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Soil Textures-Based Evaluation of Horton and Philip's Infiltration Models for Equatorial Small Watersheds

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ABSTRACT

The global database underscores Indonesia's scant 0.47% global contribution, of which 7.7% is from humid tropical climates. However, existing infiltration studies have primarily focused on specific soil textures and limited research points, resulting in a lack of comprehensive data. This knowledge gap is particularly evident in the Papua region of Indonesia, which boasts many small watersheds with abundant water resources but limited hydrologic data, especially regarding infiltration rates. Previous studies indicated that Horton and Philip's models excelled in equatorial regions but were limited in the number of soil textures and watersheds analysed or focused mainly on larger watersheds. Therefore, this study aimed to address this research gap by conducting a comprehensive analysis of the performance of the Horton and Philip's models across different soil textures in small watersheds, using the Hydrologic Soil Group classification as a reference. A performance analysis was conducted to assess Horton and Philip's performance using the Moriasi technique (based on R, RSR, and NSE best values). Field observations were conducted at 95 points in eleven small watersheds in Papua as representatives of equatorial small watersheds globally. Observations were suspended for 48 hours if rainfall occurred; thus, ten months were needed to finish the observation. The results of this study demonstrated that the Horton model performed exceptionally well for six of nine soil textures, whereas the Philip's model showed excellent performance for five out of nine. The obtained research results were compared with similar studies from Ghana, Nigeria, and India, reinforcing the conclusion that globally, the Horton and Philip's model effectively describes infiltration rates in equatorial small watersheds. Further research was recommended in equatorial small watersheds with sand and loamy sand soil textures, two of the nine soil textures that were not covered in the conducted study.

Keywords: soil water infiltration, Horton model, Philip's model, equatorial small watersheds.

INTRODUCTION

The hydrological cycle reveals that 29% of rainfall becomes runoff within the watershed (Tkachuk et al., 2022), with a portion evaporating and the remainder infiltrating the soil. Infiltration occurs when water enters the soil through the surface and passes through four soil layers. Starting from a thin layer of moist soil, the transition layer towards a layer where the humidity begins to decrease (uniform moisture content and unsaturated flow). The last layer is the layer with soil moisture close to field capacity, and its depth depends on the amount of infiltrated water and the soil properties (Subramanya, 2013). Infiltration data is pivotal for agricultural irrigation and flood management, yet many areas with high surface runoff have limited data. The Soil Water Infiltration Global (SWIG) database underscores Indonesia's scant 0.47% global contribution, of which 7.7% is from humid tropical climates (Rahmati et al., 2018). Changes in land use often result in diminished infiltration rates, which are crucial for stable watershed flows (Shiraki et al., 2017; Yamamoto et al., 2020) and managing surface water drainage (Tkachuk et al., 2022). Therefore, investigating infiltration rates is imperative (Sayama et al., 2021). Not all current studies on infiltration models emphasise soil texture in guides to infiltration model selection, or sometimes only based on a small part of soil texture. For instance, the study by Rahmati *et al.* study did not categorise infiltration data by soil texture (Rahmati et al., 2018). The SWIG database only has the data from Sumbawa Besar in Indonesia. Horton's model excels in dryland conditions (Ayu et al., 2013) and outperforms others in various watersheds, including Merawu, Indonesia and Madjez Ressoul, Algeria (Ngadisih et al., 2020; Dahak et al., 2022). Philip's model is well-suited for wetlands in Ghana and Nigeria's forest zones (Oku et al., 2011; Thomas et al., 2020) and has proven effective in areas like Abia State, Nigeria (Ruth et al., 2015) as well as Progo's upper watershed in Indonesia (Ritawati et al., 2012). In the tropical river basins of Ghana, multiple models, including Philip, Horton, and Kostiakov, have demonstrated good performance (Henry et al., 2016). Lastly, while Philip's model stood out in clay soils in Jordan (Albalasmeh et al., 2022), the Horton model was superior under diverse soil conditions from regions, like Nigeria and India (Zakwan, 2019).

The Papua region, situated at Indonesia's eastern tip, boasts 2,214 watersheds, mostly small (Watershed Management Laboratory, 2018). Despite extensive global infiltration model research, a notable gap remains in understanding their performance and applicability in Papua, Indonesia, especially given its distinct hydrological and soil characteristics. Radhika's findings suggest suboptimal hydrologic model calibrations in this region due to data constraints, even though Papua contributes to 29% of Indonesia's annual surface water (Radhika et al., 2017). Previous studies indicated that Horton and Philip's models excelled in tropical climates but were limited in the number of soil textures and watersheds analysed or focused mainly on larger watersheds. Additionally, given Papua's critical role in Indonesia's water resources, having accurate and reliable infiltration models for this region is paramount. The authors aimed to bridge these knowledge gaps by analysing Horton and Philip's performance models across diverse soil textures in Papua's small watersheds, leveraging 95 observation points in 11 distinct watersheds.

RESEARCH METHODS

Location research

As representatives of equatorial small watersheds globally, the research's data was sourced from eleven small watersheds in the Southwest Papua Province of Indonesia, each with a catchment area under 100,000 hectares. The study was done from January to November 2022. Figure 1 shows the details of the 95 observation points across these watersheds Rufei 1 (8 points), Rufei 2 (8 points), Boswesen (8 points), Pasar Baru (8 points), Remu (9 points), Klagison (8 points), Klawoguk (9 points), Klasaman (8 points), Klafma (11 points), Wermon (10 points), and Mariat (8 points).

Soil texture

Observations at these 95 points are investigations of soil properties to analyse soil texture classification. The centre for soil data analysis and processing activities is the Laboratory of Soil Mechanics, Muhammadiyah University of Sorong. The determination of soil texture is based on the mass ratio of the three soil fractions, namely soil with a percentage of sand, silt, and clay, as explained in the explanation of the soil texture triangle diagram (Hillel, 1973).

Infiltration rate

Theoretically, Figure 2 helps explain the concept of infiltration rate based on soil texture as one of the topics discussed during the JICA training course on soil water infiltration in Jordan in 2017 (Strohmeier, 2017). To obtain the infiltration rate, researchers had to measure the water absorption rate of soil in a clear area using instruments (Ponce, 2014). The research instrument used was a double-ring infiltrometer, and in conducting the research in the field, the procedures referred to the Indonesian National Standard number 7752:2012 (BSN, 2012). There were strict requirements for observing the area. Namely, if rain exceeded 12.7 mm/day, they could only continue the research after 48 hours (Atta-Darkwa et al., 2022). Silt content is the most critical parameter in predicting infiltration rate, and other parameters included: time, clay content, water content, sand content, and soil density (Panahi et al., 2021).

In this study, the infiltration rate analysis used the Horton and Philip infiltration model, with a brief description as follows:

1. Horton model. In the Horton equation, f(t) is the infiltration capacity at time t (hour), f_c (cm/hour) is the steady-state infiltration value, f_o (cm/hour) is the infiltration at t=0, and k is the infiltration decay factor (Mishra et al., 2003).

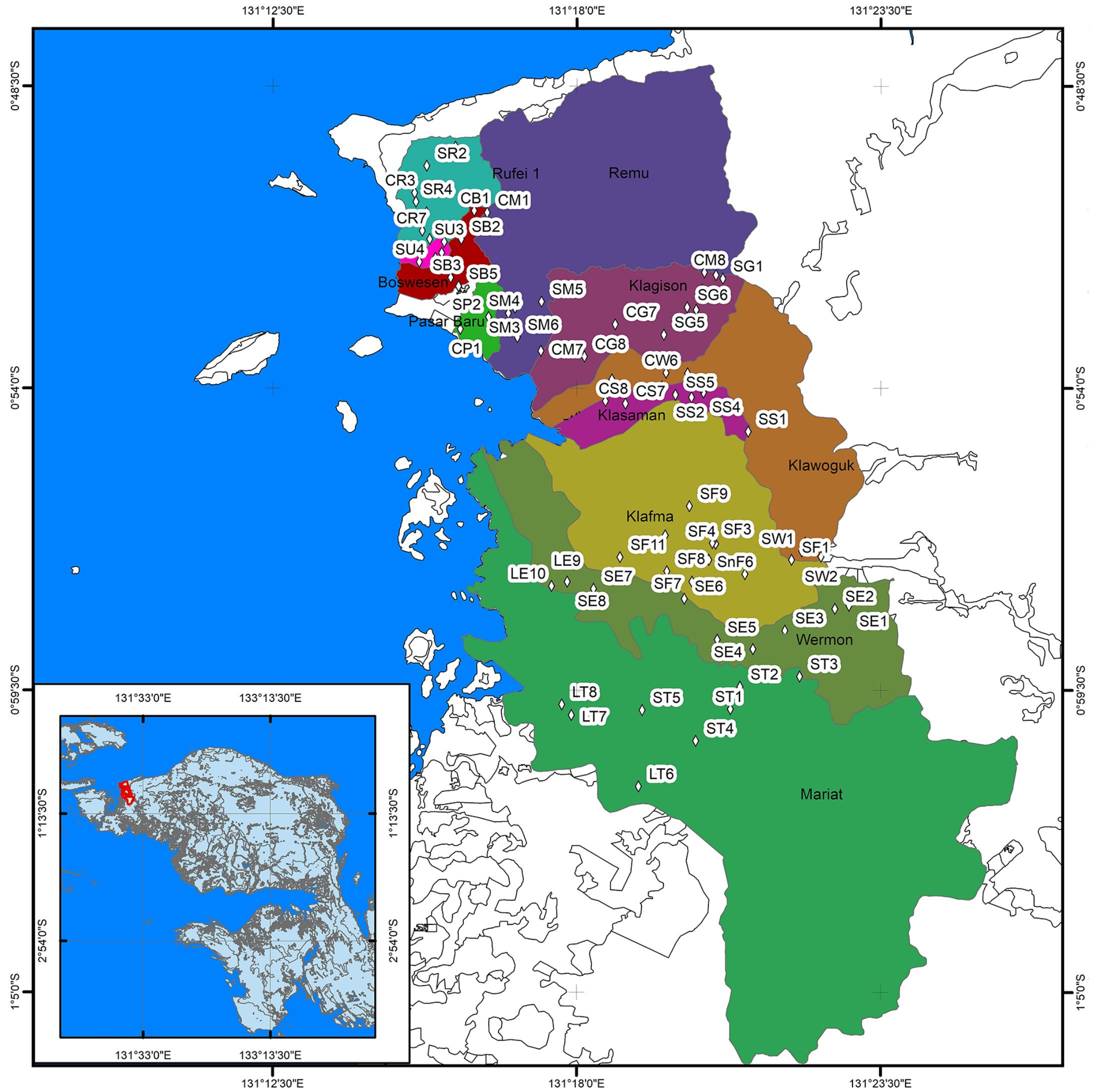

Figure 1. Research location as global representatives of equatorial small watersheds

$$f(t) = f_c + (f_0 - f_c).e^{-kt} \quad (1)$$

2. Philip's model. Philip's equation form (Chow et al., 1998):

$$f(t) = \frac{1}{2}S.t^{-1/2} + K \quad (2)$$

where: t – time (min), f(t) – infiltration rate (cm/min); S – soil sorptivity (cm/hour$^{0.5}$), K – hydraulic conductivity (cm/hour).

Procedure for estimating the parameters of infiltration models

Infiltration data analysis yields f values at different observation times (t). Subramanya outlined the methods for estimating the Horton and Philip's parameters (Subramanya, 2013):

1. Horton model: Using a plot of ln(f-fc) vs. time (t), the linear regression equation $y=ax+b$ gives ln(f-fc) from b and k from a.
2. Philip's model: Plotting f vs. $t^{0.5}$ yields the equation $y=ax+b$, where K is derived from b and (S/2) from a. Positive K values are considered, and early data with small t values are excluded.

Infiltration rate classification based on soil texture according to hydrologic soil group

Infiltration rates vary according to the soil profile, with each Hydrologic Soil Group (HSG) displaying unique water transmission characteristics (Quan, 2010):

- A – low runoff, high infiltration (sand, loamy sand, sandy loam).
- B – moderate runoff and infiltration (silt loam, loam).

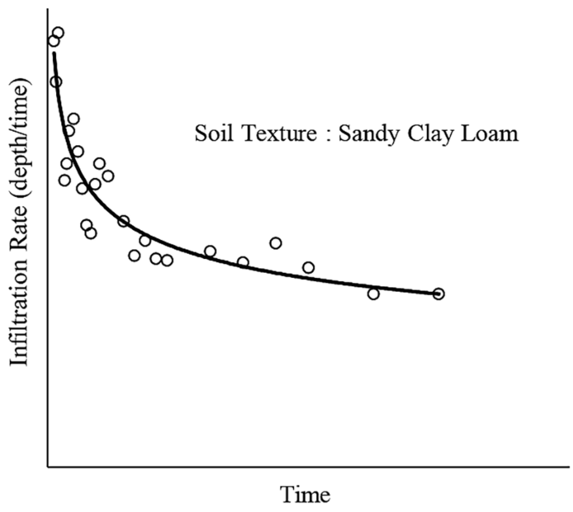

Figure 2. Infiltration rate

- C – low runoff and infiltration (sandy clay loam).
- D – high runoff, shallow infiltration (clay loam, silty clay loam, sandy clay, silty clay, clay).

Evaluation techniques for assessing the performance of infiltration models

According to Moriasi, the suitable techniques for evaluating watershed models are graphical and statistical (Moriasi et al., 2007).

1. Graphical techniques – these visually compare simulated vs. measured data, elucidating model performance.
2. The statistical model evaluation techniques in this study are:

a) standard regression – utilising R and R^2 coefficients, this technique measures how closely the simulated data aligns with the observed data. R represents the linear relationship strength, with values ranging from -1.0 to 1.0. R^2 quantifies the model's variance and is deemed acceptable when over 0.5. Sugiyono's correlation strengths based on R values are (Sugiyono, 2007): $0 \leq R < 0.2$ (very low), $0.2 \leq R < 0.4$ (low), $0.4 \leq R < 0.6$ (moderate), $0.6 \leq R < 0.8$ (strong), and $0.8 \leq R < 1.0$ (powerful).

b) dimensionless – the Nash-Sutcliffe Efficiency (NSE) determines how well observed vs simulated data plots align, with values between 0 and 1.

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{mean}\right)^2}\right] \tag{3}$$

c) index errors – the RSR standardises the RMSE and serves as an error index.

$$RSR = \left[\frac{\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}}{\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y^{mean}\right)^2}}\right] = \frac{RSME}{STDEV_{obs}} \tag{4}$$

The performance classification of watershed models that Moriasi has prepared based on the NSE and RSR values is very good ($0.75 < NSE < 1.0$; $0.0 < RSR < 0.5$), good ($0.65 < NSE < 0.75$; $0.50 < RSR < 0.60$), satisfactory ($0.50 < NSE < 0.65$; $0.60 < RSR < 0.70$) and unsatisfactory ($NSE < 0.50$; $RSR > 0.70$).

Research stages

As the first step, soil samples were gathered from 95 distinct locations across eleven watersheds in Papua. Following the soil texture triangle diagram, these samples were subjected to texture classification at the Soil Mechanics Laboratory of Muhammadiyah University of Sorong (Hillel, 1973). The research team measured the water absorption capacity of these samples in clear areas using a double-ring infiltrometer (Ponce, 2014), adhering to the Indonesian National Standard 7752:2012 (BSN, 2012). Infiltration observations in the field were conducted three times at each research point. Observations were suspended for 48 hours if rainfall surpassed 12.7 mm/day (Atta-Darkwa et al., 2022). On the basis of these observations, the gathered infiltration data were sorted according to soil texture according to the HSG theory (Quan, 2010). Subsequent statistical analyses covered various tests, including normality, ANOVA, nonlinear regression, and coefficient evaluations (Razali et al., 2011). The study also analysed and determined the parameters of Horton and Philip's models for each identified soil texture (Subramanya, 2013). Finally, a rigorous performance analysis was conducted, comparing real-world infiltration rates against predictions from the two models. The superior model was then selected based on R, RSR, and NSE values (Moriasi et al., 2007).

RESULTS

Data distribution

The research began by categorising data from eleven small watersheds (Figure 1) based on the Hydrologic Soil Group's soil texture. Nine of eleven textures were identified from ninety-five soil samples in eleven equatorial small watersheds

(Table 1). These findings explain that the conducted research significantly represents 81.8% of soil textures in the HSG classification system.

Statistical analysis

All infiltration rate groups passed the statistical analysis (Table 2). The analysis outputs have revealed a significant relationship between infiltration rate and the observation time variable (t) at a 95% confidence level.

Estimate parameters for the Horton and Philip infiltration models

After passing statistical analysis, we used procedures from the Engineering Hydrology book (Subramanya, 2013) to estimate parameters for the Horton and Philip's infiltration models. The predicted parameters for both models across different soil textures are detailed in Table 3. These parameters helped construct the respective model equations. Moriasi's model evaluation technique (Moriasi et al., 2007) encompasses graphical methods, dimensionless measures (NSE), and error indices (RSR). Figure 3 visualises the results using the correlation coefficient (R) derived from the square root of R^2. This figure presents the graphical performance of the Horton and Philip's models across various soil textures. Using the R^2 values from Figure 3, R-values (Sugiyono, 2007) were calculated and added them to Table 4. Performance assessments of the models were then based on R, NSE, and RSR values (Moriasi et al., 2007) and the best infiltration model for each type of soil texture. Table 4 shows that the Horton model excels in 6 out of 9 soil textures in Indonesia's small watersheds, while the Philip's model is superior for 5 out of 9 soil textures. From the findings presented in Table 4, it can be deduced that the optimal infiltration model for each specific soil texture is as follows:

1. The Horton and Philip's infiltration models provide accurate results for the sandy loam texture.
2. The Philip's infiltration model works well for silt loam texture, and its performance is slightly better than the Horton model.
3. The Horton and Philip's infiltration models provide accurate results for loam texture.
4. The Philip's infiltration model works very well for the sandy clay loam texture, and the performance is slightly better than the Horton model.
5. The Horton and Philip's infiltration models provide accurate results for the sandy clay texture.
6. For clay loam texture, Horton infiltration model works very well, and its performance is much better than Philip's model.
7. The Horton infiltration model works very well for the silky clay loam texture, and the performance is slightly better than the Philip's model.
8. The Horton infiltration model works well for the silty clay texture and performs slightly better than the Philip's model.
9. The Horton and Philip's infiltration models provide accurate results for clay textures.
10. The Horton model averaged an R of 0.901, an NSE of 0.785, and an RSR of 0.453. In

Table 1. Data distribution based on soil texture classification

Hydrologic soil group (HSG)	Soil texture	Observation points
A	Sand	0
	Loamy sand	0
	Sandy loam	17
B	Silt loam	9
	Loam	17
C	Sandy clay loam	12
D	Clay loam	23
	Silty clay loam	6
	Sandy clay	1
	Silty clay	2
	Clay	8
Total	95	

Table 2. The statistical analysis results for the existing infiltration rate data set

Statistical analysis (α = 5%)	p-values								
	Sandy loam	Silt loam	Loam	Sandy clay loam	Clay loam	Sandy clay	Silty clay loam	Silty clay	Clay
Tests of normality (Shapiro-Wilk Test)	0.068	0.058	0.121	0.056	0.684	0.071	0.056	0.060	0.919
Analysis of variance (ANOVA)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Coefficients model	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 3. Predicted results of infiltration model parameters

Soil texture	Infiltration model		Model Parameter Prediction (Subramanya, 2013)	
Sandy Loam	Horton	k=2.057	fo=23.804cm/h	fc=10.361cm/h
	Philip	S=10.871cm/h$^{0.5}$	K=7.128cm/h	
Silt Loam	Horton	k=0.955	fo=5.723 cm/h	fc=3.288 cm/h
	Philip	S=1.954cm/ h$^{0.5}$	K=3.185cm/h	
Loam	Horton	k=1.334	fo=5.285 cm/h	fc=1.476 cm/h
	Philip	S=1.610cm/ h$^{0.5}$	K=1.903cm/h	
Sandy Clay Loam	Horton	k=1.467	fo=5.381 cm/h	fc=2.641 cm/h
	Philip	S=2.009cm/ h$^{0.5}$	K=2.341cm/h	
Sandy Clay	Horton	k=1.018	fo=7.629 cm/h	fc=1.333 cm/h
	Philip	S=5.254cm/ h$^{0.5}$	K=0.660cm/h	
Clay Loam	Horton	k=0.880	fo=2.578 cm/h	fc=1.066 cm/h
	Philip	S=0.513cm/ h$^{0.5}$	K=1.464cm/h	
Silty Clay Loam	Horton	k=3.120	fo=4.083 cm/h	fc=1.768 cm/h
	Philip	S=0.774cm/ h$^{0.5}$	K=1.801cm/h	
Silty Clay	Horton	k=1.118	fo=1.969 cm/h	fc=0.133 cm/h
	Philip	S=1.363cm/ h$^{0.5}$	K=0.099cm/h	
Clay	Horton	k=1.006	fo=1.897 cm/h	fc=0.217 cm/h
	Philip	S=1.563cm/ h$^{0.5}$	K=0.005cm/h	

Table 4. The performance evaluation of Horton and Philip models

Soil texture	Infiltration model	Model Evaluation (Moriasi et al., 2007)						Overall performance rating
		R	Relationship	NSE	Performance	RSR	Performance	
Sandy loam	Horton	0.953	Powerful	0.897	very good	0.322	very good	very good
	Philip	0.947	Powerful	0.897	very good	0.320	very good	very good
Silt loam	Horton	0.821	Powerful	0.579	satisfactory	0.649	satisfactory	satisfactory
	Philip	0.854	Powerful	0.729	good	0.521	good	good
Loam	Horton	0.918	Powerful	0.825	very good	0.418	very good	very good
	Philip	0.894	Powerful	0.799	very good	0.449	very good	very good
Sandy clay loam	Horton	0.877	Powerful	0.737	good	0.513	good	good
	Philip	0.926	Powerful	0.857	very good	0.378	very good	very good
Sandy clay	Horton	0.915	Powerful	0.803	very good	0.443	very good	very good
	Philip	0.939	Powerful	0.881	very good	0.345	very good	very good
Clay loam	Horton	0.897	Powerful	0.791	very good	0.458	very good	very good
	Philip	0.780	Strong	0.608	satisfactory	0.626	satisfactory	satisfactory
Silty clay loam	Horton	0.936	Powerful	0.876	very good	0.352	very good	very good
	Philip	0.805	Powerful	0.648	satisfactory	0.593	good	good
Silty clay	Horton	0.872	Powerful	0.713	good	0.536	good	good
	Philip	0.811	Powerful	0.601	satisfactory	0.632	satisfactory	satisfactory
Clay	Horton	0.919	Powerful	0.848	very good	0.390	very good	very good
	Philip	0.865	Powerful	0.835	very good	0.406	very good	very good

comparison, the Philip's model averaged R, NSE, and RSR values of 0.879, 0.762, and 0.474, respectively. Both models proved highly effective in characterising infiltration rates within Papua's small watersheds. This is evident from the analysed data obtained from 95 observation points scattered across 11 small watersheds in Papua.

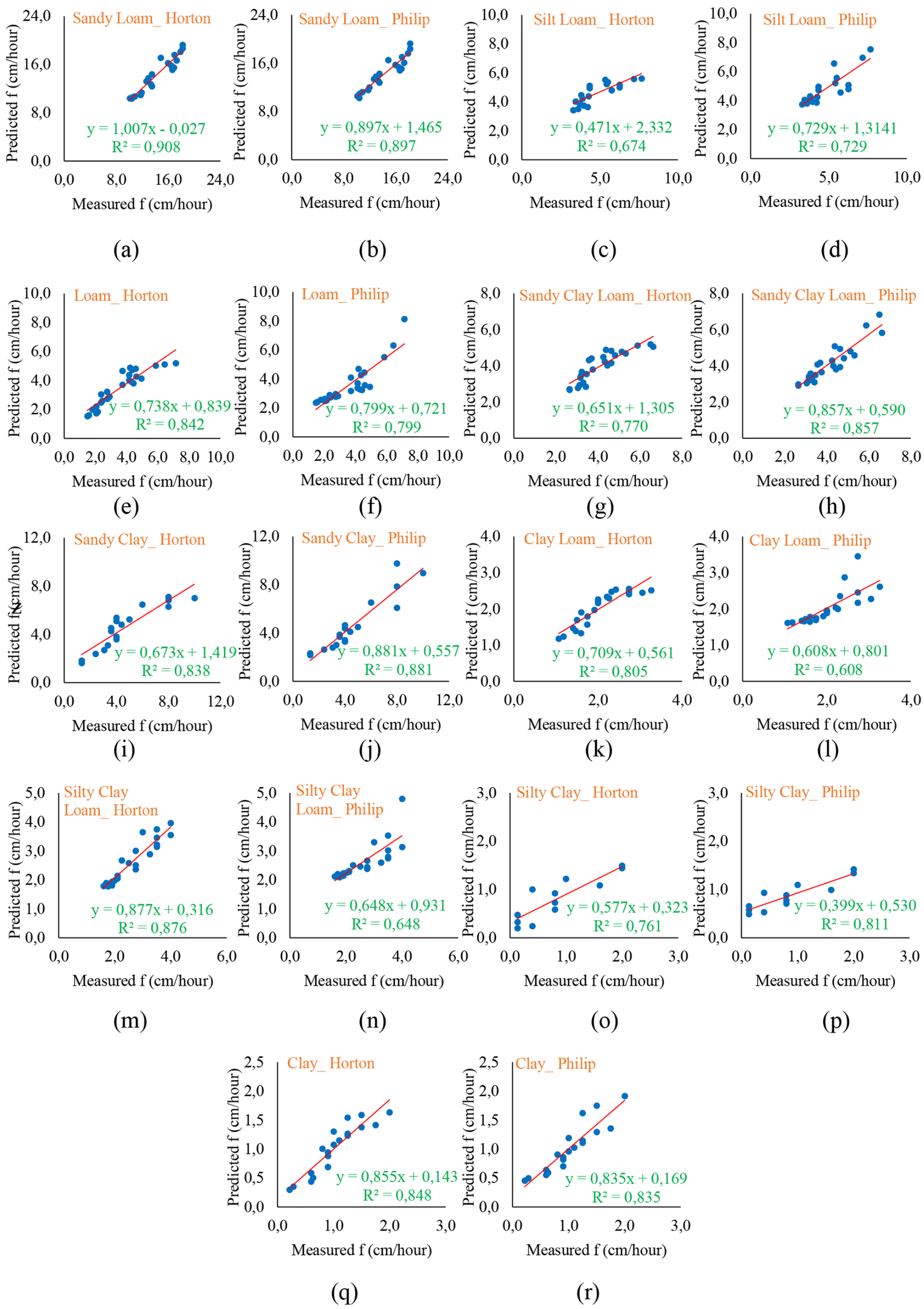

Figure 3. Performance evaluation results for each type of soil texture

DISCUSSION

Description of research results on climate factors

In pursuing accurate and comprehensive data collection from 95 research points in eleven small watersheds, a meticulous approach was incorporated by instituting a mandatory suspension of observations for 48 hours following any rainfall within the research area (Atta-Darkwa et al., 2022). This strategic decision aimed to mitigate the potential distortions in the observed variables due to the immediate influence of precipitation. Given that the study site is situated within a humid tropical (equatorial) climate (Rubel et al., 2010), characterised by frequent and intense rainfall events, this precautionary measure was deemed essential to uphold the integrity and precision of our findings. Rainfall in Sorong is 2,852 mm/year; thus, it is in the wet category (Farida et al., 2022). The unique climatic conditions of equatorial regions, marked by high temperatures, abundant moisture, and the propensity for sudden and heavy rainfalls, necessitated careful consideration of the potential impact of these climatic factors on the observational data. Consequently, the decision to suspend observations for a specified duration after each rainfall event was made to account for the intricate interplay between soil properties, infiltration processes, and the dynamic nature of equatorial climates.This deliberate approach to temporarily halt data collection following rainfall occurrences had the consequential effect of elongating the overall duration of the conducted observational study to ten months. This lengthy timeframe was a deliberate adaptation to the climatic challenges inherent to equatorial regions, ensuring that the research outcomes provide a nuanced and comprehensive understanding of small watershed infiltration processes in these unique and climatically dynamic environments.

Novelty of the research

The novelty of the research resulting from the summary of the previous analysis is the recommendation of the Horton and Philip's model parameters for each type of soil texture found. Therefore, for each soil texture according to the HSG classification system, a model equation is obtained integrated with the model parameters (Table 3) and follows the recommendations from the model performance analysis (Table 4). Two primary research novelties to fill the gap described in the introduction were identified. First, the equations and parameters of the infiltration model developed for each soil texture (based on Table 3). The Soil Hydrology Group theory previously did not offer specific infiltration equations for each soil texture within a small watershed context. The second novelty involves a detailed examination of the infiltration rate in small watersheds. The performance of infiltration models by Horton and Philip's were specifically evaluated for each soil texture, which has yet to receive detailed attention at this level. This result provides

Table 5. Research novelties and recommendations

Soil texture	Infiltration model	Equation model for each watershed soil texture (first novelty)	Performance rating (second novelty)	Recommendation model for each watershed soil textures
Sandy loam	Horton	$f=10.361+13.442e^{-2.057.t}$	very good	Horton and Philip's model
	Philip	$f=5.436t^{-0.5}+7.128$	very good	
Silt loam	Horton	$f=3.288+2.435e^{-0.955.t}$	satisfactory	Philip's model
	Philip	$f=0.977t^{-0.5}+3.185$	good	
Loam	Horton	$f=1.476+3.809e^{-1.334.t}$	very good	Horton and Philip's model
	Philip	$f=0.805t^{-0.5}+1.903$	very good	
Sandy clay loam	Horton	$f=2.641+2.740e^{-1.467.t}$	good	Philip's model
	Philip	$f=1.005t^{-0.5}+2.341$	very good	
Sandy clay	Horton	$f=1.333+6.295e^{-1.018.t}$	very good	Horton and Philip's model
	Philip	$f=2.627t^{-0.5}+0.660$	very good	
Clay loam	Horton	$f=1.066+1.511e^{-0.880.t}$	very good	Horton model
	Philip	$f=0.256t^{-0.5}+1.464$	satisfactory	
Silty clay loam	Horton	$f=1.768+2.315e^{-3.120.t}$	very good	Horton model
	Philip	$f=0.387t^{-0.5}+1.801$	good	
Silty clay	Horton	$f=0.133+1.835e^{-1.118.t}$	good	Horton model
	Philip	$f=0.681t^{-0.5}+0.099$	satisfactory	
Clay	Horton	$f=0.217+1.680e^{-1.006.t}$	very good	Horton and Philip's model
	Philip	$f=0.781t^{-0.5}+0.005$	very good	

a deeper insight into the suitability of these models within the context of small watershed areas based on soil textures (Table 4). Table 5 below summarises the two research novelties.

Comparison with the results of similar research

The obtained research results were compared with similar ones from Ghana, Nigeria and India. It is essential to analyse these research results (Tables 3 and 4) and compare them with the previous studies. The final result can be better understood by examining the comparison in Table 6.

Table 6 strengthens the conclusion of the conducted research that globally, the Horton and Philip's modes perform well in describing infiltration rates in small watersheds. The hope for the results of this research in Indonesia is that it can contribute to infiltration data, which globally is significantly underrepresented by humid tropical climates and lacking infiltration data from loamy sand, silty clay and sandy clay textured areas (Rahmati et al., 2018). According to the World Map of Koppen-Geiger climate classification, all regions of Indonesia are humid tropical (equatorial) climate areas, and the Horton model performs very well for both soil textures in predicting infiltration rates (Rubel et al., 2010). It is necessary to compare the results of this study with the results of identical studies from other regions in the same climate, taking into account that rain is one of the climatic factors that affect the rate of soil infiltration (Limantara, 2018). There are not many studies on infiltration rates and evaluation of infiltration models that focus on research by making the distribution of soil texture in small watersheds with humid tropical climates so that in determining the number of research points, it should consider the representation of all types of soil texture. Countries with a similar focus of study are Ghana, Nigeria and India, although the number of soil textures and watersheds is smaller than in this research. Some of these studies are:

Research on the constant infiltration rate of sandy and clay textured soils in India to determine the constant infiltration rate of these soils under different soil conditions and compare it to the infiltration rate of the Kostiakov, Modified Kostiakov, Horton and Green-Ampt models. The results showed that the Horton and Green-Ampt models were the most suitable for observational data (Dagadu et al., 2012). Field infiltration research at 6 points in the Oda Watershed of Ghana (included in the small watershed criteria), with performance testing of Horton, Philip's, Kostiakov, and Green Ampt models. The result is that Philip's model has the best performance, and this study is limited to describing areas with sandy loam and silt loam soil textures (Thomas et al., 2020).

Research on three irrigated areas in the northern region of Ghana to test the performance of six infiltration models. The result is that the Horton, Philip's, Green-Ampt, Kostiakov, Holtan, and Soil Conservation Service infiltration models perform well against field data (Salifu et al., 2021). Figure 4 juxtaposes the outcomes of the Horton and Philip's models' theoretical equations of prominent infiltration models in countries like Nigeria, Ghana, and India, which share a humid tropical climate akin to Indonesia (Rubel et al., 2010). The Horton model, spotlighted in Figure 4a, is tailored for clay-textured soils and draws upon data from Indonesia, Ghana, and India. Intriguingly, there is ambiguity regarding Ghana's soil texture. However, a consistent average infiltration across the three

Table 6. Summary of model performance test results for each soil texture in small watersheds

Tested Infiltration Model	Comparison of infiltration model performance										
	Sand	Loamy sand	Sandy loam	Silt loam	Loam	Sandy clay loam	Sandy clay	Clay loam	Silty clay loam	Silty clay	Clay
Horton	- VG [2] - VG [5]	- - - -	VG [1] VG [2] G [4] -	S [1] - G [4] -	VG [1] - - -	G [1] - - -	VG [1] - - -	VG [1] - - -	VG [1] - - -	G [1] - - -	VG [1] VG [2] - VG [5]
Philip	- - -	- - -	VG [1] G [3] VG [4]	G [1] - VG [4]	VG [1] G [3] -	VG [1] - -	VG [1] - -	S [1] - -	G [1] - -	S [1] G [3] -	VG [1] G [3] -

Note: VG – very good; G – good; S – satisfactory; US – unsatisfactory; [1] – (Pristianto et al., 2023), [2] – (Zakwan, 2019), Research results from Nigeria and India; [3] – (Rahmati et al., 2022); [4] – (Thomas et al., 2020); Research result from Ghana; [5] – (Dagadu et al., 2012); research results from India.

nations suggests Ghana possibly has clay-textured soil. An in-depth look reveals that all the regions mentioned have sluggish infiltration rates (Hillel, 1973). Clay-textured soils in Indonesia and Ghana are moister than in India. Interestingly, Indonesia (Papua) and Ghana's clay-textured soils are wetter than India's. Shifting the focus to Figure 4b and the Philip's model, it is designed for sandy loam and silty loam soils, leveraging data from Indonesia, Ghana, and Nigeria. The constant infiltration rate analysis displays Indonesia's and Nigeria's soils predominantly aligning with Hillel's moderate infiltration benchmark. In contrast, Ghana's soils, specifically sandy loam and silt loam, display a negative infiltration constant. This result might be influenced by factors like excessive moisture or rainfall, compelling the soil to discharge water, especially given the Oda River location in a humid forest zone. This result contrasts with Indonesia's grassy lands and Nigeria's arid agricultural terrains. A notable observation is the starting similarity in infiltration rates between Nigeria and Indonesia's sandy loam soils, but with Nigeria having a diminished constant rate, potentially reflecting reduced soil porosity, a feature backed by studies which identified an average porosity of 35.86% in Nigeria's sandy loam soil (Uloma et al., 2014).

Research limitation and recommendation for future research

The conducted study is constrained because it only encompasses 9 of the 11 soil textures from the Hydrologic Soil Group classification. None of the 95 sample points exhibited sand and loamy sand textures. Hence, a pronounced need for subsequent research focusing on small watersheds with these omitted soil textures is needed to refine the findings.

The potential impact of research result

The study insights into equatorial small watershed infiltration processes, addressing prior limitations and offering detailed soil texture performance comparisons, significantly enhance understanding in equatorial regions. These findings are valuable for future regional hydrological research and water resource management. The research results also hold significance by addressing hydrology data gaps in Indonesia, improving small watershed management, and representing infiltration models based on soil texture for small equatorial watersheds. This study contributes crucial knowledge for advancing hydrological understanding and sustainable water resource practices in equatorial regions, particularly Indonesia.

CONCLUSIONS

In conclusion, on average, the Horton model has R=0.901, NSE=0.785, and RSR=0.453, while the Philip's model posts R=0.879, NSE=0.762, and RSR=0.474. Both models very well depict infiltration rates in Papua's small watersheds. This research enriches the understanding of infiltration model parameters and equations based on soil

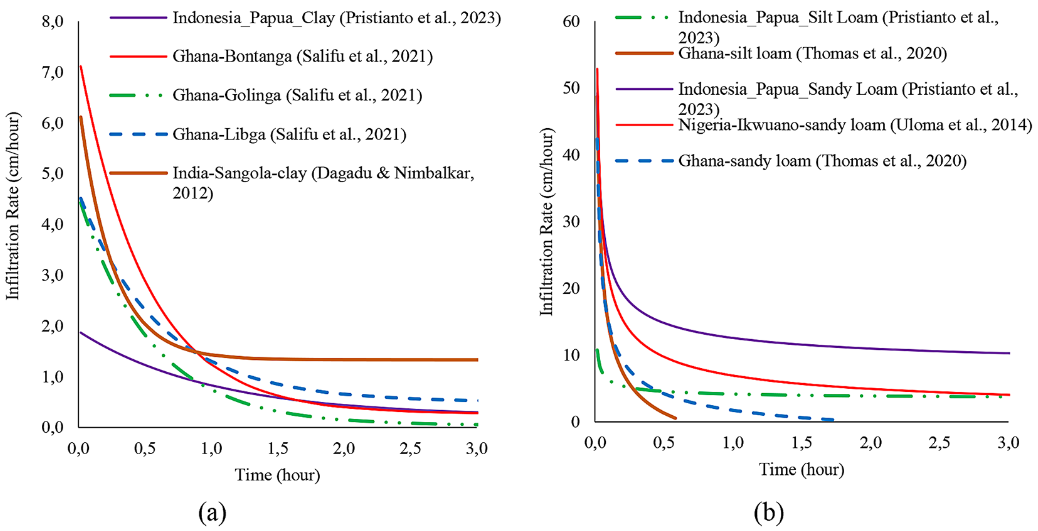

Figure 4. Comparison of the theoretical lines of Horton model (a), and Philip's model (b), with model parameters from research results in Indonesia, Ghana, Nigeria and India

texture within small watersheds. The obtained research results were compared with similar studies from Ghana, Nigeria, and India, reinforcing the conclusion that globally, the Horton and Philip's model effectively describes infiltration rates in small watersheds. Further research is recommended in equatorial small watersheds with sand and loamy sand soil textures, two of the nine soil textures that were not covered in this study. With this additional research, the authors hope it can more accurately predict infiltration rates for small watersheds based on each soil texture type in equatorial regions.

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REFERENCES

1. Albalasmeh A.A., Alghzawi M.Z., Gharaibeh M.A., Mohawesh O. 2022. Assessment of the effect of irrigation with treated wastewater on soil properties and on the performance of infiltration models. Water, 14(9), 1520. https://doi.org/10.3390/w14091520
2. Atta-Darkwa T., Asare A., Amponsah W., Oppong E.D., Agbeshie A.A., Budu M., Larbi I., Akolgo G.A., Quaye D.N.D. 2022. Performance evaluation of infiltration models under different tillage operations in a tropical climate. Scientific African, 17, 1–13. https://doi.org/10.1016/j.sciaf.2022.e01318
3. Ayu I.W., Prijono S., Soemarno S. 2013. Assessment of infiltration rate under different drylands types in Unter-Iwes subdistrict Sumbawa Besar, Indonesia. Journal of Natural Sciences Research, 3(10), 71-77.
4. BSN. 2012. Indonesian national standard: 7752 2012: Procedures for measuring soil infiltration rates with double rings. BSN, Jakarta.
5. Chow V.T., Maidment D.R., Mays L.W. 1998. Applied hydrology. McGraw-Hill, Singapore.
6. Dagadu J., Nimbalkar P. 2012. Infiltration studies of different soils under different soil conditions and comparison of infiltration models with field data. International Journal of Advanced Engineering Technology, III(II), 154–157.
7. Dahak A., Boutaghane H., Merabtene T. 2022. Parameter estimation and assessment of infiltration models for Madjez Ressoul Catchment, Algeria. Water, 14(8), 1185. https://doi.org/10.3390/w14081185
8. Farida A., Rosalina F. 2022. Landslide danger level in the Klagison watershed, Sorong City using a geographic information system. Econews, 5(1), 1–6. https://doi.org/10.47826/econews.5.1.p.1-6
9. Henry U.I., Ibrahim I.I., Habib L.I., Henry M.U. 2016. Evaluation of water infiltration equations on Fadama soils of Jos – North, Plateau State, Nigeria. Journal of Biology, Agriculture and Healthcare, 6(16), 25–32.
10. Hillel D. 1973. Soil and water, physical principles and processes - Google Play Books. Academic Press, New York and London.
11. Limantara L.M. 2018. Hydrological Engineering-Revised Edition. Andi Yogyakarta, Yogyakarta.
12. Mishra S.K., Tyagi J.V., Singh V.P. 2003. Comparison of infiltration models. Hydrological Processes, 17(13), 2629–2652. https://doi.org/10.1002/hyp.1257
13. Moriasi D., Arnold J.G., Van Liew M.W., Bingner R.L., Harmel R.D., Veith T.L. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE, 50(3), 885–900. http://dx.doi.org/10.13031/2013.23153
14. Ngadisih N., Suryatmojo H., Satriagasa M.C., Annisa M., Kumolo C. 2020. Comparison of three infiltration models on agricultural and agroforestry land in the Merawu watershed, Banjarnegara. Jurnal Ilmiah Rekayasa Pertanian dan Biosistem, 8(1), 20–32. https://doi.org/10.29303/jrpb.v8i1.157
15. Oku E., Aiyelari A. 2011. Predictability of Philip and Kostiakov infiltration models under inceptisols in the humid forest zone, Nigeria. Agriculture and Natural Resources, 45(4), 594–602.
16. Panahi M., Khosravi K., Ahmad S., Panahi S., Heddam S., Melesse A.M., Omidvar E., Lee C.W. 2021. Cumulative infiltration and infiltration rate prediction using optimized deep learning algorithms: A study in Western Iran. Journal of Hydrology: Regional Studies, 35, 1-19. https://doi.org/10.1016/j.ejrh.2021.100825
17. Ponce V.M. 2014. EH, Chap. 03, reading, hydrologic measurements, engineering hydrology, principles and practices, second edition. San Diego State University.
18. Quan Q.D. 2010. Win TR55 small watershed hydrology overview modelling single. https://slidetodoc.com/win-tr55-small-watershed-hydrology-overview-modeling-single/
19. Radhika R., Firmansyah R., Hatmoko W. 2017. Computation of surface water availability in Indonesia based on satellite data. Jurnal Sumber Daya Air, 13(2), 115–130. https://doi.org/10.32679/jsda.v13i2.206
20. Rahmati M., Weihermüller L., Vanderborght J., Pachepsky Y.A., Mao L., Sadeghi S.H., Moosavi N., Kheirfam H., Montzka C., Van Looy K., Toth B., Hazbavi Z., Al Yamani W., Albalasmeh A.A., Alghzawi M.Z., Angulo-Jaramillo R., Antonino A.C.D., Arampatzis G., Armindo R.A. et al. 2018.

Development and analysis of the soil water infiltration global database. Earth System Science Data, 10(3), 1237–1263. https://doi.org/10.5194/essd-10-1237-2018

21. Rahmati M., Latorre B., Moret-Fernández D., Lassabatere L., Talebian N., Miller D., Morbidelli R., Iovino M., Bagarello V., Neyshabouri M.R., Zhao Y., Vanderborght J., Weihermüller L., Jaramillo R.A., Or D., Th. van Genuchten M., Vereecken H. 2022. On infiltration and infiltration characteristic times. Water Resources Research, 58(5), 1–19. https://doi.org/10.1029/2021WR031600
22. Razali N.M., Wah Y.B. 2011. Power comparisons of Shapiro-Wilk, Kolmogorov-Smirnov, Lilliefors and Anderson-Darling tests. Journal of Statistical Modeling and Analytics, 2(1), 21–33.
23. Ritawati S., Mawardi M., Goenadi S. 2012. Suitability Philips infiltration model for surface runoff prediction using curve number method. Agritech, 32(3), 331-339.
24. Rubel F., Kottek M. 2010. Observed and projected climate shifts 1901-2100 depicted by world maps of the Köppen-Geiger climate classification. Meteorologische Zeitschrift, 19(2), 135–141. https://doi.org/10.1127/0941-2948/2010/0430
25. Ruth A., Kelechi I., Ijeoma D. 2015. Philip model capability to estimate infiltration for solis of Aba, Abia State. Journal of Earth Sciences and Geotechnical Engineering, 5(2), 1792–9660.
26. Salifu A., Abagale F.K., Kranjac-Berisavljevic G. 2021. Estimation of infiltration models' parameters using regression analysis in irrigation fields of Northern Ghana. Open Journal of Soil Science, 11, 164–176. https://doi.org/10.4236/ojss.2021.113009
27. Sayama T., Araki R., Yamamoto K., Apip. 2021. Characteristics of soil and hillslope responses in humid tropical forests in Sumatra, Indonesia. Hydrological Research Letters, 15(2), 23–30. https://doi.org/10.3178/hrl.15.23
28. Shiraki K., Tanaka N., Chatchai T., Suzuki M. 2017. Water budget and rainfall to runoff processes in a seasonal tropical watershed in northern Thailand. Hydrological Research Letters, 11(3), 149–154. https://doi.org/10.3178/hrl.11.149
29. Strohmeier S. 2017. Soil water plant relationship. Integrated Water and Land Management Program (IWLMP) International Center for Agricultural Research in the Dry Areas (ICARDA) Amman, JORDAN. https://repo.mel.cgiar.org/handle/20.500.11766/10179
30. Subramanya K. 2013: Engineering hydrology 4th edn. McGraw Hill Education, India.
31. Sugiyono. 2007. Statistics for research. 11th edn. PT Alfabeta Bandung, Bandung.
32. Thomas A.D., Ofosu A.E., Emmanuel A., De-Graft A.J., Ayine A.G., Asare A., Alexander A. 2020. Comparison and estimation of four infiltration models. Open Journal of Soil Science, 10(2), 45–57. https://doi.org/10.4236/ojss.2020.102003
33. Tkachuk O., Yaruta Y., Shevchuk O. 2022. Assessment of Application Conditions of Infiltration Basins for Regulation of Urban Rainwater Drainage. Journal of Ecological Engineering, 23(2), 191–195. https://doi.org/10.12911/22998993/144718
34. Uloma A. R., Samuel A. C., Kingsley I. K. 2014. Estimation of Kostiakov's infiltration model parameters of some sandy loam soils of Ikwuano – Umuahia, Nigeria. Open Transactions on Geosciences, 1(1), 34–38. http://dx.doi.org/10.15764/GEOS.2014.01005
35. Watershed Management Laboratory, G.M.U. 2018. Watersheds in the Papua Region – Watershed Conservation. https://konservasidas.fkt.ugm.ac.id/2018/05/11/das-di-wilayah-papua/
36. Yamamoto E.M.S., Sayama T., Yamamoto K., Apip. 2020. Comparison of runoff generation methods for land use impact assessment using the SWAT model in humid tropics. Hydrological Research Letters, 14(2), 81–88. https://doi.org/10.3178/hrl.14.81
37. Zakwan M. 2019. Comparative analysis of the novel infiltration model with other infiltration models. Water and Environment Journal, 33(4), 620–632. https://doi.org/10.1111/wej.12435