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Evaluation of infiltration models for mineral soils with different land uses in the tropics

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Abstract

The aims of this study were to evaluate five infiltration models for mineral soils in the tropics with different land use types, such as settlements, plantations, rice fields, and forests. The infiltration models evaluated were Green–Ampt, Kostiakov, Kostiakov–Lewis, Philip, and Horton. The research was conducted at the Amprong watershed, Malang, Indonesia. The infiltration rate of the thirteen soil samples was analysed. The infiltration was tested using Turf-Tech infiltrometer. Moreover, each soil sample was tested in terms of the bulk density, specific gravity, porosity, soil moisture, and soil texture. The results of the study indicate that there is no significant difference ($\alpha = 5\%$) in the infiltration rate among the five models of infiltration. The infiltration rate in the study site was considered fast. Three models exhibiting the best performance are Kostiakov, Kostiakov–Lewis, and Horton model, respectively. The highest infiltration rate occurred in the forest land use while the lowest occurred in the rice field land use. The results of this study suggest that the infiltration model parameters correlate closely with the initial infiltration rate (*fo*) and the final infiltration rate (*fc*). In other words there is a correlation between the soil's ability to absorb water (representing the capillary force or horizontal flow) at the beginning of the infiltration (*fo*) and the gravity or the vertical flow upon reaching the final infiltration rate (*fc*).

Key words: *infiltration models, land use, mineral soil, tropical climate*

INTRODUCTION

Land use affects the rate of erosion, the level of soil moisture, the availability of soil nutrients, the return of biomass to the soil, interception, and the soil structure [PRIJONO *et al.* 2015]. Changes in land use can reduce the soil quality and increase the soil degradation [AGHASI *et al.* 2010], causing a devastating impact on the physical and chemical characteristics, fertility and erodibility of soil. The results of several studies suggested that changes in land use in tropical ecosystems result in changes in soil characteristics. The most rapid change occurs in the chemical and biological characteristics of the soil [SCHIPPER, SPARLING 2000]. The changes in land use also influence the amount of runoff [LI *et al.* 2009].

Infiltration is the process by which water (generally derived from rainfall) flows into the soil as a result of capillary force (water movement in the vertical direction). Once the topsoil is saturated, the excess of water flows deeper into the ground as a result of the gravity; this process is known as the percolation process [Asdak 2002].

The infiltration rate is influenced by a number of factors such as the physical characteristics of the soil, rainfall, vegetation cover, initial soil moisture, and fertilization [Czyżyk, Świerkot 2017; Oruk 2011]. The physical characteristics of soil are affected by the soil textures which consist of mineral particles including sand, silt, and clay [Haghnazari *et al.* 2015]. Another factor influencing the infiltration is land use [Thornleya, Cannell 2010].

According to Indonesian Centre for Agricultural Land Resources Research and Development (Ind. Balai Besar Litbang Sumberdaya Lahan Pertanian Indonesia), the soil in Indonesia, in terms of its parent material, is divided into two major groups, namely organic soil (peat soil) and mineral soil [Subardja *et al*. 2014]. Mineral soil is made up of horizons consisting of 20 to 35% organic matter, or in other words, the horizons of mineral soil are approximately 65 to 80% [USDA, NRCS 2010]. The fact that Indonesia's land area lies across the equator provides benefits in terms of the tropical wet climate and the high temperature which can accelerate the process of weathering of rocks and provide a high biodiversity. In addition, the high diversity of soil parent materials provides a wide variety of nature and types of soil formed. Each type of soil has its own distinctive characteristics and properties [Subardja *et al*. 2014]

This study aimed at evaluating five infiltration models for mineral soils in the tropics with different land uses.

RESEARCH MATERIALS AND METHODS

RESEARCH MATERIALS AND SETTING

The research was conducted in a 349 km^2 watershed in Amprong, Malang. The measurements were carried out in January to March 2017. The soil samples were analysed in Soil Physics Laboratory, Department of Soil Science, Faculty of Agriculture, University of Brawijaya. The type of tests, method, and the equipment used in this research are listed in Table 1.

The research materials were a map of the research setting and soil samples. The apparatus used consisted of a soil-sampling ring kit, and a turf-tech for measuring infiltration rate [Fulazzaky *et al*. 2014]. The infiltration measurement was for one hour.

The rainfall data from 2000–2014 were obtained from National Agency of Water Resources Development (UPT PSAWS) of Bango-Gedangan, Malang, while the data on temperature, evaporation, relative humidity, and wind speed from 2005 to 2015 were obtained from the Agency for Meteorology, Climatology and Geophysics or BMKG located in Karangploso, Malang.

Five types of minerals soils samples were collected from different land uses i.e. settlements, plantations, rice fields, and forests (Tab. 2). According to the Roscoe method [Roscoe 1975], a sample size of over 30 and less than 500 samples are appropriate for most studies. Due to the research schedule and the cost estimation consideration, the sampling has only collected in 39 locations with triplicates. It was reported by Lemeshow *et al*. [1990] that the number of 39 sample with 95% confidence level will produce a margin error at approximately ±16%.

The research setting was located at an elevation between +500 m and +1500 m a.s.l. with the coordinates of longitude 112.65–112.94° East and latitude 7.89–8.06° South.

The data in this quantitative descriptive study were collected through the field survey. The soil sampling locations were selected by using simple stratified random sampling based on the type of mineral soil (5 types of mineral soils).

MODEL DESCRIPTION

The five infiltration models evaluated in this study were the Green–Ampt, Kostiakov, Kostiakov–Lewis, Philip, and Horton model.

1) The Green–Ampt model

Green and Ampt [1911] developed a physical theory that can be solved with an exact analytical so-

Table 1. The list of instruments used in the research

Test types	Method	Equipment
Bulk density (ρ_{bulk})	undisturbed soil (sample ring)	3-inch diameter ring with depth of 3 inches, analytical balance (0.1 g precision), microwave oven
Particle density (ρ_{particle})	undisturbed soil (sample ring)	scale (0.1 g precision), microwave oven, volumetric flask (100 cm^3), graduated cylinder (0.1 cm^3 scale)
Porosity (ϕ)	$\phi = 1 - \frac{\rho_{bulk}}{\rho_{particle}}$	–
Soil moisture	gravimetric	similar equipment of bulk density test was used
Soil texture	pipette method, grain sieve analysis, chart of USDA soil texture	500 cm^3 Erlenmeyer flask, 10 cm^3, 50 cm^3, and 1.000 cm^3 graduated cylinder, beaker glass, 0.05 mm sieve, mechanical sieve shaker, pipette, analytical balance (0.1 g precision), stirrer, microwave oven
Organic matter	Walkley–Black method	Erlenmeyer flask, 10 cm^3 $K_2Cr_2O_7$ 1 N, 20 cm^3 H_2SO_4, aquades
Statistical tests and programs	mean, standard deviation, graph, *RMSE*, *NSE*, r^2	spreadsheet software

Explanations: *RMSE* = root mean square error, *NSE* = Nash–Sutcliffe efficiency coefficient, r^2 = determination coefficient.
Source: Soil Physics Laboratory, Faculty of Agriculture, University of Brawijaya.

Table 2. Types of mineral soil and land use in Amprong watershed

No	Type of mineral soil	Land use	Code	Number of samples
1	dark-grey alluvium	settlements	AP1-PMK	3
		plantation	AP1-KBN	3
		rice field	AP1-SWH	3
		forest	–	–
2	association of reddish brown latosol and brown latosol	settlements	AP2-PMK	3
		plantation	AP2-KBN	3
		rice field	–	–
		forest	–	–
3	brown regosol	settlements	AP3-PMK	3
		plantation	AP3-KBN	3
		rice field	AP3-SWH	3
		forest	–	–
4	reddish brown latosol	settlements	AP4-PMK	3
		plantation	AP4-KBN	3
		rice field	–	–
		forest	–	–
5	association of brown andosol and brown regosol	settlements	AP5-PMK	3
		plantation	AP5-KBN	3
		rice field	–	–
		forest	AP5-HTN	3

Explanations: the code shows consecutively the name of the watershed, the type of mineral soil, and the land use. Example: AP1-PMK; AP = amprong watershed, number 1 = first mineral soil type (dark gray alluvium), PMK = settlements; "–": the type of land use is not available.
Source: own study.

lution to determine infiltration [BRAKENSIEK, ONSTAD 2000]. The Green–Ampt model can be expressed as [VAGHEFI, RAHIDEH 2011]:

$$f(t) = K\left(\frac{\psi\Delta\theta}{F(t)} + 1\right) \tag{1}$$

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

$$\Delta\theta = \eta - \theta i \tag{3}$$

Where: $f(t)$ = the infiltration rate (mm·min^{-1}); $F(t)$ = the cumulative infiltration (mm); K = the hydraulic conductivity (mm·min^{-1}); η = the degree of porosity, θi = the initial moisture content, ψ = the suction head (mm), t = the time (min).

The values of K and $\psi\Delta\theta$ were obtained from observational data.

2) Kostiakov model

KOSTIAKOV [1932] proposed the following empirical infiltration equation [SUBRAMANYA 2013]:

$$f(t) = abt^{b-1} \tag{4}$$

Where: $f(t)$ = the infiltration rate (mm·min^{-1}); t = the time (min), a and b = the empirical parameters ($a > 0$ and $0 < b < 1$).

3) Kostiakov–Lewis model

Kostiakov empirical equation has a limitation i.e. the longer the time. The lower the infiltration rate (nearly zero). This contradicts the fact that the infiltration rate will reach a constant value on a much longer time scale. To fix this drawback, the Kostiakov equation was modified into the Kostiakov–Lewis model [WALKER, SKOGERBOE 1987]:

$$f(t) = abt^{(b-1)} + fc \tag{5}$$

Where: fc = the final infiltration rate (mm·min^{-1}), t = the time (min).

4) Philip model

Philip model [PHILIP 1957] was developed from the RICHARD [1931] equation, with the assumption that the soil moisture profile will approach a constant state and move downward at a constant speed after a long time [HADISUSANTO 2011]. The form of Philip equation is:

$$f(t) = 0.5St^{-0.5} + A \tag{6}$$

Where: $f(t)$ = the infiltration rate (mm·min^{-1}); S = the sorptivity which is soil suction potential (mm·min$^{-0.5}$), A = the saturated hydraulic conductivity (mm·min^{-1}).

5) Horton model

HORTON's [1940] observation about infiltration showed that the infiltration begins at an initial rate (fo) and decreases exponentially until it reaches a constant value (fc). Horton proposed an empirical equation for a condition where the rainfall intensity is greater than the infiltration rate $f(t)$ [ABDULKADIR *et al.* 2011]:

$$f(t) = fc + (fo - fc)^{-\alpha t} \tag{7}$$

Where: $f(t)$ = the infiltration rate at time t (mm·min^{-1}), fo = the initial infiltration rate (mm·min^{-1}), fc = the final infiltration rate (mm·min^{-1}), α = a constant of the infiltration rate (min^{-1}) which depends on the characteristics of the soil and plant cover.

EVALUATION OF MODEL PERFORMANCE

The model performance in this study was evaluated based on the following efficiency criteria [KRAUSE *et al.* 2005]:

1) The coefficient of determination (denoted by r^2)

The coefficient of determination (r^2) is formulated as follows:

$$r^2 = \left(\frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}\sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2}}\right)^2 \tag{8}$$

Where: n = the number of observation data during the period under review, O_i = the observed value of the i^{th} model, $\bar{O}$ = the average observed value, P_i = the output value of the i^{th} model, $\bar{P}$ = the average output value.

2) Nash–Sutcliffe efficiency coefficient (*NSE*)

NSE coefficient, originally proposed by NASH and SUTCLIFFE [1970], is formulated as follows:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \tag{9}$$

The range of *NSE* lies between 1.0 (perfect fit) and –∞.

3) Root mean square error (*RMSE*)

RMSE is expressed as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \tag{10}$$

RMSE value = 0 indicates a very satisfactory model performance.

The statistical criteria for assessing the model performance are summarised in Table 3 [SILVA *et al.* 2015].

Table 3. The criteria for assessing the performance of hydrological models

Statistical criterion	Value	Classification
Coefficient of determination (r^2)	$0.00 \le r^2 \le 0.50$	unsatisfactory
	$0.50 < r^2 \le 1.00$	satisfactory
Nash–Sutcliffe efficiency coefficient (*NSE*)	$0.75 < NSE \le 1.00$	very good
	$0.65 < NSE \le 0.75$	good
	$0.50 < NSE \le 0.65$	satisfactory
	$0.40 < NSE \le 0.50$	acceptable
	$NSE \le 0.40$	unsatisfactory
Root mean square error (*RMSE*)	values below half standard deviation of the observed data	satisfactory

Source: own elaboration based on SILVA *et al.* [2015]

RESULTS AND DISCUSSION

CLIMATOLOGY

The average annual precipitation in the study site varies between 1,000 and 1,300 mm·year^{-1}. Due to the influence monsoon, the rainy season occurs from November to March, while the dry season occurs from April to October. The type of climate of the study site, according to the Schmidt–Ferguson classification, is included in the C/D category which means a semi-humid area, while based on the Oldeman method, it belongs to the type C3 which is a wet area (5–6 months) [BMKG 2016]. Judging from Koppen–Geiger climate classification, the climate of the study site is categorised into Aw group i.e. a tropical climate area with longer dry season [PEEL *et al.* 2007].

CHARACTERISTICS OF SOIL

The results of the infiltration tests in the field and the soil characteristics testing in the soil physics laboratory are presented in Table 4 and Figure 1. Figure 1 shows the coefficient determination (r^2) of the relationship between soil properties and infiltration rate. The figure revealed that the infiltration rate of the soil was influenced by several soil properties: 54, 83% of bulk density, 46.57% of porosity, and 24.58% of soil moisture. Whereas the remaining percentage from each soil properties of 45.17%, 53.43%, and 76,42% respectively from bulk density, porosity, and soil moisture were not considered in this study due to they were influenced by the other variables.

Texture. In general, the texture of mineral soils at the study site was dominated by silt fraction (51%), sand (32.23%), and clay (16.77%).

Bulk density. HARDJOWIGENO [2002] stated that the bulk density indicates the degree of soil compaction. The higher the bulk density, the more solid the soil, which means the more difficult the movement of water into the soil. The soil in the settlements had the highest average bulk density of 1.26 g·cm^{-3}, while the average bulk density in the plantation was 1.13 g·cm^{-3}, in the forest was 1.03 g·cm^{-3}, and in the rice field was 1.02 g·cm^{-3}.

Porosity and soil moisture. Soil porosity is associated with the ability of soil to absorb water. The soil porosity is also closely related to the bulk density. The more solid the soil, the more difficult the movement of water into the soil. and thus the smaller the soil porosity. The level of soil moisture content (the degree of saturation) affects the rate of infiltration; the more saturated the soil, the lower the infiltration rate [HAGHNAZARI *et al.* 2015]. The results of porosity analysis showed that the soil in the rice field had the highest porosity value of 56.03%, while the porosity

Table 4. Soil characteristics

Code	Texture sand	Texture silt	Texture clay	Texture class	Bulk density	Porosity	Actual soil moisture	Organic matter
	%				g·cm^{-3}	%	cm^3·cm^{-3}	%
AP1-PMK	21	61	18	silt loam	1.31	44.95	0.49	1.54
AP1-KBN	66	25	9	sandy loam	1.39	42.50	0.47	7.51
AP1-SWH	37	46	17	clay	0.92	59.73	0.91	2.34
AP2-PMK	22	59	19	silt loam	1.04	54.90	0.49	1.40
AP2-KBN	10	66	24	silt loam	0.82	66.12	0.36	6.32
AP3-PMK	31	60	9	silt loam	1.35	43.37	0.49	1.33
AP3-KBN	31	45	24	loam	1.31	48.92	0.56	6.50
AP3-SWH	7	51	42	silty clay	1.12	52.32	0.49	1.98
AP4-PMK	36	53	11	silt loam	1.27	44.43	0.52	1.20
AP4-KBN	38	47	15	loam	1.21	43.39	0.59	7.03
AP5-PMK	60	37	3	sandy loam	1.31	43.64	0.44	1.10
AP5-KBN	26	61	13	silt loam	0.90	58.64	0.50	6.80
AP5-HTN	34	52	14	sandy loam	1.03	53.14	0.50	9.01
Mean	32.23	51.00	16.77	–	1.15	50.47	0.52	4.16
Standard deviation	16.80	11.27	9.64	–	0.19	7.68	0.13	3.01

Explanation: the codes as in Table 2. Source: own study.

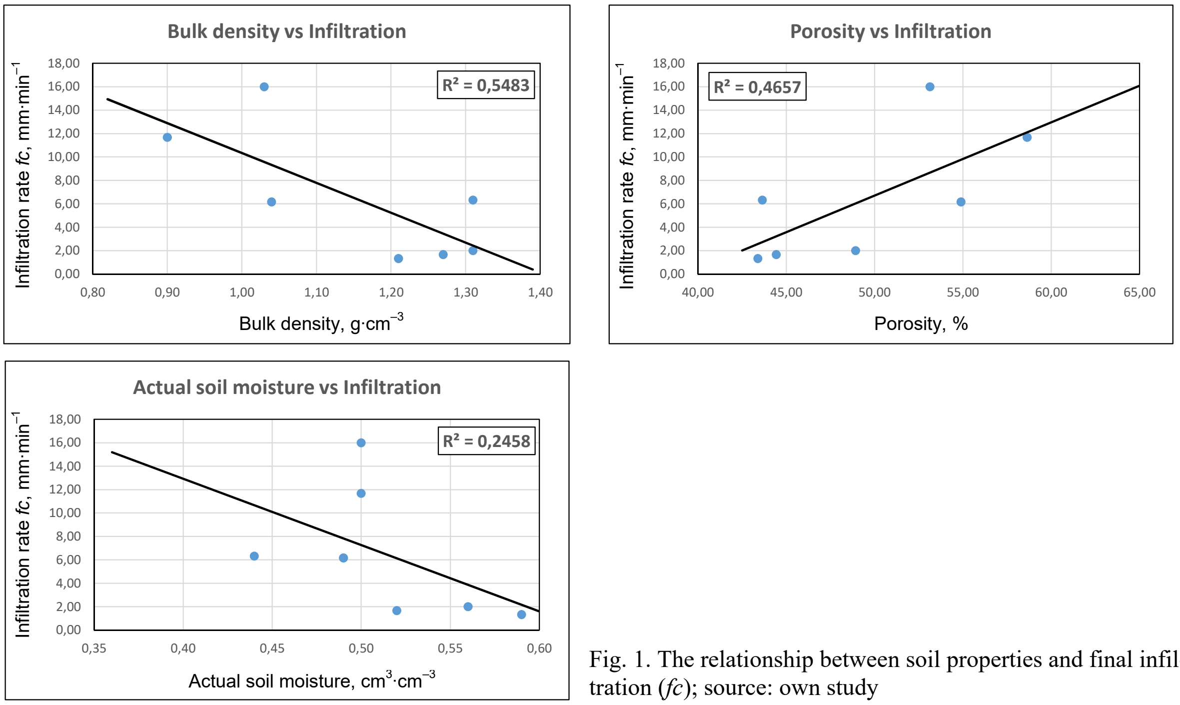

Fig. 1. The relationship between soil properties and final infiltration (*fc*); source: own study

level of soil in the forest was 53.14%, in the plantation was 51.91%, and in the settlements was 46.26%. The greater the porosity, the greater the hydraulic conductivity and the smaller the bulk density; this is in line with DEC *et al*. [2008].

Regarding the soil moisture content (the degree of saturation), the soil in the rice field had the highest degree of saturation of 0.70 $cm^3 \cdot cm^{-3}$, while the degree of saturation of soil in the forest and plantation is 0.50 $cm^3 \cdot cm^{-3}$, and in the settlements was 0.49 $cm^3 \cdot cm^{-3}$.

INFILTRATION MODEL PARAMETERS

The parameters of the infiltration models are presented in Table 5 and Table 6.

Table 5 shows the correlation between the model parameters and the infiltration rate. In the Green–Ampt model, the parameters of unsaturated soil ($\Delta\theta$) and suction head (ψ) are directly proportional to the infiltration rate. In other words, the more unsaturated the soil and the higher the suction head, the higher the infiltration rate. The hydraulic conductivity (K) approaches the final infiltration rate (fc) at a constant state, which means the gravity plays a more dominant role than the capillary force as the infiltration rate increases. Sandy loam soil had the highest K value; this is in accordance with BRESLER *et al.* [1984] stating that 24–35% of the variability of hydraulic conductivity could be connected with the content of the sand. The parameter values of $\Delta\theta$ and ψ correlate fairly well with the ones suggested by RAWLS *et al.* [1983], while

Table 5. Parameters of Green–Ampt and Kostiakov model

Code	*fo* observ	*fc* observ	Green–Ampt			Kostiakov	
	mm·min⁻¹		$\Delta\theta$	ψ, mm	K, mm·min⁻¹	*a*	*b*
AP1-PMK	2.17	0.33	0.40	953.90	0.04	1.79	0.47
AP1-KBN	15.00	8.00	0.38	213.52	7.16	17.43	0.20
AP1-SWH	0.67	0.07	0.37	593.80	0.001	0.56	0.61
AP2-PMK	6.17	1.50	0.29	681.07	0.94	5.55	0.35
AP2-KBN	0.33	0.17	0.28	29.20	0.17	0.64	0.31
AP3-PMK	9.33	5.33	0.28	144.53	5.24	9.63	0.14
AP3-KBN	2.00	0.67	0.24	124.02	0.55	2.28	0.31
AP3-SWH	4.00	0.67	0.27	1 068.50	0.30	8.24	0.61
AP4-PMK	1.67	0.67	0.28	88.64	0.46	2.13	0.31
AP4-KBN	1.33	0.33	0.23	256.08	0.16	1.53	0.41
AP5-PMK	6.33	2.33	0.26	310.91	1.89	6.36	0.26
AP5-KBN	11.67	5.00	0.32	263.34	4.81	12.49	0.22
AP5-HTN	16.00	5.00	0.38	215.47	5.49	17.17	0.27

Explanation: the codes as in Table 2; *fo* observ = observed initial infiltration rate (mm·min⁻¹), *fc* observ = observed final infiltration rate (mm·min⁻¹), $\Delta\theta = \eta - \theta i$, η = the degree of porosity, θi = the initial moisture content, ψ = the suction head (mm), K = the hydraulic conductivity (mm·min⁻¹), *a*, *b* = the empirical parameters.
Source: own study.

Table 6. Parameters of Kostiakov–Lewis, Philip, and Horton model

Code	*fo* observ	*fc* observ	Kostiakov–Lewis model		Philip model		Horton model
	mm·min^{-1}		*a*	*b*	*S*, mm·min$^{-0.5}$	*A*, mm·min^{-1}	*α*, min^{-1}
AP1-PMK	2.17	0.33	4.89	0.94	3.34	0.04	0.25
AP1-KBN	15.00	8.00	15.67	0.82	17.56	7.16	0.08
AP1-SWH	0.67	0.07	2.77	1.54	0.88	0.00	0.22
AP2-PMK	6.17	1.50	6.85	0.93	7.84	0.94	0.09
AP2-KBN	0.33	0.17	0.28	0.28	0.69	0.17	0.03
AP3-PMK	9.33	5.33	4.95	0.56	7.62	5.24	0.10
AP3-KBN	2.00	0.67	1.76	0.50	2.77	0.55	0.06
AP3-SWH	4.00	0.67	7.87	0.78	8.38	0.30	0.06
AP4-PMK	1.67	0.67	1.82	0.63	2.75	0.46	0.09
AP4-KBN	1.33	0.33	2.07	0.82	2.18	0.16	0.11
AP5-PMK	6.33	2.33	4.90	0.65	7.56	1.89	0.14
AP5-KBN	11.67	5.00	10.93	0.70	12.68	4.81	0.07
AP5-HTN	16.00	5.00	11.03	0.49	17.42	5.49	0.18

Explanations: *fo* observ = observed initial infiltration rate (mm·min^{-1}), *fc* observ = observed final infiltration rate (mm·min^{-1}), *a, b* = the empirical parameters, *S* = sorptivity (mm·min$^{-0.5}$), *A* = saturated hydraulic conductivity (mm·min^{-1}), *α* = constant of the infiltration rate (min^{-1}).
Source: own study.

the value of *K* is quite similar with the research results of ASKARI *et al.* [2008] and OLORUNFEMI [2011].

Regarding the Kostiakov and Kostiakov–Lewis model, the parameter value of "*b*" is inversely proportional to the initial infiltration rate (*fo*), whereas the value of "*a*" is directly proportional to the initial infiltration rate (*fo*). Since the value of *a* approached the initial infiltration rate (*fo*), it can be concluded that the value of *a* is correlated with the capillary force at the beginning of infiltration. The value of sorptivity (*S*) in the Philip model was close to the value of the initial infiltration rate (*fo*). This is due to the function of *S* parameter which has the soil suction potential. In the Horton model the value of *α* is directly proportional to the initial infiltration rate (*fo*); the higher the *α*, the higher the initial infiltration rate.

COMPARISON BETWEEN THE OBSERVED FIELD DATA AND THE INFILTRATION MODELS

The results of hypothesis testing using the chi-square test at 5% of confidence level indicated that there is no significant difference between the observed infiltration rate and the results obtained from different infiltration models. The highest infiltration rate was in the forest, while the lowest was in the rice field (see Fig. 1). Figure 2 shows the average of direct measurement infiltration values from each land use type.

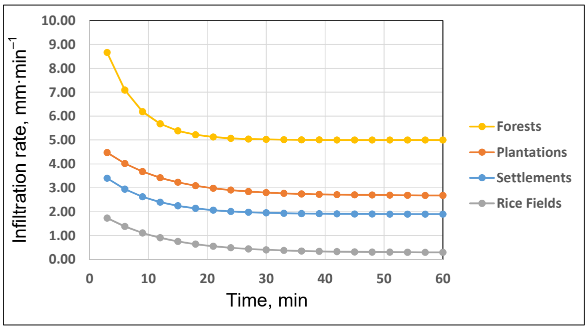

Fig. 2. Infiltration rate in different land uses; source: own study

The figure shown that the smallest infiltration on rice fields. This low value was caused by high soil moisture as rice fields require high amount of water. The highest of soil moisture has an impact on the infiltration rate [HAGJNAZARI *et al.* 2015] even though the soil has a low bulk density and high porosity.

EVALUATION OF THE PERFORMANCE OF THE INFILTRATION MODELS

The performance of each infiltration model was evaluated based on the value of *RMSE*, *NSE*, and r^2. The results of evaluation, as presented in Table 7, suggest that Kostiakov is the best performing model, followed by Kostiakov–Lewis, Horton, Philip and Green–Ampt model.

Table 7. Performance score of each infiltration model

Infiltration model	Performance score		
	RMSE	*NSE*	r^2
Green–Ampt model	0.53	0.50	0.76
Kostiakov model	0.46	0.69	0.75
Kostiakov–Lewis model	0.48	0.65	0.80
Philip model	0.57	0.57	0.76
Horton model	0.55	0.64	0.77

Explanations: *RMSE*, *NSE*, r^2 as in Tab. 1.
Source: own study.

Table 8. The most suitable infiltration model for each different land use

Land use	Suitable model	Performance score		
		RMSE	*NSE*	r^2
Settlements	Kostiakov model	0.42	0.68	0.73
Plantation	Kostiakov model	0.35	0.73	0.75
Rice field	Kostiakov–Lewis model	0.14	0.91	0.94
Forest	Green–Ampt model	1.89	0.49	0.52

Explanations: *RMSE*, *NSE*, r^2 as in Tab. 1.
Source: own study.

Table 9. Infiltration model for each different soil texture

Soil texture	Green–Ampt model			Kostiakov model			Kostiakov–Lewis model			Philip model			Horton model		
	RMSE	*NSE*	r^2	*RMSE*	*NSE*	r^2	*RMSE*	*NSE*	r^2	*RMSE*	*NSE*	r^2	*RMSE*	*NSE*	r^2
Silty loam	0.48	0.41	0.74	0.46	0.56	0.74	0.43	0.66	0.75	0.39	0.68	0.73	0.39	0.60	0.80
Sandy loam	1.08	0.63	0.72	1.25	0.54	0.72	1.31	0.52	0.69	1.06	0.67	0.68	1.12	0.63	0.72
Loam	0.17	0.47	0.79	0.16	0.55	0.80	0.14	0.69	0.80	0.13	0.68	0.79	0.14	0.71	0.87
Silty clay	0.38	0.79	0.95	0.40	0.75	0.95	0.31	0.86	0.95	0.19	0.95	0.95	0.25	0.90	0.94

Explanations: *RMSE*, *NSE*, r^2 as in Tab. 1.
Source: own study.

Results in Table 8 reveal that the Kostiakov model is suitable for settlements and plantations. Moreover, the Kostiakov–Lewis model is reported as the most suitable method for the rice fields, while Green–Ampt model is more applicable for forest land.

In addition, the suitability of the model on various soil textures is presented in Table 9 in which based on model performance test results, the Kostiakov model showed as the most applicable method for a wide range of soil texture.

CONCLUSIONS AND SUGGESTIONS

The results of this study have led us to conclude that Kostiakov model, compared to Kostiakov–Lewis, Green–Ampt, Philip, and Horton, is the most suitable for mineral soils with rapid infiltration rate (the final infiltration rate (*fc*) bigger than 0.42 mm min^{-1}). This is in contrast with the results of MBAGWU [1993], showing that that modified models of Kostiakov and Philip were more suitable.

The findings of the present study also indicate that the infiltration rate is influenced by a number of factors such as bulk density, porosity, soil moisture, and soil texture; this is in good agreement with HAGHNAZARI *et al.* [2015]. Moreover, the infiltration model parameters correlate closely with the initial infiltration rate (*fo*) and the final infiltration rate (*fc*). In other words, there is a correlation between the soil's ability to absorb water (representing the capillary force or horizontal flow) at the beginning of the infiltration (*fo*) and the gravity or the vertical flow upon reaching the final infiltration rate (*fc*).

As suggestion, taking into account the drawback of the Kostiakov model, namely the tendency of infiltration rate to approach zero at long elapsed times, it is recommended to use Kostiakov–Lewis or Horton model that adding final infiltration rate parameter (*fc*); as shown in this study, these two also showed a fairly good performance and were the next best models after the Kostiakov model.

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Ocena modeli infiltracji opracowanych dla gleb mineralnych o różnym typie użytkowania w tropikach

STRESZCZENIE

Celem badań prezentowanych w niniejszej pracy była ocena pięciu modeli infiltracji opracowanych dla gleb mineralnych o różnym typie użytkowania w tropikach, takich jak: obszary zabudowane, plantacje, pola ryżowe i lasy. Oceniano modele Greena–Ampta, Kostiakova, Kostiakova–Lewisa, Philipa i Hortona. Badania prowadzono w zlewni Amprong, Malang w Indonezji. Analizowano tempo infiltracji w trzynastu próbkach glebowych z użyciem infiltrometru Turf-Tech. Ponadto w każdej próbce gleby analizowano gęstość objętościową, ciężar właściwy, porowatość, wilgotność gleby i skład granulometryczny. Wyniki badań dowiodły, że nie ma istotnej różnicy w tempie infiltracji ($\alpha = 5\%$) obliczonej za pomocą wymienionych pięciu modeli. Uznano, że tempo infiltracji było duże. Trzy modele, kolejno: Kostiakova, Kostiakova–Lewisa i Hortona okazały się najbardziej odpowiednie. Największe tempo infiltracji stwierdzono w glebach leśnych, a najmniejsze w glebach pod polami ryżowymi. Wyniki badań sugerują, że parametry modelu infiltracji są ściśle skorelowane z początkowym (fo) i końcowym (fc) tempem infiltracji. Innymi słowy, istnieje korelacja między zdolnością gleby do absorbowania wody (reprezentowana przez siły kapilarne i przepływ poziomy) na początku infiltracji (fo) oraz siłą ciążenia i przepływem pionowym po osiągnięciu końcowego tempa infiltracji (fc).

Słowa kluczowe: *gleby mineralne, klimat tropikalny, modele infiltracji, użytkowanie ziemi*