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# VERTISOLS INFILTRATION RATE AND MODEL PERFORMANCE EVALUATION OF VARIOUS LAND-USE CONDITIONS DURING SOUTHERN ETHIOPIA'S DRY SEASON

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**Abstract:** The research was conducted on the field and models of vertisol soil types under varied land in southern Ethiopia's semi-arid Arba Minch university research centre site to measure infiltration and determine infiltration rates. The infiltration rate and model performance evaluation of the specific land use conditions affect the design and evaluation of surface and sub-surface irrigation methods. The infiltration rate is investigated on two different types of land (vegetable-covered land and bare land) and two different types of models (Horton and Kostiakov models). The experimental infiltration depth of the above soil conditions is measured using a double-ring infiltrometer. The research aims to figure out the field-measured infiltration rate, model infiltration rates, and basic infiltration rate, identify the impact of infiltration factors on infiltration rate, and find the best-fitted infiltration model. The findings from multiple infiltration models were compared with actual field data. The graphs of infiltration were generated to find the best fitting model for a certain vertisol soil type and two lands. The determination, correlation coefficient, bias, root mean square error (RMSE), model efficiency, determination coefficient ($R^2$), slope, correlation coefficient (r), average percentage error, and the gradient were the performance indicators examined for the optimum fitting of the model. The Kostiakov model's results are the best fit to observe field data for estimating infiltration rates at any given period in the research region by taking into account the infiltration numerical software performance indicators. The vegetable cover land infiltration rate is higher than un-disturbed bare land.

**KEY WORDS:** land use, Infiltration rate, model performance, Dry season, vertisols

Journal of Digital Food, Energy & Water Systems, 3 (1): 16 - 28, 2022
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## 1.0 INTRODUCTION

Water availability is critical for the development of agriculture and food security. The satisfaction of increasing population and per capita consumption demands forecasts that agricultural productivity will need to expand by 70% by 2050 (FAO, 2009). This population increase affects the hydrologic cycle from a local to a global scale through agricultural expansion (Rockstrom et al., 2014). The infiltration is the most significant process in the hydrologic cycle that affects agricultural water production (Brouwer et al., 1988). In recent years, the population has increased rapidly, and rising water consumers from many sectors have made the study region's water supply a cause of concern and conflict.

Surface irrigation system design and evaluation are simplified when infiltration modes simulate surface and subsurface flow. The soil's infiltration characteristics are quantified when in-situ infiltration data is computationally matched to models' infiltration (Oku E., and Aiyelari A., 2011). Several studies on different infiltration models have been conducted to determine model parameters, model effectiveness and applicability to various soil conditions and land uses (Abubakr Rahimi and Bayzedi, 2012; Asma et al., 2022; Ogbe et al., 2011; Sunith et al., 2018; Parveen et al., 2018; and Rashidi et al., 2014). They do not, however, consider the interplay between soil and agricultural land use factors in spatial variation. Additionally, despite these facts, no clear finding demonstrates infiltration capacity, the best fit model, and diverse land-use conditions of the study region's most prominent soil types (Vertisols).

As a result, developing models for specific time and space is critical for accurate in-situ quantification of this process. The study's objective was to determine the soils' infiltration capacity, model infiltration rate, evaluate infiltration factor on infiltration rate value variation, and choose the optimal infiltration model for the study location. Therefore, the infiltration rate of different land use and performance of infiltration models (Kostiakov, Horton's infiltration models) was investigated in this study using infiltration model performance indicators as tools under a vertisols soil type.

Journal of Digital Food, Energy & Water Systems, 3 (1): 16 - 28, 2022
ISSN 2709-4529


## 2.0 MATERIALS AND METHODS

### 2.1 Descriptions of the Study Area

The field experiment was implemented in the south-western zone of the South Nation and Nationality and People (SNNP) regional state at Arba Minch university demonstration farm, located 454 km south of Addis Ababa. Geographically, it is located at a latitude of 5°40'0" N to 6°20'0" N, a longitude of 37°20'0" E to 37°40'0" E, and an altitude of 1203m, as shown in Figure 1.

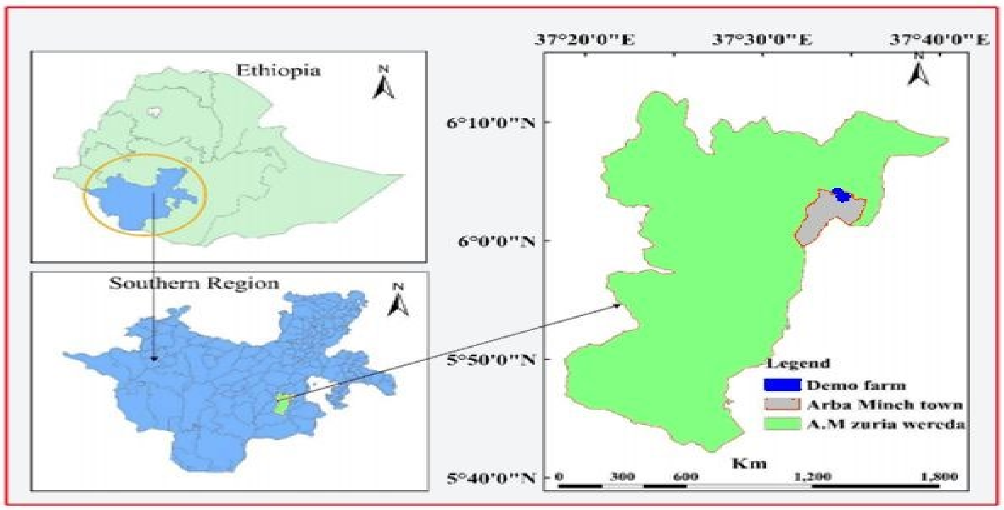


Figure 1. The study area Location map

### 2.2 Treatments' design and setting

The treatment of this study consists of one field infiltration measurement method (Double Ring infiltrometer method), two types of land use conditions (bare and vegetable cover land), and a vertisol soil type, which were used for the measurement of all infiltration data. There were a total of 4 samples for each land use condition site.

The double ring infiltrometer instrument was settled and driven 15cm deep into the soil. The size of the infiltrometer is 25cm in-depth, 30 cm in inner and 60 cm in outer diameter.

### 2.3 Materials to Conduct an Infiltration Test

- **The infiltrometer (double ring)** has a diameter of 30 & 60 cm and a 25cm height.
- **A hammer** is used to drive the ring into the soil.
- **A spade** is used to collect soil samples from the site to determine physical properties.
- **Bags** are used to transport soil samples to the laboratory.
- **A transparent ruler** measures the amount of water depleted in the soil with respect to time.

Journal of Digital Food, Energy & Water Systems, 3 (1): 16 - 28, 2022
ISSN 2709-4529


- **A Stop Watch** is used to read the proposed time.
- **A sufficient amount of water** is added to rings for depletion measurement
- **Plastic wrap** is used to prevent soil disturbance during the initial water application

## 2.4 Infiltration Models

The following infiltration models were evaluated to determine which model is the best fit for the experimental field infiltration rate:

**Horton's model:** Horton described the loss of infiltration capability as an exponential drop over time and generated the following equation (Horton RL., 1938)

$$f = fc + (fo - fc)e^{2-kt} \quad (1)$$

Where: f = infiltration capacity at any time t; fc = final steady-state infiltration capacity; fo = initial infiltration capacity; k = Horton's constant representing the rate of decrease in infiltration capacity; t = time in hours.

**Kostiakov model (Kostiakov AN, 1932)**

$$f = at^b \quad (2)$$

Where: f = cumulative infiltration at any time t; a and b = constants, t = time in minute,

**Model Performance Indicators:** Two infiltration models (Horton, and Kostiakov) were evaluated with the comparison of field observed infiltration rate simultaneously using the infiltration parameters. Several researchers used a variety of statistical methods for comparison of infiltration model performance like: Nash-Sutcliffe (NS), root means square error (RMSE), and determination coefficient ($R^2$) indicator (Parveen et al., 2018; Asma et al., 2022).

The $R^2$ and the RMSE were used to assess each model's goodness of fit in terms of how it describes the field measured infiltration well. The $R^2$ value reflects how well each model explains data variances, but the RMSE reveals how far the model results differ from the observed values. As a result, a high $R^2$ value near 1 and a low RMSE value around 0 both imply that the anticipated and observed infiltration curves are in good agreement.

**The RMSE** is a measure of the difference between projected and measured values and is widely used to assess the exact hydrology models. The RMSE formula describes as follow:

$$\boldsymbol{RMSE} = \sqrt{\frac{(\sum_{i=1}^{n}(pi - oi)^2)}{n}} \quad (3)$$

Where: Pi is Predicted results; Oi is Measured results, and n is the measurements number

**Determination coefficient ($R^2$)** is the predicted value of the infiltration rate plot versus observed values. Its value is greater than 0.75, indicating that the best fit to the observed data is described as the following formula.

$$R^2 = 1 - \frac{SSE}{SST} \quad (4)$$

Journal of Digital Food, Energy & Water Systems, 3 (1): 16 - 28, 2022
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Where: SSE is explained as the Sum of Square simulated data, and SST is the Total Sum of Square simulated data

The $R^2$ values indicate the degree to which each model explains data variations. RMSE shows the amount of divergence of the model values from the observed values.

**Nash Sutcliffe:** When comparing hydrological parameters, Nash-Sutcliffe is the most commonly utilized method. Nash-equation is:

$$NS = 1 - \frac{\sum_{ti=1}^{n}((yti^{m}) - yti)^2}{\sum_{ti=1}^{n}((yti - \bar{y})^2)} \qquad (5)$$

Where: n is the observed data number; yti is the value of observation; $yti^m$ is value of model, and y is the value of average observation

A very satisfactory performance indicates of Nash-Sutcliffe is above 90%, 80–90% value range indicates fairly good performance, and below 80% indicates an unsatisfactory fit.

**Bias:** it is the performance indicator of an infiltration model, which calculates the average difference between the observed and predicted index values. The bias value is zero, called "unbiased." It is defined by:

$$Bias = \frac{\sum_{i}^{n}(x-y)}{n} \qquad (6)$$

**Percentage average error** is defined as follows:

$$PAE = \frac{\sum_{i=1}^{n}\left(\frac{x-y}{y}\right)}{n} * 100 \qquad (7)$$

Where: PAE is average percentage error, x is values of observed data, y is values of computed data

**Models selection criteria:** the selection of the model's criteria are: they are most popular, simple, and applicable in the irrigation field, and the main one is to compare semi-empirical (Horton equation) and empirical (Kostiakov equation).

## 1.5 Data Collection and Analysis

Field infiltration tests, laboratory analysis, and documentation were all used to collect data. Soil infiltration rates were measured on two different soil types. The primary data for the infiltration test and the examination of soil physical parameters were obtained in the laboratory.

The soil infiltration rate of the study locations during the dry season was measured with a Double Ring Infiltrometer. For vegetable cover land conditions found at the Arba Minch demo farm, readings were obtained at regular intervals of 2, 5, 10, 20, 25, 30, 45, 60, and 80 minutes. Similarly, for bare land condition, which is found at Arba Minch demo farm,

Journal of Digital Food, Energy & Water Systems, 3 (1): 16 - 28, 2022
ISSN 2709-4529


infiltration data were taken at 2, 5, 10, 20, 25, 30, 45, 60, and 80 minutes until a steady infiltration rate is achieved on vertisol soil type.

## 3.0 RESULTS AND DISCUSSION

### 3.1 Field Measured Infiltration and Basic Infiltration Rate

The observed infiltration rate on vertisols for bare and vegetated land use conditions was calculated using the double ring method. It is shown in table 3.1, and the infiltration rate in vegetable-covered land is higher than in bare land throughout the same elapsed time interval.

Table 3.1 displays the experimental infiltration rate under different land-use.

| Elapsed Time, min. | Elapsed Time, hr. | Cumulative Time, hr. | Cumulative infiltration (I) cm | | Infiltration depth (d) cm | | Infiltration rate (i) cm hr⁻. | |
|---|---|---|---|---|---|---|---|---|
| | | | Vegetable cover land | Bare land | Vegetable cover land | Bare land | Vegetable cover land | Bare land |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0.033 | 0.033 | 5.74 | 4.1 | 5.74 | 4.1 | 172.2 | 123 |
| 2 | 0.033 | 0.067 | 9.94 | 7.1 | 4.2 | 3 | 126 | 90 |
| 5 | 0.083 | 0.117 | 13.44 | 9.6 | 3.5 | 2.5 | 42 | 30 |
| 5 | 0.083 | 0.167 | 16.66 | 11.9 | 3.22 | 2.3 | 38.64 | 27.6 |
| 10 | 0.167 | 0.25 | 19.74 | 14.1 | 3.08 | 2.2 | 18.48 | 13.2 |
| 10 | 0.167 | 0.333 | 22.68 | 16.2 | 2.94 | 2.1 | 17.64 | 12.6 |
| 15 | 0.25 | 0.417 | 25.2 | 18 | 2.52 | 1.8 | 10.08 | 7.2 |
| 15 | 0.25 | 0.5 | 27.58 | 19.7 | 2.38 | 1.7 | 9.52 | 6.8 |
| 30 | 0.5 | 0.75 | 29.68 | 21.2 | 2.1 | 1.5 | 4.2 | 3 |
| 30 | 0.5 | 1 | 31.64 | 22.6 | 1.96 | 1.4 | 3.92 | 2.8 |
| 45 | 0.75 | 1.25 | 33.32 | 23.8 | 1.68 | 1.2 | 2.24 | 1.6 |
| 45 | 0.75 | 1.5 | 34.72 | 24.8 | 1.4 | 1 | 1.867 | 1.333 |
| 60 | 1 | 1.75 | 35.98 | 25.7 | 1.26 | 0.9 | 1.26 | 0.9 |
| 60 | 1 | 2 | 37.1 | 26.5 | 1.12 | 0.8 | 1.12 | 0.8 |
| 80 | 1.333 | 2.333 | 38.08 | 27.2 | 0.98 | 0.7 | 0.735 | 0.525 |
| 80 | 1.333 | 2.667 | 38.99 | 27.82 | 0.91 | 0.62 | 0.6825 | 0.465 |
| 80 | 1.333 | 2.667 | 39.89 | 28.43 | 0.9 | 0.61 | 0.68 | 0.4575 |

The final steady infiltration rate ($i_{c}$), and the initial infiltration rate (io), under different land-use conditions within vertisols, were calculated by a graphical approach. The vegetable-covered land basic infiltration rate and the initial infiltration rate values are 0.68 and 172.2 cm $hr^{-}$ respectively, as well as the bare land basic (final) infiltration rate and initial infiltration

Journal of Digital Food, Energy & Water Systems, 3 (1): 16 - 28, 2022
ISSN 2709-4529


rate values, are 0.46 and 123 cm $hr^{-1}$, respectively. As the result, the value of the final and initial infiltration rates differ for all land use conditions.

The result observed that the initial and basic infiltration rates were higher in vegetable cove land than in bare land. There is a slight deviation for initial infiltration in the case of vegetable cove land and bare land, and the difference is (49cm $hr^{-1}$), but the basic infiltration rates difference is almost small (0.21 cm $hr^{-1}$) in both cases.

### 3.2 Modeling Soil Water Infiltration

The results of the computed values of infiltration rates using developed model equations for vegetable cover soil condition and bare land are tabulated in Table 3. 2. From the result, the values of infiltration rate of the Kostiakov model in both vegetable cover land and bare land are most closely matched to the field measured value compared to the Horton model throughout the same elapsed time interval.

Kostiakov model infiltration rates go to a constant at the time of 180 minutes for both vegetable land use conditions and undisturbed bare soil conditions, which is 0.798 cm $hr^{-}$ and 0.56 cm $hr^{-1,}$ respectively. The Horton model basic constant infiltration rate for both vegetable soil use condition and undisturbed bare soil condition at the same time of 180 minutes is different at 0.74 cm $hr^{-}$ and 0.52 cm $hr^{-1}$. respectively.

Therefore, the basic constant rate of infiltration is different from model to model and different soil use conditions at the same measurement time and elapsed time.

Table 3. 2: Different model infiltration rate values.

| Time, hr | Obs. infil. rate (cm $hr^{-1}$) | | Horton's infil. rate (cm $hr^{-1}$) | | kostikove infil. rate (cm $hr^{-1}$) | |
|---|---|---|---|---|---|---|
| | vegetable cover land | bare land | vegetable cover land | bare land | vegetable cover land | bare land |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.03 | 172.2 | 123 | 159.33 | 114.04 | 270.14 | 194.28 |
| 0.067 | 126 | 90 | 144.51 | 103.67 | 107.51 | 77.1 |
| 0.12 | 42 | 30 | 124.84 | 89.86 | 51.1 | 36.56 |
| 0.16 | 38.64 | 27.6 | 107.86 | 77.89 | 31.81 | 22.72 |
| 0.25 | 18.48 | 13.2 | 84.56 | 61.4 | 18.55 | 13.23 |
| 0.33 | 17.64 | 12.6 | 66.33 | 48.43 | 12.66 | 9.02 |
| 0.42 | 10.08 | 7.2 | 52.05 | 38.21 | 9.41 | 6.76 |
| 0.5 | 9.52 | 6.8 | 40.88 | 30.17 | 7.38 | 5.25 |
| 0.75 | 4.2 | 3 | 19.95 | 14.95 | 4.31 | 3.06 |
| 1 | 3.92 | 2.8 | 9.91 | 7.52 | 2.939 | 2.084 |

Journal of Digital Food, Energy & Water Systems, 3 (1): 16 - 28, 2022
ISSN 2709-4529


| | | | | | | |
|---|---|---|---|---|---|---|
| 1.25 | 2.24 | 1.6 | 5.1 | 3.9 | 2.18 | 1.55 |
| 1.5 | 1.87 | 1.33 | 2.79 | 2.14 | 1.71 | 1.21 |
| 1.75 | 1.26 | 0.9 | 1.69 | 1.28 | 1.4 | 0.99 |
| 2 | 1.12 | 0.8 | 1.16 | 0.86 | 1.17 | 0.83 |
| 2.33 | 0.735 | 0.525 | 0.85 | 0.61 | 0.95 | 0.67 |
| 2.67 | 0.68 | 0.465 | 0.74 | 0.52 | 0.798 | 0.56 |
| 2.67 | 0.675 | 0.4575 | 0.74 | 0.52 | 0.798 | 0.56 |

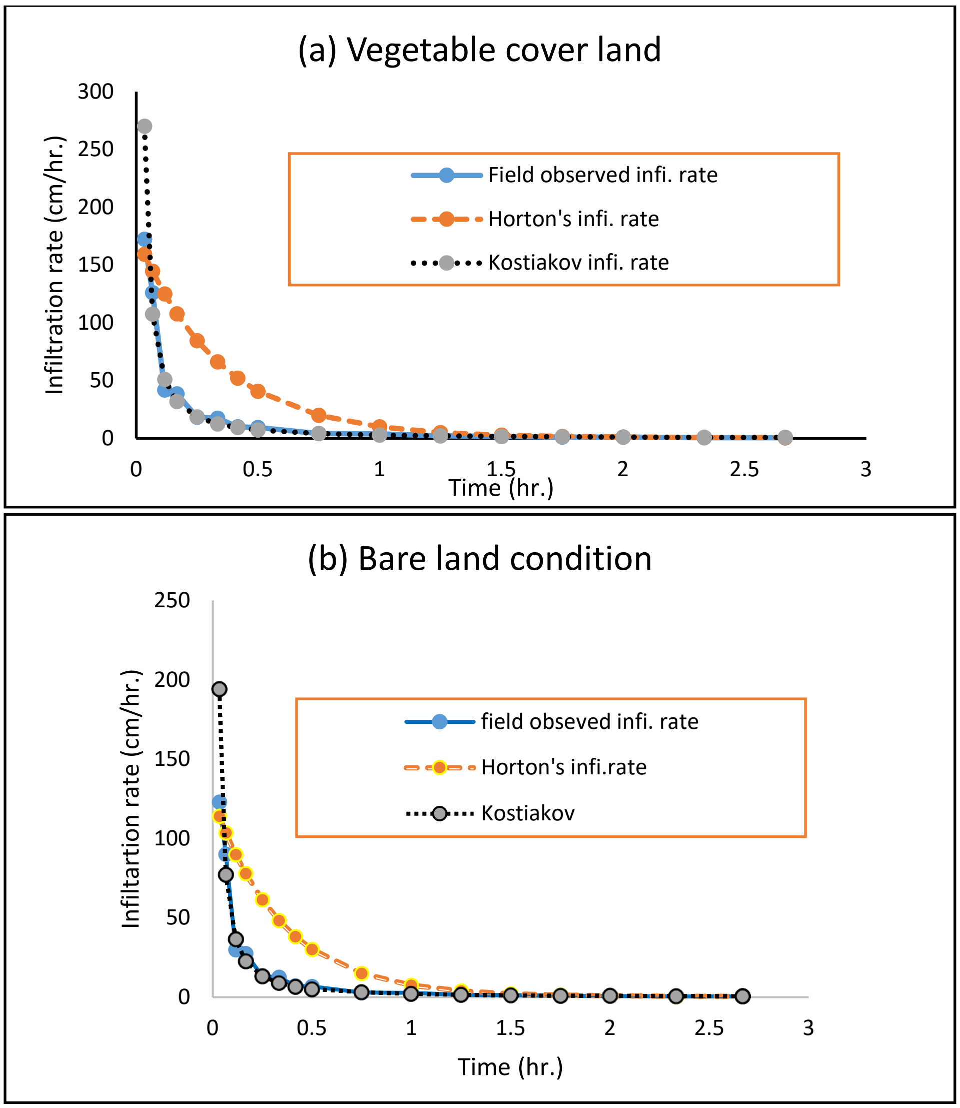



Figure 4. 1: Observed and model's Infiltration Rate: (a) Vegetable cover land and (b) Bare land

Journal of Digital Food, Energy & Water Systems, 3 (1): 16 - 28, 2022
ISSN 2709-4529


The values of the two infiltration model parameters, the basic infiltration rate $i_c$ and the initial infiltration rate io under various land use conditions within vertisols, were determined by a graphical approach. From the results, the values of infiltration models are constant; the final and initial infiltration rates vary for all land use conditions and are presented in table 3. 3.

Table 3.3: Models' parameters, initial and final basic infiltration rates

| Land use condition | Observed | | Kostiakov | | | | Horton's | | |
|---|---|---|---|---|---|---|---|---|---|
| | $i_o$ | $i_c$ | $i_o$ | $i_c$ | a | b | $i_o$ | $i_c$ | k |
| Vegetable land | 172.5 | 0.68 | 270.14 | 0.8 | 2.939 | -1.33 | 159.33 | 0.74 | -2.94 |
| Bare land | 123.5 | 0.46 | 194.28 | 0.56 | 2.084 | -1.334 | 114.04 | 0.52 | -2.87 |

Kostiakov and Horton's regional equations were generated from two land conditions (vegetable land cover and bare land) on vertisol soil type, shown in Table 3.4. The results of the generated equations were used to determine the Horton and Kostiakov model's infiltration rate in the study area.

Table 3. 1: Generated regional equation of Kostiakove and Horton equation.

| Land use condition | Kostiakov | Horton's |
|---|---|---|
| | Generate equation | Generate Equation |
| Vegetable land | $i(t) = 2.939t^{-1.33}$ | $i_t = 0.67+ 175e^{-2.94t}$ |
| Bare land | $i(t) = 2.08t^{-1.334}$ | $i_t = 0.46+ 125e^{-2.87t}$ |

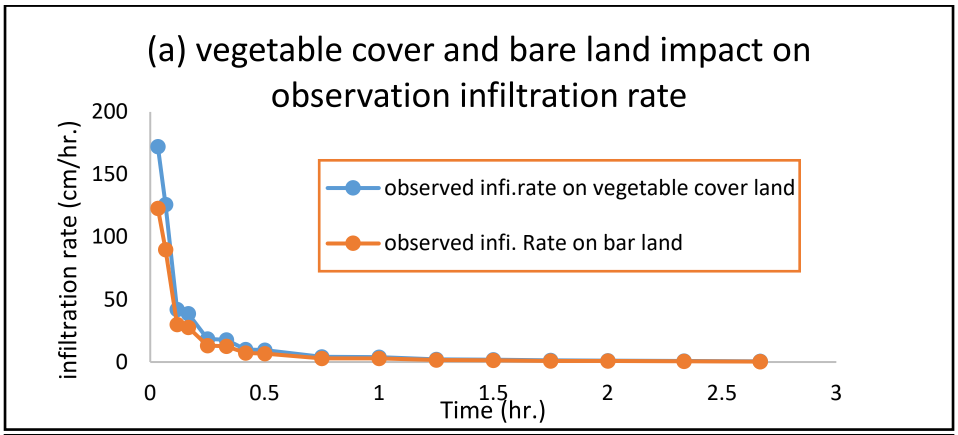
### 3.3 Impact of Different Land Use on Infiltration Rate and Models

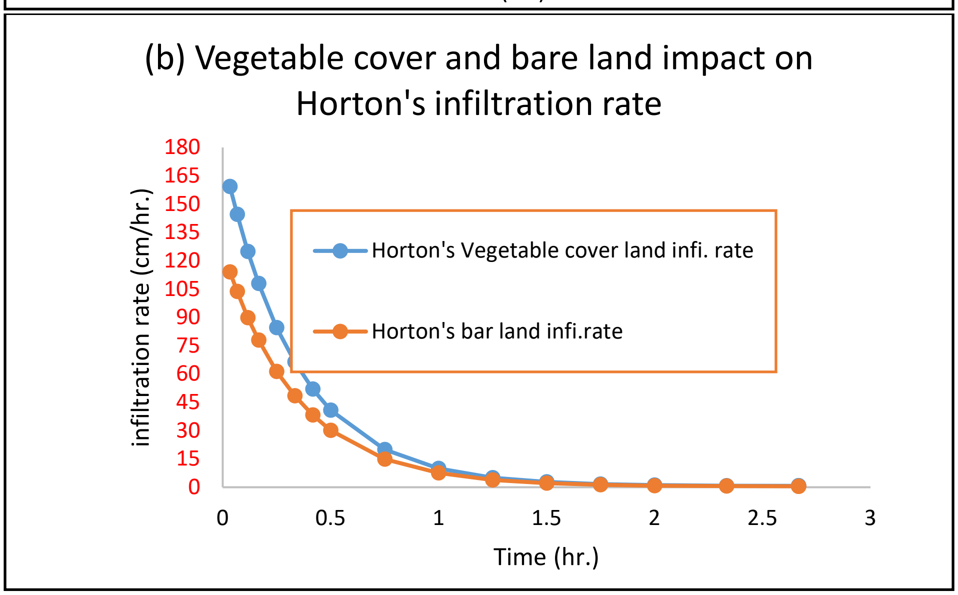
The impact of infiltration factors (vegetable cover and bare land condition) on the observed and model's infiltration varies with the same time interval, shown in table 3.5 and figure 4.2. The basic, initial, and instantaneous infiltration rates vary between the vegetable cover and bare land condition on observed, Horton's, and Kostiakov model results, which are presented in table 4 in per cent. The result shows that the factor of vegetable cover land condition contains high infiltration while bare land condition contains low infiltration, which varies between 67.65% and 70.2%; and 71.6 and 71.72% of the basic and initial infiltration rate, respectively.

Journal of Digital Food, Energy & Water Systems, 3 (1): 16 - 28, 2022
ISSN 2709-4529


Table 3.5: Infiltration variation vegetable cover and bare land condition on field observation, Horton's, and Kostialove models

| infiltration condition | Field Observed | | Kostiakov | | Horton's | |
|---|---|---|---|---|---|---|
| | $i_o$ | $i_c$ | $i_o$ | $i_c$ | $i_o$ | $i_c$ |
| Vegetable cover land greater than Bare land infiltration rate (%) | 71.6 | 67.65 | 71.72 | 70 | 71.57 | 70.2 |



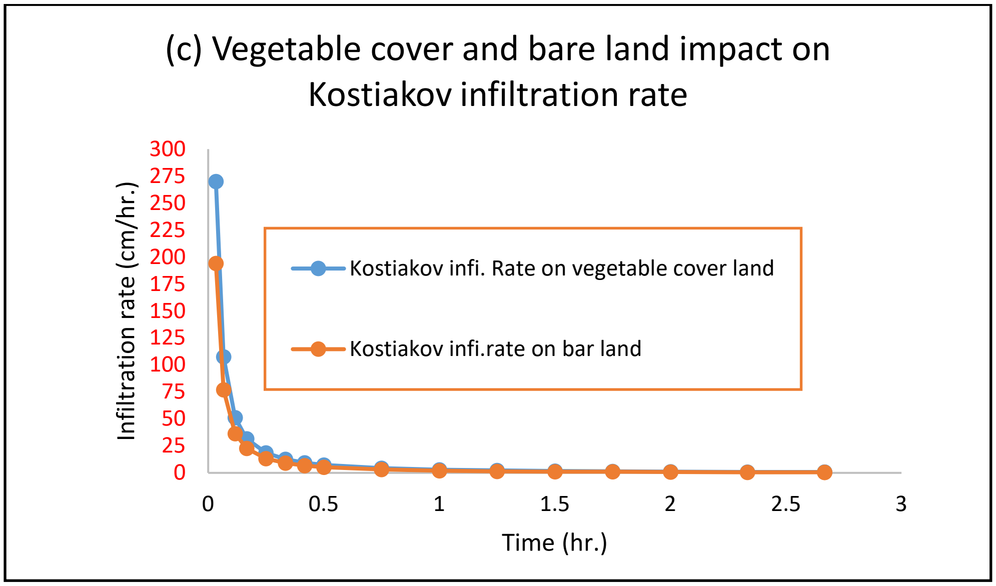



Figure 4. 2: vegetable cover and bare land condition impact on: (a) infiltration rate of observed, (b) infiltration rate of Horton's model, (c) infiltration rate of Kostiakov model

### 3.4 Model Performance Evaluation

The prediction was done using both empirical infiltration models (Horton's, and Kostialove) and compared with the field-measured cumulative infiltration. The infiltration models' performance was evaluated using bias, and root mean square error (RMSE), model efficiency, determination coefficient ($R^2$), slope, correlation coefficient (r), and average percentage error (PAE) statistical criteria. The best fit model was selected by considering infiltration model performance indicators like the minimum bias, average percentage error, root mean square error (RMSE), slope, and maximum model efficiency criteria, tabulated in Table 3.6.

The results are in table 3.6, which shows that for both land use (vegetable land and bare land) conditions, the Kostiakove model under: determination coefficient, correlation coefficient, bias, determination coefficient ($R^2$), root mean square error (RMSE), model efficiency, slope, correlation coefficient (r), average percentage error, and slope performance indicator consideration, is the best fit to the observed values, than Horton's model the study area.

Table 3. 2: The infiltration model performance indicators

| Model performance indicator | Kostiakov | | Horton | |
|---|---|---|---|---|
| | Vegetable cover land | Bare land | Vegetable cover land | Bare land |
| Coefficient of determination ($R^2$) | 0.949 | 0.946 | 0.987 | 0.986 |
| Slope | 1.329 | 1.334 | 2.94 | 2.87 |

| | | | | |
|---|---|---|---|---|
| Correlation coefficient (r) | 8.8E-06 | 1.7E-05 | 6.7E-06 | 1.3E-05 |
| Roor mean squir error (RMSE) | 35.92 | 26.2 | 24.37 | 17.71 |
| Bias | -21.88 | -16.1 | -4.33 | -3.18 |
| Nash–Sutcliffe efficiency coefficient (NS) | 41.81 | 42.3 | 73.22 | 73.63 |
| Percentage average error (PAE) | -43.03 | -44.7 | 2.06 | 2.07 |

## 4.0 CONCLUSION AND RECOMMENDATIONS

### 4.1 Conclusion

This study determined the infiltration rate on vegetable cover land and bare land using an infiltration factor, identified models' infiltration rates and evaluated the Horton's and Kostiakov infiltration models' performance on vertisols in Arbaminch southern Ethiopia. The double ring infiltrometer infiltration measure method was used on both vegetable cover land and bare land within the study area.

The results show that the constant or basic infiltration rates of the field observed, Korsakov and Horton's models on vegetable land-use conditions were 0.68, 0.8, and 0.74 cm $hr^{-1}$, and on bare, land conditions were 0.46, 0.56, and 0.52 cm $hr^{-1}$, respectively. It shows that different land conditions affect field infiltration rates as well as model infiltration rates. The vegetable land cover conditions considerably impacted the infiltration rate by increasing soil porosity, so vegetable cover soils showed more infiltration rate than bare soil conditions for both models and fields.

Infiltration models with field data use the determination coefficient ($R^2$), root means square error (RMSE), model efficiency, slope, correlation coefficient (r), percentage average error, and the slope performance indicator. After analysis, the values of the constant infiltration rate of vegetable cover land are higher than the bare land. The constant infiltration rates of both Horton and Kostiakov models vary from land use. It is observed that for both types of land use conditions, the infiltration rates for experimental data and models infiltration data do not exactly coincide. However, the kostiakov model, is more fit to observe field data than Horton's model in the study area.

### 4.2 Recommendations

The vegetable land cover condition had a considerable impact on increasing infiltration rate by controlling the runoff soil, so vegetable cover soils showed more infiltration rate than bare soil conditions in vertisols during dry seasons. So we utilized different infiltration rate for their design and evaluated surface irrigation methods on both vegetable land use conditions and bare land.

The best-fitting model in the study area is kostiakov Model for both vegetable land cover and bare land use conditions by considering Bias, root mean square error (RMSE), model efficiency, determination coefficient ($R^2$), Slope, Correlation coefficient (r), average percentage error, and the slope performance indicator. Therefore, compared to that Horton's model, the kostiakov infiltration model is recommended to calculate the infiltration rate of Vertisols for the dry season.

We recommend that further study can identify other hydrologic processes, addressing additional land use conditions, soil type, model performance indicator, infiltration measurement methods, and all infiltration factors during both dry and wet seasons.

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