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Evaluating Model Effectiveness for Soil Infiltration Attribute: Comparison of Green-Ampt, Horton and Modified Green-Ampt Infiltration Models

Mosammat Mustari Khanaum[1], Md. Saidul Borhan[2]

[1]Civil, Construction and Environmental Engineering, North Dakota State University, Fargo, ND, USA
[2]Texas Department of Transportation, Maintenance Division, TxDOT, Austin, TX, USA
Email: mosammat.khanaum@ndsu.edu

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Abstract

Soil infiltration is a very important concept in hydrology as well as irrigation, which plays a vital role in estimating surface runoff and groundwater recharge. It is a complicated process that varies with numerous factors. Accurate estimation of soil infiltration is required for future irrigation, and many other purposes. To estimate the infiltration process, there are numerous models. The majority of them have some presumptions, a unique calculation method, and some limitations. The purpose of the paper was to assess the model's performance for a similar hypothetical scenario involving soil infiltration. It compared the infiltration rate, runoff rate, and incremental infiltration versus time for three different infiltration models: the Green-Ampt model (GA), the Horton model and the Modified Green-Ampt (MGA) model. A spreadsheet was used to calculate the Horton model, and HYDROL-INF (V 5.03) was used to simulate the other two models. Among those three models, the MGA model outperformed those three models, while the GA model produced greater infiltration rate than rainfall, which was insensible. The study showed that the MGA model, which provides useful infiltration predictions, outperformed the other two infiltration models. Since the Horton model does not consider ponding conditions, it is only applicable when the effective rainfall intensity exceeds the final infiltration capacity. Moreover, the GA model's initial infiltration rate is irrational because it disregards the intensity of the rainfall. The results of this study will assist in selecting the most accurate method for estimating soil infiltration for agricultural purposes.

Keywords

Infiltration, Groundwater Recharge, Green-Ampt, Horton Model, Modified Green-Ampt

1. Introduction

Infiltration refers to the process by which precipitation moves downwards through the surface of the earth and fills soil moisture, recharges aquifers, and eventually supports stream flows during dry periods (Viessman & Gary, 2003). It is the flow of fluid into a substance through pores or small openings. The word is commonly used to denote the flow of water into the soil. It plays a key role in surface runoff and groundwater recharge. Infiltration is a very important concept in hydrology which depends on many factors and is influenced by different soil parameters.

Soil layer, texture, and other soil properties affect soil infiltration rate. Various soil properties affect moisture content levels to fluctuate from one layer to the other causing a decrease in the infiltration rate. Scientists have developed equations/simulation techniques to represent this infiltration process. There are several models to estimate infiltration. For computing infiltration there exist several empirically based equations, such as Horton's equation (Horton, 1933), and physically based equations, such as the Green & Ampt (1911) infiltration equation, which were developed using the laws of physics. Some researchers also modified the existing model to produce a better result for example Modified Green-Ampt model developed by Chu & Mariño (2005).

Few studies have been done on different soil infiltration models (Sihag et al., 2017, Song et al., 2021, Niyazi et al., 2022, Khanaum & Borhan, 2022). To the best of our knowledge, little research has been done comparing common and simple methods of infiltration from an agricultural perspective. The objective of this paper was to evaluate model effectiveness for soil infiltration in identical situations. It compared infiltration rate; runoff rate and incremental infiltration over time with three models—the Green-Ampt model (GA), Horton model, and Modified Green-Ampt (MGA). The paper described similarities and dissimilarities among the results produced separately with those three infiltration models.

2. Materials and Methods

For infiltration computation with three models, identical hypothetical events and scenarios with a steady, single rainfall event with 5 cm/hr and identical soil parameters were considered (**Table 1**). Three models: the Green-Ampt (GA) model, the Horton model, and the Modified Green-Ampt (MGA) model—were run for that particular situation. The Modified Green-Ampt model was run by HYDROL-INF software (version 5.03) (Chu & Mariño 2006) and its output .txt file was converted to an excel file for producing charts and comparison purposes.

Table 1. Soil hydraulic and meteorological parameters used in this study.

Soil type	Initial Water Content θ_0 (cm³/cm³)	Saturated Water Content θ_s (cm³/cm³)	Effective Hydraulic Conductivity K_e (cm/hr)	Suction Head h_s (cm)	Initial infiltration capacity f_0 (cm/hr)	Final infiltration capacity f_c (cm/hr)	Recession constant k (1/hr)	Rainfall intensity (cm/hr)
Silt loam	0.135	0.45	0.65	18.03175	44.95	1.45	4.25	5 (steady & single event)

After simulating the Modified Green-Ampt model, initial and final infiltration capacities data was taken from the output to use in the Horton model. The recession constant for the Horton model was chosen so as to exactly fit with the final infiltration capacity value obtained from the Modified Green-Ampt model.

All three calculations/simulations were done for a 2-hour duration. For the Modified Green-Ampt model, 120 steps of 0.01667 hr. each (in total, 2 hours) were selected for the simulation purposes. Calculation of the Horton model also performed for 2 hours duration. However, time was not an initial parameter for the Green-Ampt model. The time needed for the wetting front to reach depth z to be calculated. For that, the computation was for up to 2 hours in order to become identical to the other two models. Calculations of Green-Ampt model and Horton Model were done in MS Excel. Finally, all output data from the three models were compared in MS Excel.

Theory and Calculation

Green-Ampt Model: The Green-Ampt model is a conceptual representation of the infiltration process which was developed by Green & Ampt (1911) based on Darcy's Law (McCuen 1998). The model follows some key assumptions: 1) piston flow with a sharply defined wetting front; 2) homogeneous soil; 3) uniform initial moisture condition; 4) the soil surface is covered with ponded water of negligible depth. The model derives the following four major equations (Green & Ampt, 1911):

$$I_z = z(\theta_s - \theta_0) = z\theta_f \tag{1}$$

$$i_z = K_e\left[1 + \frac{h_s\theta_f}{I_z}\right] = K_e\left[1 + \frac{h_s(\theta_s - \theta_0)}{I_z}\right] \tag{2}$$

$$K_e t_z = I_z - h_s\theta_f \ln\left[\frac{h_s\theta_f + I_z}{h_s\theta_f}\right] = I_z - h_s(\theta_s - \theta_0)\ln\left[1 + \frac{I_z}{h_s(\theta_s - \theta_0)}\right] \tag{3}$$

$$t_z = \frac{z\theta_f}{K_e} - \frac{h_s\theta_f}{K_e}\ln\left(\frac{h_s + z}{h_s}\right) \tag{4}$$

where,

i_z = infiltration rate when the wetting front reaches depth z (cm/hr).

K_e = effective hydraulic conductivity (cm/hr) (For bare ground conditions, K_e is about a half of the saturated hydraulic conductivity K_s).

z = depth of the wetting front (cm).

h_s = suction head at the wetting front (cm).

I_z = amount of the cumulative infiltration water when the wetting front is at depth z (cm).

θ_s = saturated volumetric water content (soil porosity).

θ_0 = initial volumetric water content.

θ_f = difference between θ_s and θ_0 (initial soil moisture deficit).

t_z = time for the wetting front to reach depth z (hr).

Compared to other empirical models, the Green-Ampt model has some advantages. It is a simple model; its parameters can be gained from the physical properties of soil. Moreover, the model has widely been used to produce good results for profiles that become dense with depth; for profiles where, hydraulic conductivity increases with depth; for soils with partially sealed surfaces; and for soils having nonuniform initial water contents (Gupta, 2017).

Horton Model: Horton (1939) introduced a three-parameter equation to estimate soil infiltration. His model is expressed with the following equation (Horton, 1939):

$$f(t) = f_c + (f_0 - f_c)e^{-kt} \tag{5}$$

where,

f_0 = initial infiltration capacity (L/T).

f_c = final/equilibrium infiltration capacity (L/T).

k = recession constant [1/T], controls the deceasing rate of the infiltration capacity.

$f(t)$ = infiltration capacity at time t (in/hr).

The parameters f_0 and k cannot be determined from soil water properties and must be ascertained from experimental data (Gupta, 2017). Errors in the estimate of these values can lead to serious errors in the calculation of the amounts of infiltration, particularly for longer periods of time (Raudkivi, 1979). Horton model is applicable only when effective rainfall intensity is greater than f_c. The potential cumulative infiltration can be obtained by following the integration equation (Horton, 1939):

$$F(t) = \int_0^t f(t) = f_c t + \left(\frac{f_0 - f_c}{k}\right)\left(1 - e^{-kt}\right) \tag{6}$$

If the soil has an infiltration capacity (f) greater than rain intensity (i) then all rain is absorbed by the soil and there is no surface runoff. When i is greater than f, a surface runoff will occur at the rate of (i-f). Horton termed this difference as "rainfall excess" (Chow et al., 1988).

Modified Green-Ampt Model: Chu & Marino (2005) developed the Modified Green-Ampt (MGA) model to determine the ponding status for layered heterogeneous soil profile under unsteady rainfall, a model for simulating infiltration and surface runoff. Using Modified Green-Ampt, they simulated the subsequent infiltration and rainfall excess during the post-ponding period and calculated the movement of the wetting front through layered soils, and identify ponding and non-ponding conditions. They emphasized dealing with the change between ponding and non-ponding calculations. In this model, drainage and soil moisture redistribution are simulated primarily based on water availability and soil permeability and some drainage criteria, such as unsaturated hydraulic conductivity, field capacity, wilting point, initial water content, inflow from the overlying cell, and evapotranspiration.

Pre-Ponding Computations: Ponding Condition ($r = i$) and Ponding Time: equations to determine how long it takes to reach the ponding status (Chu & Marino, 2005):

$$t_p = \frac{1}{r_{m_p}}\left(I_p - \sum_{k=1}^{m_p-1} r_k \Delta t\right) + \left(m_p - 1\right)\Delta t \tag{7}$$

$$t_0 = t_p - t_{pd} \tag{8}$$

$$\begin{aligned} t_{pd} = {} & t_{z_{n_p-1}} + \frac{\theta_{fn_p}}{K_{n_p}}\left(z_p - z_{n_p-1}\right) \\ & + \theta_{fn_p}\left[\sum_{j=1}^{n_p-1} z_j\left(\frac{1}{K_j} - \frac{1}{K_{j+1}}\right) - \frac{h_{sn_p}}{K_{n_p}}\right]\ln\left(\frac{z_p + h_{sn_p}}{z_{n_p-1} + h_{sn_p}}\right) \end{aligned} \tag{9}$$

Location of the wetting front: equation to determine how deep the wetting front moves at the ponding time (Chu & Marino, 2005):

$$z_p = \frac{K_{n_p} h_{sn_p} + r_{m_p} z_{n_p-1} - r_{m_p} K_{n_p} \sum_{j=1}^{n_p-1} \frac{z_j - z_{j-1}}{K_j}}{r_{m_p - K_{n_p}}} \tag{10}$$

Pre-Ponding Computations-Cumulative Infiltration: equation to determine how much rainwater has infiltrated into soils at the ponding time (Chu & Marino, 2005):

$$I_p = \sum_{j=1}^{n_p-1}\left(z_j - z_{j-1}\right)\theta_{fj} + \left(z_p - z_{n_p-1}\right)\theta_{fn_p} \tag{11}$$

Equation to calculate infiltration Rate at the ponding time (Chu & Marino, 2005):

$$r_{m_p} = i_{z_p} = \frac{z_p + h_{sn_p}}{\sum_{j=1}^{n_p-1} \frac{z_j - z_{j-1}}{K_j} + \frac{z_p - z_{n_p-1}}{K_{n_p}}} \tag{12}$$

Equation to calculate Post-Ponding Computations-mass balance checking (Chu & Marino, 2005):

$$P_k = I_k + S_k + R_k \tag{13}$$

Equation to calculate Ponding status checking (Chu & Marino, 2005):

$$r_k < f_k = i_z \quad S_{k-1} = 0 \tag{14}$$

This model follows some key assumptions: 1) homogeneous, layered soils; 2) uniform and variable initial soil moisture distribution. The major advantage of the Modified Green-Ampt model is that it is very simple and has a user-friendly Windows-based interface. This model easily deals with the shift between ponding and non-ponding conditions and tells the exact ponding time and depth. The model is applicable for both steady and unsteady rainfall; single and multiple rainfall events, *i.e.*, it can continuously simulation for combined wet and dry time periods. Chu & Mariño (2006) introduce a simple and very efficient Windows-based software, HYDROL-INF, to calculate infiltration using both Green-Ampt and Modified methods (Khanaum & Borhan, 2022).

3. Results

Incremental infiltration over time for Modified Green-Ampt (MGA) model and Horton model is shown in **Figure 1**. It shows a steady and highest infiltration of 0.085 cm initially for both models. For the Modified Green-Ampt model, incremental infiltration is sharply decreased after 0.18 hours and after 1 hour the incremental infiltration is pretty stable at 0.03 - 0.025 cm. Horton's model reveals a more stable initial incremental infiltration for 0.65 hours. For this model, incremental infiltration is sharply decreased after 0.65 hours and after 1 hour it shows a similar trend as the Modified Green-Ampt model.

Figure 2 shows incremental infiltration and incremental runoff over time for the Modified Green-Ampt model. It shows a steady and high infiltration of 0.085 cm initially and sharply decreased after 0.18 hours, and after 1 hour, the incremental infiltration is stable at 0.03 - 0.025 cm. The incremental runoff curve is just the opposite of the incremental infiltration curve. As 100% rainfall is precipitated for 0.18 hours; therefore, there initiate no runoff for 0.18 hour. After

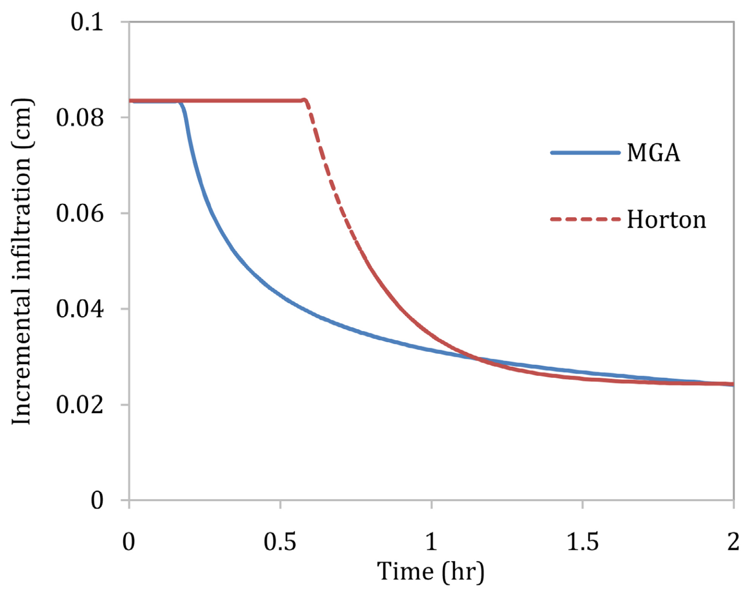

Figure 1. Comparing incremental infiltration in modified green-ampt and Horton models.

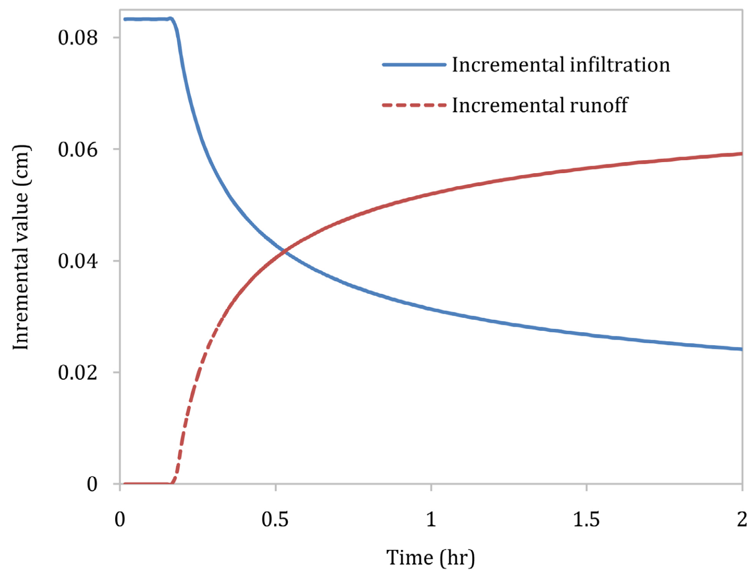

Figure 2. Incremental infiltration and runoff in modified Green-Ampt model.

0.18 hours there is a sharp increase in runoff as the ponding condition happens at 0.183 hours. The Modified Green-Ampt model specifically shows ponding time; before that time 100% of rainfall is precipitated by the soil. After 1-hour, incremental runoff increases slowly with time.

Infiltration capacity, actual infiltration rate, and rainfall intensity curves were generated using the Horton model is shown in **Figure 3**. The chart shows that initially, the infiltration capacity of the soil is fairly high which is 44.95 cm/hr. even though the rainfall intensity is 5 cm/hr. As it is a steady and single event, therefore, the rainfall intensity curve shows a straight horizontal line at 5 cm/hr. Finally, the actual infiltration rate curve follows a rainfall rate before the rainfall is lower than the infiltration capacity. After that when the infiltration capacity rate becomes lower than the rainfall rate, the actual infiltration rate follows the infiltration capacity curve.

The infiltration rate over time among the three models was compared (**Figure 4**). The initial infiltration rate chart differs significantly for the Green-Ampt model from that of the other two models. On the other hand, Horton and the Modified Green-Ampt model showed the almost identical initial results. After an hour, all three models had a similar trend. Though the rainfall intensity was 5 cm/hr, the Green-Ampt model showed that initial infiltration rate of 12.37 cm/hr which is inconceivable.

Though Horton and Modified Green-Ampt models show similar results initially, the Horton model shows 100% infiltration for more than half an hour. After that period, it follows a similar trend as the other two models. As the Horton model does not give any emphasis on ponding or non-ponding condition, and only depends on infiltration capacity (f) and decay constant, it shows 100% infiltration until rainfall intensity (i) become less than infiltration capacity (f).

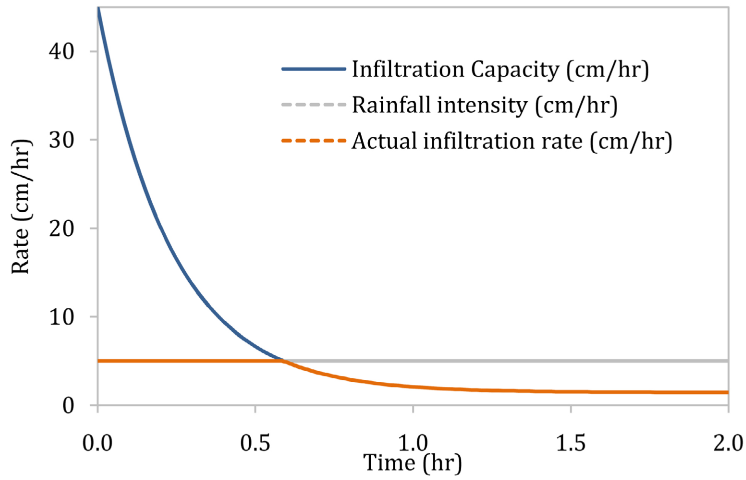

Figure 3. Comparing rainfall intensity, infiltration capacity and actual infiltration rate in Horton model.

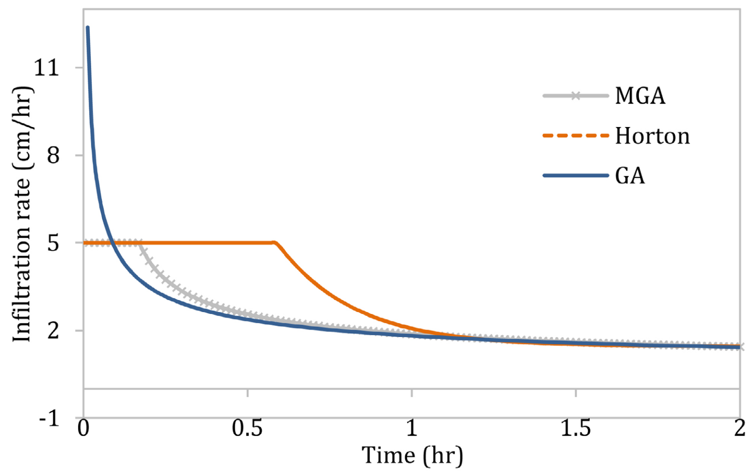

Figure 4. Comparing infiltration rate in three models.

When i become higher than f, from that time the infiltration curve follows infiltration capacity, which is the basic principle of this model. The statistics of cumulative infiltration, cumulative runoff, and infiltration rate for three models till the ponding condition were shown in **Table 2**.

Among these three models, Modified Green-Ampt produces more authentic result as it considers more variables/parameters than the other two. Infiltration is a complex process that depends on several parameters. Therefore, it is wise to consider as many parameters as possible for computation or simulation. However, previous research showed different result, where the Horton model fit better compare to other models under different experimental conditions (Song et al., 2021).

Green-Ampt and Modified Green-Ampt models show an almost similar trend for runoff rate over time, though Horton's model initially differs from those two (**Figure 5**). As mentioned earlier, the model does not consider ponding or non-ponding condition, and only depends on infiltration capacity, so it follows rainfall

Table 2. Comparison of modelling results of three models up to ponding time.

Time (hr)	Cumulative infiltration (cm)			Cumulative runoff (cm)			Infiltration rate (cm/hr)		
	GA	Horton	MGA	GA	Horton	MGA	GA	Horton	MGA
0.0167	0.315	0.084	0.083	0	0	0	10.417	5	5
0.0333	0.473	0.167	0.167	0	0	0	7.487	5	5
0.0500	0.315	0.251	0.250	0	0	0	6.506	5	5
0.0667	0.315	0.334	0.333	0	0	0	5.974	5	5
0.0833	0.315	0.418	0.417	0.246	0	0	4.984	5	5
0.1000	0.315	0.501	0.500	0.401	0	0	4.55	5	5
0.1167	0.315	0.585	0.583	0.051	0	0	4.521	5	5
0.1333	0.315	0.668	0.667	0.175	0	0	4.213	5	5
0.1500	0.315	0.752	0.750	0.198	0	0	3.961	5	5
0.1667	0.315	0.835	0.833	0.395	0	0	3.865	5	5
0.1833	0.315	0.919	0.914	0.41	0	0.0022	3.696	5	4.687

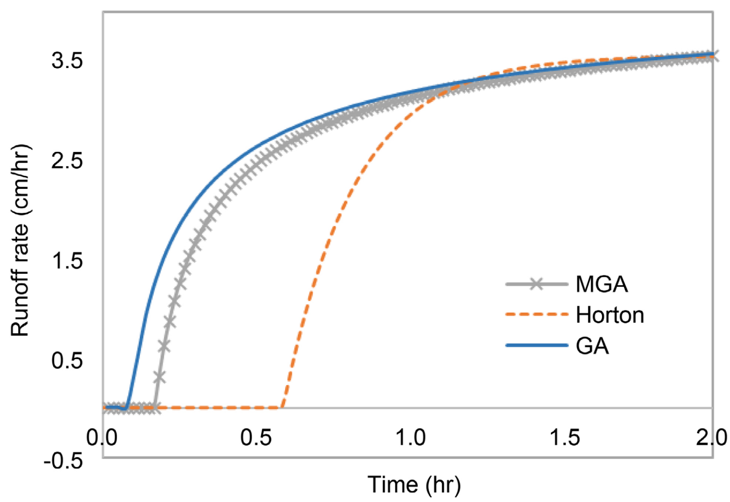

Figure 5. Comparing runoff rate in three models.

intensity (i) until i is less than f. Therefore, in **Figure 5** Horton model shows no runoff for more than 1/2 hour. Niyazi et al. (2022) noted a similar pattern and conclude that the results generated by the Horton model were highly inconstant due to the initial infiltration rates f_o. Actually, when infiltration capacity becomes higher than the rainfall rate, at that time the model shows the initiation of runoff. The highest runoff rate of the study was almost similar for each model, 3.45 cm/hr. at 1.5 hour time.

4. Discussion

Infiltration is a critical perception in hydrology that is used to estimate infiltration and runoff modeling. Many models exist to estimate the infiltration process;

however, the process is influenced by a variety of factors. The study employed three different infiltration models: the Green-Ampt model, the Horton model, and the Modified Green-Ampt. In comparison with the modified Green-Ampt model, the Horton model produced nearly identical results; however, the Horton model does not consider the ponding conditions, which leads to a measurement that is more than the original period due to the 100% infiltration rate. For this reason, the model applies only when effective the rainfall intensity exceeds the final infiltration capacity. As a result, the infiltration capacity decreases exponentially over time if rainfall is continuous and exceeds infiltration capacity. With the cutoff of the rainfall event, infiltration capacity will recover over time depending on how dry the dry period is.

A significant component of the Green-Ampt model and the Modified Green-Ampt model was the consideration of ponding conditions, which is an important factor in the estimation of infiltration. Under the ponding condition, as the wetting front moves deeper and deeper into the soil with time, the infiltration rate decreases. Depending on the Green-Ampt model, it is unlikely that it will produce more infiltration than rain. This model assumes that the soil is homogeneous and that the initial moisture conditions are uniform. However, in reality, these assumptions are not accurate. Nonetheless, this earliest model gives researchers the opportunity to work with and develop different infiltration models.

The Modified Green-Ampt model incorporates pre-ponding, ponding, and post-ponding conditions. Additionally, this model is capable of outperforming the Green-Ampt model due to its ability to incorporate layered soils and variables in soil moisture conditions at the start of the simulation. In order to estimate soil infiltration, it is important to consider as many variables as possible. Otherwise, this could lead to an underestimation of runoff and other critical parameters.

5. Conclusion

Infiltration is a very important perception in hydrology which plays a vital role in watershed modeling, runoff modeling, flood frequency analysis, hydrologic structure design, and above agricultural purposes. It is a complicated process that is affected by numerous factors. The paper revealed that among Green-Ampt, Horton, and Modified Green-Ampt models; Modified Green-Ampt produces a more realistic result as it considers more variables/parameters than the other two. Horton's model produces almost similar results as the Modified Green-Ampt model, but the model does not consider ponding condition, for that it measures a 100% infiltration rate more than the authentic period. Among those three models, depending on the Green-Ampt model is much more unlikely, as it produces a much higher infiltration rate than rain, which is not sensible. However, the Green-Ampt model is the earliest model, which gives us the opportunity to work and develop an infiltration model. It is very important to consider as many parameters as possible for simulating soil infiltration. Otherwise, runoff and other important parameters are likely to be miscalculated. Based on the results of the study, the Modified Green-Ampt model performed better than the other two models in determining the variations in infiltration rates across different soil profiles. The study will be able to provide guidance to future scientists in simulating soil infiltration using a variety of models. In addition, the study will provide insight into irrigation in agriculture, thereby helping agricultural policymakers to make informed decisions regarding irrigation in the future.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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