterranean soil infiltration rate with a clay texture was 0.91 cm/min and was relatively higher in the soil without tillage. The suitable infiltration rate model to be applied in soil conditions without and with tillage is the Kostiakov Model f = 0.700 t-0.25 and f = 0.682 t-0.22, respectively. The Kostiakov model is the most suitable infiltration rate model in Mediterranean textured clay, without tillage conditions, with a determination value of 0.988 and a deviation value of 0.005.

1. INTRODUCTION

The amount of water stored on the earth's surface is relatively constant. However, the water can occur in different states and bodies due to the hydrological cycle. The rain falls on the ground surface may accumulate on plants' leaves buildings, and some may directly infiltrate the soil (Jajarmizad *et al*., 2012), depending on the biophysical conditions of the soil surface. The rain falls on the surface moves into the ground through the soil pores (Kirkby, 2019; Vaezi *et al*., 2017). The infiltration process of rainwater into the soil is affected by gravity and ground capillary force (Kirkby, 2019; Vaezi *et al*., 2017). Gravity affects rainwater to move vertically into the ground, while the capillary force causes the water to move vertically and laterally (Haghnazari *et al*., 2015). Capillary force only works with ground structure with small pores.

The infiltration is one of the components in the hydrological cycle, and it is entering water into the soil will affect soil moisture (Sihag *et al*., 2017). Soil structure (Horton, 1941), soil bulk density (Gong *et al*., 2018), porosity, and organic carbon content with pores, affects the infiltration capacity of water saturation compared to dry soil (Fischer *et al*., 2015; Jung *et al*., 2007; Rai *et al*., 2017). The infiltration rate is essential in managing the surface runoff (Kirkham, 2014) soil and water conservation (Abu-Hashim, 2011; Asdak, 2002; Lowery *et al*., 2015). Infiltration on the soil determined the sustainability of the groundwater system (Archer *et al*., 2020; Wu *et al*., 1997). Therefore, the infiltration disruption could decrease groundwater potential and cause a higher chance of puddle formation and surface runoff, which eventually causes soil erosion (Pamungkas *et al*., 2016; Santi *et al*., 2013).

The infiltration rate varied according to the intensity of rainfalls. However, after reaching its limit, the infiltration rate will decrease depending on the absorption rate of each soil type. The infiltration rate depends on soil characteristics such as soil texture (Wakindiki *et al*., 2001), hydraulic conductivity, soil structure, ground cover vegetation (Jagdale & Nimbalkar, 2012). Infiltration capacity may vary even in a similar type of soil. These differences were due to the ground structure, soil texture, plants, and tillage conditions (Jagdale & Nimbalkar, 2012). Mediterranean soil is categorized as alfisol type (Soil Survey Staff, 1999). Alfisol soil can be found in humid and sub-humid climates. The average rainfall for Alfisol soil formation ranges from 800 to 2500 mm year^{-1} (Subardja *et al*., 2014).

The measurement of the infiltration rate can be performed through laboratory simulation, field measurement, and hydrograph separation using an infiltrometer (Lin, 2012). A number of infiltration models have been proposed and used in some hydrological analyses. These models can be grouped into three categories: empirical, semi-empirical, and physical models *(Sihag et al*., 2017). The empirical model has been quite popular and frequently used in various studies in water resources due to its simplicity and satisfactory results in most of their applications (Igboekwe & Adindu, 2014).

The Empirical model views the infiltration capacity as a function of time. Soil moisture levels have a dynamic property with time. The effect of temperature on the value of the diffusion coefficient of water depends on soil moisture (Dobrzański & Czachor, 1981). Therefore, the infiltration rate may be measured by the initial soil moisture condition when an infiltration process is started (An *et al*., 2021). Many infiltration models have been evaluated in soils from different locations with specific characteristics (Chahinian *et al*., 2005; Mishra & Singh, 1999; Shukla *et al*., 2003).

However, so far, research concerning infiltration models on clay-textured Mediterranean soils is still rare. This study aims to analyze the most appropriate infiltration rate model for Mediterranean soils with clay texture on soils both in zero-tillage and tillage systems. The study may provide contributive insight into soil conservation efforts in preventing and managing erosion (Ghorbani *et al*., 2008; Singh & Ryan, 2015; Suhardi *et al*., 2017). In dealing with climate change, floods, droughts, lack of clean water, and environmental damage both physically and biologically, one way is to utilize rainwater optimally using the zero run-off concept. Implementing the zero run-off system can also reduce natural erosion by eliminating surface runoff (Lestari *et al*., 2019; Suhardi *et al*., 2019).

2. MATERIALS AND METHODS

The experiment took place on the land in a research farm at Hasanuddin University

Makassar, Indonesia, with a coordinate of 5°7'39.9” S latitude, 119°28'51.5" E longitude, and elevation of about 25 m above sea level. The temperature at the research site was 24 – 31 °C, and the average rainfall rate was 311 mm month^{-1} or about 3.730 mm year^{-1} . The soil type employed in this experiment was Mediterranean soil (soil classification according to United States Department of Agriculture, USDA), with soil properties presented in Table 1. Soil properties tests were conducted at Chemistry and Soil Fertility Laboratory, Hasanuddin University, Makassar.

Table 1. Topsoil properties

No.	Soil properties	Value
1	Soil texture	Clay
	Clay (%)	58
	Silt (%)	30
	Sand (%)	12
2	Bulk density (g·cm^{-3})	1.2
3	Particle density (g·cm^{-3})	2.6
4	Soil porosity (%)	53.8

2.1. Materials and Equipment

The materials and equipment used in this study include double-ring infiltrometers 60 and 30-cm in diameter and 50-cm in height, hoe, rubber hammer, stopwatch, measuring cup, soil moisture meter, 50-liters clay crock, soil sample rings, label, and meter tape.

2.2. Design of Experiment

This experiment was performed at the soil conditions in both the soil undisturbed (no tillage = NT) and soil treated manually with a hoe (with tillage = WT) systems, each with three measurement points and three replicates. The infiltration rate was measured with the double ring infiltrometer method. Gregory *et al*. (2005) placed a ring infiltrometer with a diameter of 30 cm and 60 cm concentrically into the soil until ±30 cm of the ring remained above the soil surface. Soil moisture was measured subsequently. Water was filled into the ring until it reached as high as ±20 cm, and water level decline was measured per unit of time every 2 min. The water was filled again into an infiltrometer ring until it reached the initial height. Measurement was performed until a constant rate of decline in water was identified.

2.3. Formula of Infiltration rate models

In determining the infiltration rate, some equation formulas were applied. These include Kostiakov's, Horton's, and Phillip's models.

2.3.1. Kostiakov’s Model

The empirical infiltration equation developed by Kostiakov is based on curve fitting field data. The infiltration equation of Kostiakov is (Kostiakov, 1932):

$$f(t) = kt^{\alpha - t} \quad (1)$$

where k and α are empirical constants that are influenced by soil properties such as texture, bulk density, and wetness. The parameters are derived from infiltration data that has been measured.

2.3.2. Horton's Model

This equation model was developed by (Horton, 1941).

$$f(t) = f_c + (f_0 - f_c)e^{-kt} \tag{2}$$

where f is the infiltration rate (m/s); f_c is the final or constant infiltration capacity (m/s); f_0 is the initial infiltration capacity (m/s); k is a constant that represents the rate at which f capacity decreases (m^{-1}). Fitting experimental infiltration data determines the parameters.

2.3.3. Philip's Model

Philip's infiltration equation can be seen as the following (Philip 1957):

$$f(t) = \frac{1}{2} s t^{-0,5} + C_a \tag{3}$$

where s is the soil sorptivity ($m/s^{1/2}$); C_a is the constant infiltration rate (m/s). The parameters depend on soil water diffusivity and the initial volumetric water content.

The obtained data were used to determine the coefficient of infiltration function for all models through the linearization method. Infiltration rate was measured with varying initial water content, as for the measurement value and the infiltration models performed curve fitting with Microsoft Excel and Curve Expert.

2.4. Accuracy of Models

A comparison was made between the measurement and model. To determine the most accurate model, an equation was applied based on the determination value (R^2) and the deviation value (P) (Supranto 2000).

$$P = \frac{100}{N} \sum \frac{(f_{ob} - f_{cal})^2}{f_{ob}} \tag{4}$$

where P is the error value; f_{ob} is the measurement value; f_{cal} is the computation value; N is the total data.

3. RESULTS AND DISCUSSION

3.1. Infiltration Rate

Soil moisture is one factor affecting the capacity and infiltration rate. This study showed that the lower the soil moisture is, the higher the soil absorption rate will be, and therefore, the infiltration rate becomes faster. As shown in Figure 1., the soil pores are initially filled with water with a fast infiltration process in all soil conditions. However, the infiltration speed became slower over time, and the infiltration would become constant.

Based on the study performed by Elfiati & Delvian (2010) and Tate (2005), soil filled with water and the blockage of soil pores will decrease the infiltration rate, and the infiltration will be constant. Infiltration rate in zero/ no-tillage soil and soil with tillage is presented in Figure 1.

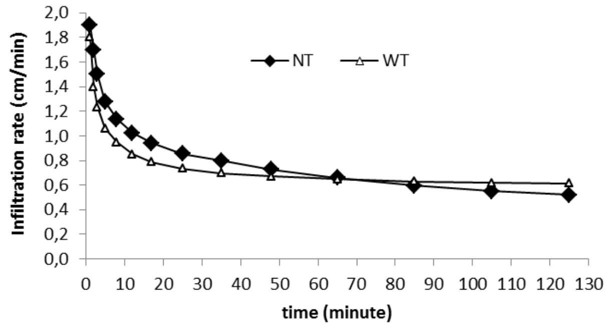

Figure 1. Infiltration rate in soil conditions zero tillage (NT) and with-tillage (WT)

The average infiltration rate for all soil conditions was 0,91 cm/min. The infiltration rate is relatively low due to the soil condition at the research site. A similar finding in the study performed by Syukur (2009) confirmed that the infiltration rate of Mediterranean soil is relatively low due to silt and clay content. Sandy loam can produce 23% higher infiltration than clay and silt loam (Zhao et al., 2002). Clay has a high water-holding capacity and could block water flow and reduce infiltration rates. Most clay soils have ventilation problems, and most crops have difficulty growing in this soil condition. So, the increase in macropores is significant for the balance between air and water in the clay. The balance between air and water in the soil causes more plant productivity (Biglouei et al., 2008). Figure 2 indicated the differences in infiltration rates in no-tillage (NT) and with-tillage conditions (WT). These were due to the difference in initial moisture content, where soils with NT contained 14% and 15% for soil with tillage (WT). In general, no-tillage systems are not suited for poorly drained soils. According to Lal (1994), compared to conventional tillage up to 10-15 cm in depth, sub-soiling up to 35-40 cm increases the infiltration rate by 7 to 10 fold, and chiseling to a depth of 25-30 cm increases the infiltration rate to 2 to 3 fold. Soil moisture substantially impacted the infiltration rate (Lal & Stewart, 2013). As confirmed by Kirkham (2014); Leuther *et al*. (2018); Wakindiki et al. (2001) that infiltration rate can be affected by soil texture and other environmental factors, including ground cover vegetation (Jagdale & Nimbalkar, 2012; Li *et al*., 2009), rainfall intensity, soil moisture (Haghnazari *et al*., 2015), water content (An *et al*., 2021; Carvalho *et al*., 2015) and groundwater depth.

The infiltration rate in no-tillage soil was 0.95 cm min^{-1}, while soil with a tillage system was 0,87 cm/min. Tillage has the greatest impact on soil infiltration, which increases with intensity (Abid & Lal, 2009). The difference in infiltration rate apart from being affected by soil texture and moisture (Ahuchaogu & Etim, 2015; Haghnazari *et al*., 2015; Wakindiki *et al*., 2001) is also affected by the treatments applied to the soil. Tillage depletes soil aggregate stability and causes plugging soil pores at the surface, and thus, it reduces infiltration rates. Among the crop production factors, tillage contributes up to 20% (Khurshid *et al*., 2006), and zero-tillage could improve soil aggregation (Cooper *et al*., 2021; Cullum, 2009), water holding capacity, organic materials, and therefore, it contributes to soil erosion (Issaka *et al*., 2019).

3.2. Infiltration Rate Model

Several experts reproduced an infiltration mechanism in a model. According to Sihag *et al*. (2017), the model can be employed in certain conditions such as soil type, land cover, and geographic location with varying levels of model accuracy.

The calculation model for soil infiltration (NT), from three different points of measurement and the results of nine equations for each model, were acquired. And each infiltration model parameter can be seen in Table 2. To simulate cumulative infiltration depth for each point, the estimated values of the infiltration model's parameters were included into the model equations for all three models. The field data were compared to the model's simulated data to assess the model's ability to mimic cumulative infiltration.

Table 2. The parameters of infiltration models on NT condition

Point	Kostiakov		Horton			Philip	
	K	A	f_0	*Fc*	K	S/2	C
A1	1.180	0.61	1.0	0.18	0.05	1.240	0.101
A2	0.700	0.75	0.4	0.21	0.05	0.145	0.187
A3	0.490	0.84	0.5	0.22	0.05	0.365	0.195
B1	3.711	0.78	3.5	1.18	0.05	3.503	0.882
B2	1.409	0.84	1.5	0.67	0.05	1.032	0.591
B3	0.482	0.85	0.5	0.23	0.04	0.339	0.214
C1	3.462	0.71	3.0	0.73	0.05	3.500	0.514
C2	1.995	0.74	1.9	0.52	0.05	1.912	0.386
C3	1.519	0.80	1.5	0.56	0.05	1.307	0.471

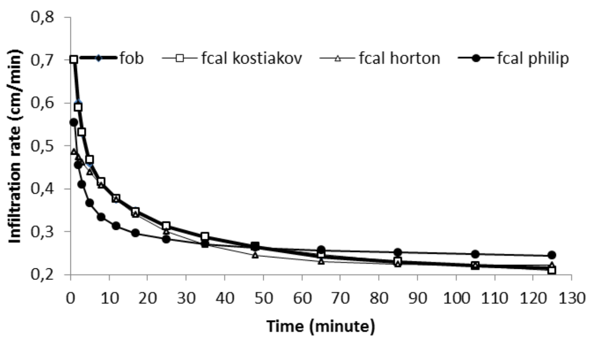

Figure 2. Infiltration rate in soil condition zero tillage (NT)

The comparison observed and predicted infiltration rate for three evaluated models further verified the prediction capability of these infiltration models (Figure 2). The figure presented fob as infiltration rates of measurement results and fcal Kostiakov as infiltration rates by Kostiakov model. The fcal Horton line presented the infiltration rates by Horton model and fcal Philip presented the infiltration rates by Philip model.

Using the estimated model's parameters, all three infiltration models demonstrated good agreement with the measured cumulative infiltration rate in the field. The one model to full the accuracy criteria was selected. The obtained constant value and equation for the Kostiakov, Horton, and Philip models can be seen in Table 3. A model may be considered good if the deviation of a measurement result is minimum. Kostiakov model had the smallest deviation value 0.018 compared to Horton and Philip model. In addition, the Kostiakov model has the highest coefficient of determination R^2 0.99 with the lowest error standard 0.005% compared to the other two models. Therefore, the Kostiakov model is the accurate model to measure the infiltration rate in no-tillage soil with a model infiltration rate f = 0.700 $t^{-0.25}$. The prediction of infiltration using model parameters demonstrates that model parameter variation is in accordance with regional soil conditions. According to the statement of Farid *et al.* (2019) the infiltration model's parameters were able to forecast cumulative infiltration depth with high accuracy, demonstrating the need to adjust the parameters based on the soil characteristics in the area.

Table 3. Comparison of some models of soil infiltration rate on NT condition

No.	Model	Model Equations	R^2	SE	P(%)	|*Dev*|
1.	Kostiakov	$f = 0.700\ t^{-0.25}$	0.988	0.003	0.005	0.018
2.	Horton	$f = 0.22 + (0.5 - 0.22)\ e^{-0.05\ t}$	0.956	0.384	0.761	0.934
3.	Philip	$f = 0.339\ t^{-0.5} + 0.214$	0.946	0.041	1.156	1.128

Kostiakov model is the closest model in measurement value compared to the Horton and Philip models. According to Zhang *et al.* (2012), The Philip model and empirical models (Kostiakov and Horton models) were both utilized to estimate infiltration functions in surface irrigation, with the Kostiakov model showing the best link between time and cumulative infiltration.

On the infiltration measurement of the soil with tillage, model parameters and the equations fulfilling the accuracy criteria were obtained, and the results are presented in Table 5. Based on the evaluation of the soil with tillage, the Kostiakov model was considered the most accurate model to determine infiltration rate compared to Horton and Philip models. This is because of the lowest deviation and standard error value while it has the highest determination value. Figure 3 shows the infiltration rate of the Kostiakov model with the closest result with measurement value.

Table 4. The parameters of infiltration models on WT condition

Point	Kostiakov		Horton			Philip	
	k	α	f_0	*Fc*	K	S/2	C
A1	1.753	0.71	1.5	0.44	0.05	1.760	0.338
A2	0.934	0.76	1.0	0.30	0.05	0.838	0.241
A3	0.732	0.85	0.8	0.36	0.04	0.505	0.325
B1	1.082	0.74	1.0	0.29	0.05	1.049	0.222
B2	0.928	0.77	1.0	0.32	0.05	0.805	0.257
B3	0.682	0.78	0.7	0.24	0.04	0.592	0.197
C1	1.055	0.67	0.9	0.20	0.05	1.081	0.136
C2	0.488	0.78	0.5	0.17	0.05	0.419	0.145
C3	0.367	0.81	0.4	0.15	0.04	0.283	0.132

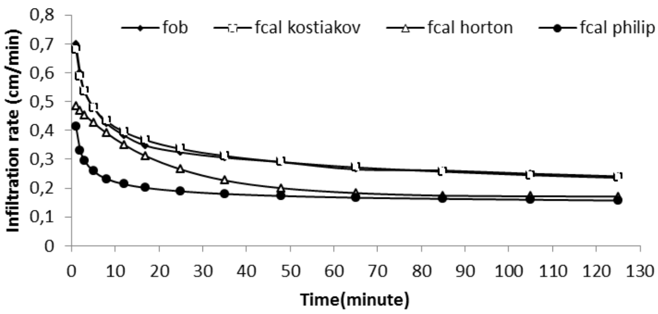

Figure 3. Infiltration rate in soil condition with tillage (WT)

Table 5. Comparison of some models of soil infiltration rate on WT condition

No.	Model	Model Equations	R^2	SE	P(%)	|*Dev*|
1.	Kostiakov	$f = 0.682\ t^{-0.22}$	0.985	0.007	0.024	0.082
2.	Horton	$f = 0.17 + (0.5 - 0.17)\ e^{-0.05\ t}$	0.979	0.027	0.365	0.188
3.	Philip	$f = 0.283\ t^{-0.5} + 0.132$	0.929	0.043	1.165	1.033

Based on Table 3 and Table 5 Kostiakov model is the most accurate model to measure the infiltration rate in no-tillage and tillage. So, the Kostiakov model is an appropriate model or approach to measuring the infiltration rate. Zhang *et al*. (2012) confirmed that the best link between time and cumulative infiltration is shown by the Kostiakov model. Musa & Adeoye (2010) also in infiltration equations to the soil, Kostiakov's model outperforms Philip's and Horton's models, according to the findings. The evaluation of the infiltration model on course-textured and homogenous soils by Al-Azawi (1986) found that Kostikov's model gave a very good representation of infiltration compared the Philip's model.

4. CONCLUSION

Mediterranean soil with clay texture has an infiltration rate of 0.91 cm min^{-1} and is relatively higher at the no-tillage system reaching 0.95 cm min^{-1} at the initial moisture content of 14%. Kostiakov model is a suitable infiltration rate model that can be applied in both no-tillage and with-tillage systems, each with $f = 0.700\ t^{-0.25}$ and $f = 0.682\ t^{-0.22}$. It is also very suitable in the zero tillage cases, with the determined values of 0.988 and deviation value of 0.005.

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