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## Article

# Impacts of Different Tillage Practices on Soil Water Infiltration for Sustainable Agriculture

Roua Amami <sup>1,\*</sup>, Khaled Ibrahim <sup>1</sup>, Farooq Sher <sup>2,3,\*</sup>, Paul Milham <sup>4</sup>, Hiba Ghazouani <sup>5</sup>, Sayed Chehaibi <sup>1</sup>, Zahra Hussain <sup>6,7</sup> and Hafiz M. N. Iqbal <sup>8</sup>

- <sup>1</sup> Higher Institute of Agricultural Sciences, University of Sousse, 4042 Chott Meriem, Tunisia; khaled.ibrahimi@iresa.agrinet.tn (K.I.); chehaibi4@yahoo.fr (S.C.)
- <sup>2</sup> School of Mechanical, Aerospace and Automotive Engineering, Faculty of Engineering, Environmental and Computing, Coventry University, Coventry CV1 5FB, UK
- <sup>3</sup> Institute for Future Transport and Cities, Coventry University, Priory Street, Coventry CV1 5FB, UK
- <sup>4</sup> Hawkesbury Institute for the Environment, Western Sydney University, LB 1797, Penrith 2751, NSW, Australia; p.milham@westernsydney.edu.au
- <sup>5</sup> Regional Centre for Field Crop Researches, 9000 Beja, Tunisia; ghazouani\_hibaunipaisa@yahoo.com
- <sup>6</sup> Department of Zoology, University of the Punjab, Lahore 54590, Pakistan; xarah@ymail.com
- <sup>7</sup> International Society of Engineering Science and Technology, Coventry CV1 5EH, UK
- <sup>8</sup> Tecnológico de Monterrey, School of Engineering and Sciences, Monterrey 64849, Mexico; hafiz.iqbal@tec.mx
- \* Correspondence: roua.amami1991@gmail.com (R.A.); Farooq.Sher@coventry.ac.uk or Farooq.Sher@gmail.com (F.S.)



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**Abstract:** Over the years, cultivation using sustainable tillage practices has gained significant importance, but the impact of tillage on soil water infiltration is still a concern for landowners due to the possible effects on crop yield. This study investigates the impact of different tillage managements on the infiltration rate of sandy clay loam soil under a semiarid environment. Field experiments were conducted in Chott Mariem Sousse, Tunisia. The tillage practices consisted of three treatments, including a tine cultivator (TC, 16 cm), moldboard plows (MP, 36 cm) and no-tillage (NT). Three infiltration models, Kostiakov, Philip and Horton, were applied to adjust the observed data and evaluate the infiltration characteristics of the studied soils. Comparison criteria, including the coefficient of determination ( $R^2$ ), along with the root mean square error (RMSE) and mean absolute error (MAE), were used to investigate the best-fit model. The results showed that moldboard plowing enhanced soil infiltration capacity relative to tine cultivation and no-tillage treatments. The mean saturated hydraulic conductivity was highest under MP, while it was lowest in NT, with 33.4% and 34.1% reduction compared to TC and MP, respectively. Based on the obtained results, Philip's model showed better results with observed infiltration due to a higher  $R^2$  (0.981, 0.973 and 0.967), lower RMSE (3.36, 9.04 and 9.21) and lower MAE (1.46, 3.53 and 3.72) recorded, respectively, for NT, MP and TC. Horton's model had a low regression coefficient between observed and predicted values. It was suggested that the Philip two-term model can adequately describe the infiltration process in the study area.

**Keywords:** sustainability; energy saving; tillage; infiltration; Philip model; unsaturated soil and water-stable aggregates

## 1. Introduction

Conservation agriculture (CA) proceeds in a way to minimize harm to the environment [1], and there is a need to fulfill necessary requirements in facilitating investment in sustainable agriculture practices [2]. Agriculture in semiarid regions is facing great challenges related to water resource availability. Hence, increasing water use efficiency (WUE) through water management strategies is crucial, especially from the perspective of climate change. In the last fifteen years, irrigated lands have doubled more than six times in Tunisia. Irrigated farms represent 8% of the total cultivable land and contribute 35% to agricultural

products [3]. Rapid infiltration of water is essential for reducing erosion potential and increasing water storage in semiarid and arid areas [4], and it is regarded as one of the most crucial parameters for irrigation in the agriculture sector [5]. Understanding the process of infiltration is crucial for agriculture, watershed management and hydrology [6], as it helps in the description of hydrological processes that possess significant importance in the design of hydraulic structures [7]. Soil water infiltration can be affected by various factors, including vegetal and tillage cover, soil porosity, density, surface roughness, organic carbon, stability level and size of the aggregates and water content in the soil [8].

Numerous models have been developed to estimate infiltration and help design irrigation schemes, and field management and can be divided into three groups [9,10]. The first group includes the physical models inferred from the law of mass conservation and Darcy's law [11]. The second group is of semiempirical models, which includes simple hypotheses about the correlation between the infiltration rate and cumulative infiltration [12], and finally, the third group of empirical models comprises the field data and laboratory experiments [13,14]. From the proposed infiltration models, only a few have been successfully applied to the field data under specific conditions. The research conducted on a wasteland in Kharagpur, India, indicated the Philip two-term infiltration model to be most suitable for the entire study area [15]. In a study, the analytical models such as empirical models (Kostiakov, Kostiakov–Lewis and Horton models) and the Philip model were widely used to predict the infiltration functions in surface irrigation, and it was concluded that the Kostiakov–Lewis model showed the best relationship between time and cumulative infiltration [16].

Another study, which was based on the uncertainty analysis of different infiltration models, suggested that the Phillip two-term model indicated the widest (8.23 mm/min) 95% confidence band, followed by the Kostiakov–Lewis model, Stroosnijder model and other models, indicating that they have poor predictability [17]. Recently, for more sustainable and productive agriculture, the use of the decision support system (DSS) is significantly increasing in the agricultural sector because of increasing climate change. This system can collect and analyze different types of data using various mathematical models [18]. As the sustainability of agricultural production has become an issue of wide public concern, the impacts of different soils and land management strategies on soil hydraulic properties have been a subject of extensive research [19,20]. Soil moisture can be regarded as a vital component in plant growth and a basic ecosystem resource in the terrestrial vegetation, managing plant transpiration [21]. In agricultural systems, the soil infiltration rate is mainly affected by tillage and increases with its intensity [22]. The physical properties of soil with respect to different tillage systems have been thoroughly documented, but there is a need for a systematic synthesis to understand how such practices can affect the physical properties of soil around the world and how changes in physical properties of soil are associated with various ecological components [23].

The literature on tillage-related effects on soil water movement suggests that the magnitude of the effects of tillage on infiltrability could vary with factors, including soil structure, aggregation and soil water content, porosity, organic matter and texture [24,25]. However, under conventional tillage, land preparation and its interaction with soil physical properties affect water infiltration [26]. Studies have compared the impact of four land-use systems of sustainable and conventional tillage on the hydraulic properties of soil, finding that tillage management had the most pronounced influence on the infiltrability of the topsoil layer [26,27]. A study suggested that under primary tillage practices, infiltration is increased with an increase in soil porosity and with the formation of voids in the upper layer of the soil that conducts water into the soil profile. However, secondary tillage-reduced pores broke the channel continuity and filled most of the voids [28]. Research was carried out to evaluate the effect of 36 years of conventional tillage to no-tillage on the physical properties of soil and indicated that long-term tillage had minimal effect on factors such as bulk density, total porosity and air-filled porosity. However, it was suggested

that there was a 26% increase in water-holding capacity with no-tillage compared to conventional tillage [29].

In Tunisia, in the past few decades, there has been an increasing interest in conservation tillage as a tool for sustainable soil management. Consequently, better and clearer information regarding the impacts of such tillage systems on soil water infiltration is required by the decision-makers, and infiltration rate estimation models have proven to be efficient for this purpose. Therefore, this study is aimed to investigate the short-term impacts of tillage management (moldboard plow, tine cultivation, no-tillage) on the infiltration capacity of a sandy clay loam soil and to examine the performance of three infiltration models, including the Kostiakov, Philip and Horton models, in predicting water infiltration rates under the three tillage treatments. The information obtained from this research could help to evaluate surface irrigation systems in the study area.

## 2. Materials and Methods

### 2.1. Characterizations of the Study Area, Soil Properties and Experimental Layout

The research was carried out at the experimental station of the Technical Center of Organic Farming located in Sousse of Eastern Central Tunisia (latitude: 35.55 °N; longitude: 10.34 °W) and at altitudes of 12 m above sea level. According to the measured data acquired by the Meteorological Service of the Technical Center of Organic Farming, the area is characterized by a semiarid climate with hot, dry summers and mild, rainy winters. The minimum and maximum temperatures are seen in January and July, respectively. The mean daily temperature ranges from 6.37 to 31.05 °C, with an average annual of 17.7 °C (Figure 1). The mean annual precipitation for the studied region is 450 mm, falling mostly between September and April (Figure 1). However, the precipitation is mainly concentrated in autumn and winter.

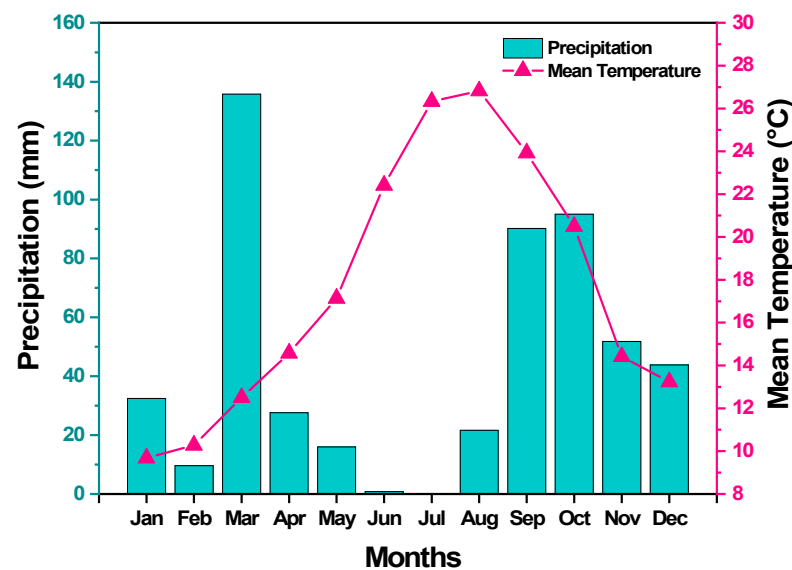


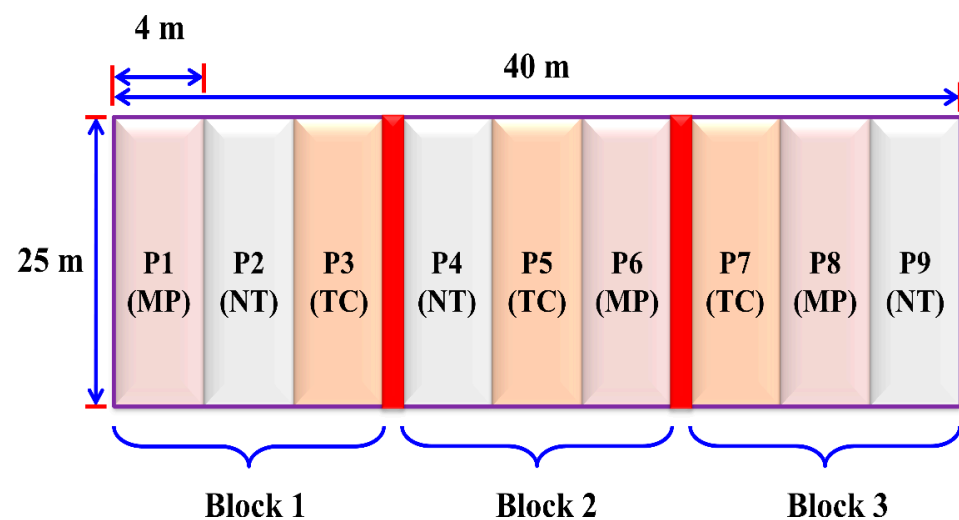
Figure 1. Air temperature and precipitation during the year at the region of Sousse in east-central Tunisia.

According to the USDA classification, the top layer of the soil (0–10 cm) is a sandy clay loam. During the investigation period, the main physical and chemical properties of the soil (bulk density, penetration resistance and total porosity) were studied. Results of this characterization are presented in Table 1.

**Table 1.** Soil physical and chemical properties in the horizon ( $0 \pm 30$  cm) of the experimental site before the commencement of the tillage treatments.

Soil Property	Value	Analysis Method	Reference
Clay (%)	25.60	Pipette method	[30]
Sand (%)	67.15	-	-
Silt (%)	6.90	-	-
Texture	Sandy clay loam	Textural triangle	[31]
Bulk density ( $\text{g}/\text{cm}^3$ )	1.69	Core method	[32]
Penetration resistance ( $\text{daN}/\text{cm}^2$ )	2.04	Electronic penetrometer	[33]
Water content ( $\text{cm}^3/\text{cm}^3$ )	13.27	Gravimetric method	[33]
Water field porosity (%)	67.58	Core method	[32]
Total porosity (%)	32.78	Core method	[32]
EC ( $\text{dS}/\text{m}$ )	0.98	Saturated paste extract	[34]
pH	7.54	pH meter	[35]
Soil organic matter (%)	2.01	Colorimetric method	[34]

The field was sown with the winter faba bean (*Vicia faba* L.) grown under no-tillage, minimum-tillage and deep-tillage treatments. It was designed as a randomized block with three replicates (blocks), each consisting of  $40 \times 25$  m, separated by 2 m spacing and divided into subplots (P1 through P9). The tillage treatments were: (1) deep tillage to 36 cm by a moldboard plow (MP), (2) shallow tillage by a tine cultivator (TC) and (3) no-tillage (NT) as the control treatment (Figure 2).

**Figure 2.** Experimental layout of tillage treatments with three replicates. MP: moldboard plow, TC: tine cultivator, NT: no-tillage. P1 through P9: subplots. The dotted areas are spacing between blocks.

## 2.2. Soil Water Infiltration Measurement

The water infiltration was measured within each replicate plot with the help of a double-ring infiltrometer [36], consisting of double concentric stainless-steel rings, a driving plate with handles for inner (23 cm) and outer rings (36 cm). The two rings driven into the ground were partially filled with water to determine the infiltration capacity of the soil. Measurements were conducted by maintaining a constant water column of 30 mm in the outer and inner rings. The initial soil water content corresponded to approximate field capacity and continued until the infiltration rate became steady or until it became equal to, or less than, a specified value. All experiments were conducted in daylight during the same time to have the same climatic conditions.

### 2.3. Infiltration Rate Estimation Models

Infiltration (noted  $i$ ) can be defined as the variation of the infiltrated water in the soil (noted  $I$ ) over time (Equation (1)).

$$i(t) = \frac{d(I)}{d(t)} \quad (1)$$

Three infiltration models, including Kostiakov, Philips and Horton, were chosen for this investigation based on their practical performance and popularity in existing studies. The data of infiltration rate and cumulative infiltration acquired from the field experiments (9 plots) were predicted by these infiltration models, and a linear curve fitting was used for the infiltration tests' data to obtain the parameters of the infiltration equations. The fitness of these three model parameters was evaluated according to the OriginLab 8.5 packages. A compressive description of the selected infiltration models is given below.

#### 2.3.1. Philip Model

The infiltration model proposed by Philip included the soil sorptivity ( $S$ ) and stable infiltration rate ( $A$ ) from the series of solutions from the Richards equation [11]. For "cumulative infiltration ( $I$ )," the two-term infiltration equation of Philip is expressed by Equations (2) and (3).

$$I(t) = At + St^{1/2} \quad (2)$$

The differentiation of Equation (2) yields the following equation for "infiltration rate ( $i$ )."

$$i(t) = \left( \frac{St^{-1/2}}{2} \right) + A \quad (3)$$

where  $i(t)$  and  $I(t)$  represent infiltration rate and the cumulative infiltration, respectively, at infiltration time  $t$ .  $A$  is related to saturated hydraulic conductivity ( $K_{sat}$ ),  $S$  is the soil water sorptivity term and  $t$  is the time elapsed.

#### 2.3.2. Kostiakov Model

Kostiakov proposed one of the earliest empirical infiltration models (Hillel, 1982). With the help of experimental data, he proposed the following model for estimating "infiltration rate" (Equation (4)) [13].

$$i(t) = at^{-b} \quad (4)$$

where  $i(t)$  is the infiltration rate ( $\text{mm} \cdot \text{min}^{-1}$ ) at time  $t$  (min), and  $>0$  (Kostiakov's time coefficient) and  $0 < b < 1$  (Kostiakov's time exponent) are the Kostiakov model parameters that depend on the soil texture and conditions, including initial moisture content. The integration of Equation (4) gives the expression of cumulative infiltration  $I(t)$  in mm, as given in Equation (5).

$$I(t) = \left( \frac{a}{1-b} \right) t^{1-b} \quad (5)$$

#### 2.3.3. Horton Model

Horton [14] proposed an infiltration model for the simulation of the infiltration process, as represented in Equation (6).

$$fp - fc = (f0 - fc)e^{-kt} \quad (6)$$

where  $f_p$ ,  $f_c$  and  $f_0$  indicate the infiltration rates at time  $t$  (min), final infiltration rate and infiltration rate at  $t = 0$ , respectively,  $k$  is the empirical constant representing the delay of time and  $e$  is a constant ( $\sim 2.71828$ ).

#### 2.4. Model Performance Evaluation Criteria

To select a suitable model between Philip, Horton and Kostiakov, there are various approaches, but the simplest is to compare the difference between observed and fitted cumulative infiltration. Three performance evaluation parameters such as root mean square error (RMSE), mean absolute error (MAE) and coefficient of determination ( $R^2$ ) were considered to determine the best model for estimating the cumulative infiltration. The parameter estimation technique with lower values of MAE and RMSE and higher values of  $R^2$  was considered providing better fitness of the observed model-predicted cumulative infiltration ( $pi$ ) and cumulative infiltration in the field ( $mi$ ). The RMSE, MAE and  $R^2$  were calculated using Equations (7) and (8) [37,38]

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^n (pi - mi)^2}{n}} \quad (7)$$

$$R^2 = \sqrt{\frac{\sum_{i=1}^n (pi - p)^2}{\sum_{i=1}^n (mi - m)^2}} \quad (8)$$

$$\text{MAE} = \frac{\sum_{i=1}^n (|pi - mi|)}{n} \quad (9)$$

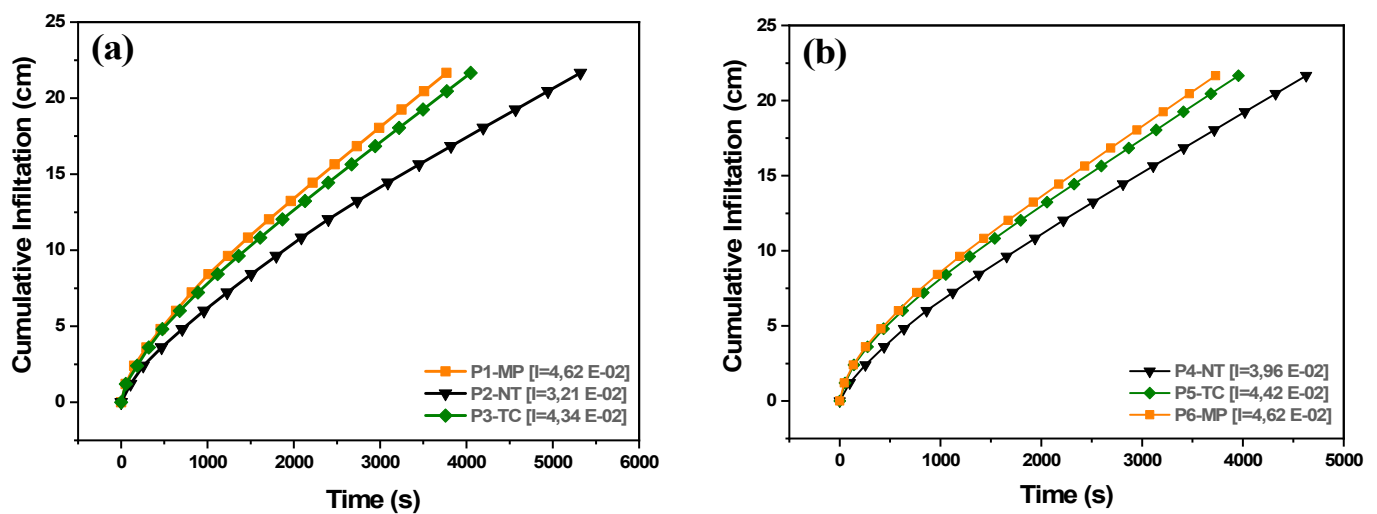
where  $n$  indicates the total number of cumulative infiltration samples,  $pi$  represents the mean simulated cumulative infiltration and  $mi$  is the mean observed cumulative infiltration. The RMSE provides an overall idea of the dispersion between measured and predicted cumulative infiltration.

### 3. Results and Discussion

#### 3.1. Effect of Tillage Practices on Measured Soil Water Infiltration

In each tillage treatment, measured infiltration rates in all plots were initially high and declined gradually toward a steady rate (Figure 3a, b). These findings are consistent with those reported by Fan et al. [39]. For example, the mean infiltration rate under moldboard plow (MP) and tine cultivator (TC) was greater than under no-tillage (NT) management by 7 and 5.6 cm/h at 5 min and by 4.6 and 2.5 cm/h at 60 min, respectively. After 60 min of measurement, there was no difference in infiltration rates between NT, TC and MP tillage. During the steady-state, the  $K_{s_{at}}$  ranged from 0.0462 to 0.0471 cm/s in MP, 0.0434 to 0.0485 cm/s in TC and from 0.0214 to 0.0396 cm/s in NT. The variation in  $K_s$  values in soil was likely due to differences in soil disturbance.

However, NT decreased water infiltration rates between 34.1% and 33.4% compared with MP and TC, respectively (Figure 3a). Studies have inferred that no-till management may increase [40] or decrease [41] water infiltration compared with plow-tilled systems. Based on this consideration, the results suggest that tilled soils can take in the water at a faster rate than untilled soil. This could be due to the porous nature of tine cultivator tillage and considering the fact that the soil is more loosened and finer than other tillage treatments [42]. These findings are in agreement with previous studies [43,44] but disagree with some other researchers [45,46]. Somewhat contrary to a conventional understanding regarding NT, a review of experiments in the Argentine Pampas found that no-till doubled infiltration rates [47]. Generally, there were no significant differences among the tillage treatments in the values for saturated hydraulic conductivity, and the same trends were observed by other studies [48,49].



**Figure 3.** Cumulative infiltration over time for treatment replications: (a) subplots P1, P2 and P3; (b) subplots P4, P5 and P6. MP: moldboard plow, TC: tine cultivation and NT: no-tillage.

### 3.2. Parameter Estimation for the Infiltration Models

The estimated parameter values for the three selected infiltration models (Philip, Kostiakov and Horton) are listed in Table 2. The fitted infiltration model parameters ( $S$ ,  $A$ ,  $a$ ,  $b$ ,  $f_c$ ,  $f_0$  and  $k$ ) varied among treatments. This variation is mainly related to soil physical and hydrological properties as affected by tillage operations [50].

**Table 2.** Estimated parameters for the three soil infiltration models of Philip, Kostiakov and Horton.

Treatments	Field/Plot Number	Infiltration Models						
		Philip		Kostiakov		Horton		
		$S$ (cm/min <sup>1/2</sup> )	$A$ (cm/min)	$a$	$b$	$f_c$ (cm/min)	$f_0$ (cm/min)	$k$
MP	1	0.159	0.0031	0.059	0.714	16.663	21.370	3.136
	6	0.168	0.0032	0.079	0.684	16.663	21.705	3.483
	8	0.183	0.0029	0.068	0.702	16.989	22.490	3.555
	Mean	0.170	0.0031	0.069	0.700	16.772	21.855	3.391
TC	3	0.140	0.0031	0.052	0.724	15.640	20.063	2.808
	5	0.149	0.0031	0.069	0.691	15.920	20.890	3.493
	7	0.151	0.0034	0.067	0.702	17.469	22.284	3.424
	Mean	0.147	0.0032	0.062	0.706	16.343	21.079	3.242
NT	2	0.139	0.0021	0.037	0.741	13.750	17.728	2.961
	4	0.116	0.0030	0.063	0.772	14.251	18.080	2.453
	9	0.094	0.0015	0.031	0.722	7.708	11.205	1.635
	Mean	0.116	0.002	0.043	0.745	11.903	14.467	2.298

MP: moldboard plow, TC: tine cultivator and NT: no-tillage.

The results in Table 2 revealed that Kostiakov's time coefficient ( $a$ ) was highest under CT (0.069 cm/min), followed by MT (0.062 cm/min), while the lowest coefficient was observed under NT treatment (0.043 cm/min). Another research obtained similar results and determined that coefficient ( $b$ ) was the largest for conventional tillage and the least for no-tillage [50]. Another study considered that the parameter ( $a$ ) in Kostiakov's model is an index of infiltrability at the beginning of the infiltration process [51]. Some studies [52,53] associated higher infiltration with higher Kostiakov's  $a$ , while lower infiltration was associated with lower values. The mean values of Kostiakov's exponent coefficient ( $b$ ) were observed as 0.700, 0.706 and 0.745 for MP, TC and NT, respectively. These ( $b$ ) values were in concordance with the theory of infiltration, whereby the values were positive and



always less than unity. Another study obtained similar results with Kostiakov's exponent coefficient  $b$ , ranging between 0.781 and 0.785 [53].

The nonlinear three-parameter Horton (1940) model showed that  $f_c$  and  $f_0$  were the highest (16.77 and 21.85 cm/min) for MP and the lowest (11.90 and 14.46 cm/min) for the NT treatment (Table 2). The parameter  $k$ , which reflects the steepness of initial portions of the infiltration curve, was the largest for MP (3.39) and the least for NT (2.29). These findings contradict the study reported in the literature [50]. The  $S$  parameter of the Philip model and  $i_0$  of the Horton model depends on initial soil infiltration rates, and both parameters were the largest for the MP treatment. This result suggests that tillage with moldboard plow increases the water transmission properties of soil.

Table 2 shows the mean values of the Philip model parameters ( $S$ ) that were 0.17, 0.147 and 0.116 cm/min<sup>1/2</sup>, while the values of ( $A$ ) were 0.0031, 0.0032 and 0.002 cm/min for MP, TC and NT, respectively. Therefore, the variations in parameter  $S$  of Philip's model may be related to the differences in the continuity and arrangement of soil pores caused or left intact by tillage treatments. A study also showed higher vertical connectivity and continuity of macropores in conservation tillage than in MP treatments [54]. Additionally, the results showed the highest values for NT, whereas the lowest values occurred under the TC treatment. This contradicts with the present study findings because the parameter  $S$  of Philip's model is highest under MP treatment (0.170 cm/min<sup>1/2</sup>) and lowest under NT (Table 2). The reason for our higher values of  $S$  and  $A$  may be attributed to the loamy sand texture and higher permeability of the soil. Some researchers have also concluded in their research work the existence of a close relationship between Philip's parameters ( $S$ ,  $A$ ) with soil permeability and the capacity of infiltration [55].

### 3.3. Performance of the Infiltration Models for Predicting Cumulative Infiltration

Predictions were made within each tillage treatment using three infiltration models (Kostiakov, Philips and Horton). The predicted and observed infiltration rates were plotted against each other and fitted with a linear equation and zero intercepts to test the validity of each prediction. At this point, the coefficient of determination ( $R^2$ ) the mean absolute error (MAE) and root mean square error (RMSE) were adopted for each model in order to verify the difference between the modeled and measured values of the infiltration water in the soil, and both performance evaluation parameters are given in Table 2. A model is considered to be better when RMSE and MAE are smaller and its  $R^2$  is higher and the model performance diminishes in the order Philip (1957) > Kostiakov (1932) > Horton (1940) [38,56].

The single most marked observation to emerge from the data comparison is that the Kostiakov and Philips models satisfactorily predicted the cumulative infiltration of the field for all tillage treatments according to the values of the coefficient of determination ( $R^2$ ), (MAE) and (RMSE). Based on the overall mean values, the Kostiakov model systematically underestimated the cumulative infiltration in the studied soil since the mean absolute error (MAE) and RMSE. The  $R^2$  values between the predicted and observed values were between 0.610–0.988 among all the models (Table 3), and the highest  $R^2$  values were linked to the Kostiakov and Philip's models, which exceeded 0.9, indicating excellent performance for all tillage treatments. The present study experimental setup has a close resemblance to that of those who have suggested that Philips's model gave the most satisfactory results [57,58].

These results indicated that the Horton three-parameter model gave the poorest fit with the largest RMSE (19, 75) and MAE (8, 32) and the lowest  $R^2$  (0.537). With the combined consideration of RMSE,  $R^2$ , MAE, the Philip and Kostiakov models were best to describe and predict the cumulative infiltration in the researched soil. On the contrary, one study suggested that the Horton model is the best fitting in measured infiltration and prediction ability for cumulative infiltration in the lawn soils with healthy growth of grass [50], and other studies have suggested the same [10,38]. In contrast, the present study findings contradict those reported in sandy soils with a fast infiltration rate on the Nsukka plains of SE Nigeria. Both the Philip (1957) [11] and Kostiakov (1932) [13] models were not

appropriate to predict cumulative infiltration because their transmissivity terms are not completely accurate for either the Ksat or the equilibrium infiltration rate [52].

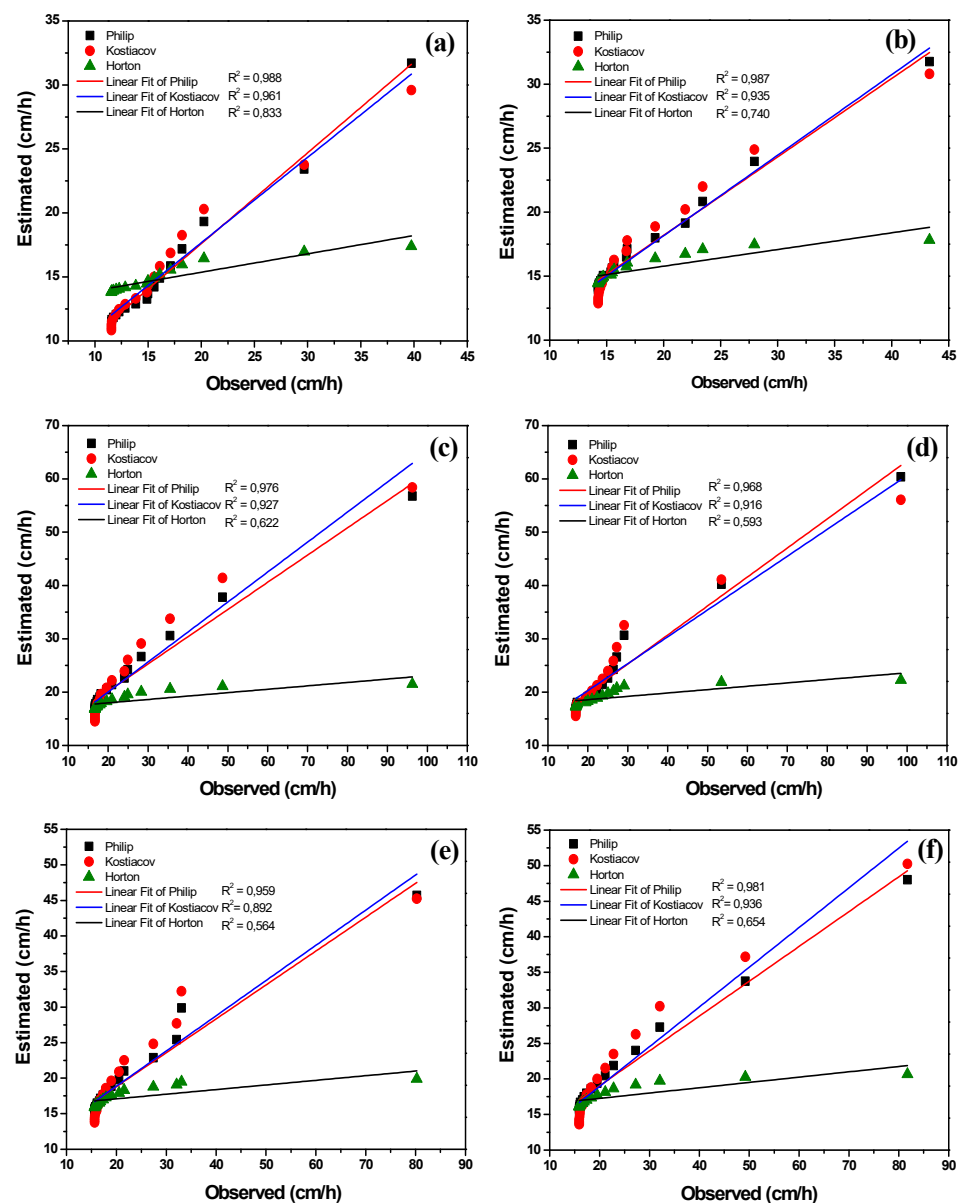
**Table 3.** Calibration accuracy measures for infiltration models under different tillage treatments.

Treatments	Field/Plot Number	Infiltration Models								
		Philip			Kostiakov			Horton		
		R <sup>2</sup>	RMSE	MAE	R <sup>2</sup>	RMSE	MAE	R <sup>2</sup>	RMSE	MAE
MP	1	0.975	7.78	3.04	0.919	7.95	2.98	0.628	15.71	6.55
	6	0.976	9.76	3.78	0.927	9.15	3.42	0.622	19.30	7.87
	8	0.968	9.58	3.77	0.916	10.46	3.89	0.593	19.75	8.32
	Mean	0.973	9.04	3.53	0.92	9.19	3.43	0.61	18.25	7.58
TC	3	0.959	8.40	2.93	0.892	8.37	2.98	0.564	15.07	5.88
	5	0.982	9.12	3.69	0.94	8.25	3.40	0.676	16.84	7.19
	7	0.962	10.12	4.53	0.927	8.66	4.08	0.671	18.09	7.82
	Mean	0.967	9.21	3.72	0.92	8.43	3.49	0.64	16.67	6.96
NT	2	0.988	2.54	1.39	0.961	2.80	1.19	0.833	6.32	3.43
	4	0.987	3.04	1.37	0.935	3.14	1.48	0.740	6.82	3.03
	9	0.968	4.50	1.62	0.906	4.34	1.64	0.626	7.34	2.76
	Mean	0.981	3.36	1.46	0.934	3.57	1.44	0.733	6.83	3.07

MP: moldboard plow, TC: tine cultivator and NT: no-tillage.

Therefore, Mizuba et al. [27] investigated the impact of soil tillage management and vegetal cover on water infiltration of the soil. Plant cover is effective in preventing infiltration as it protects the soil surface from the impact of precipitation and slows the speed of rain runoff, changing the soil properties [8,59] along with the infiltration characteristic [59,60]. Figure 4 illustrates a representative comparison between the observed and fitted infiltration curves. The Kostiakov model gave a relatively good estimation of the observed infiltration rates, while the Horton model failed to accurately predict infiltration rates, especially at the early stage of the infiltration process in all types of tillage practices. Contrary to this, research conducted in India indicated that the Kostiakov model and the Philip two-term model had the lowest rank in the infiltration models in predicting “cumulative infiltration” before and after paddy cultivations [61].

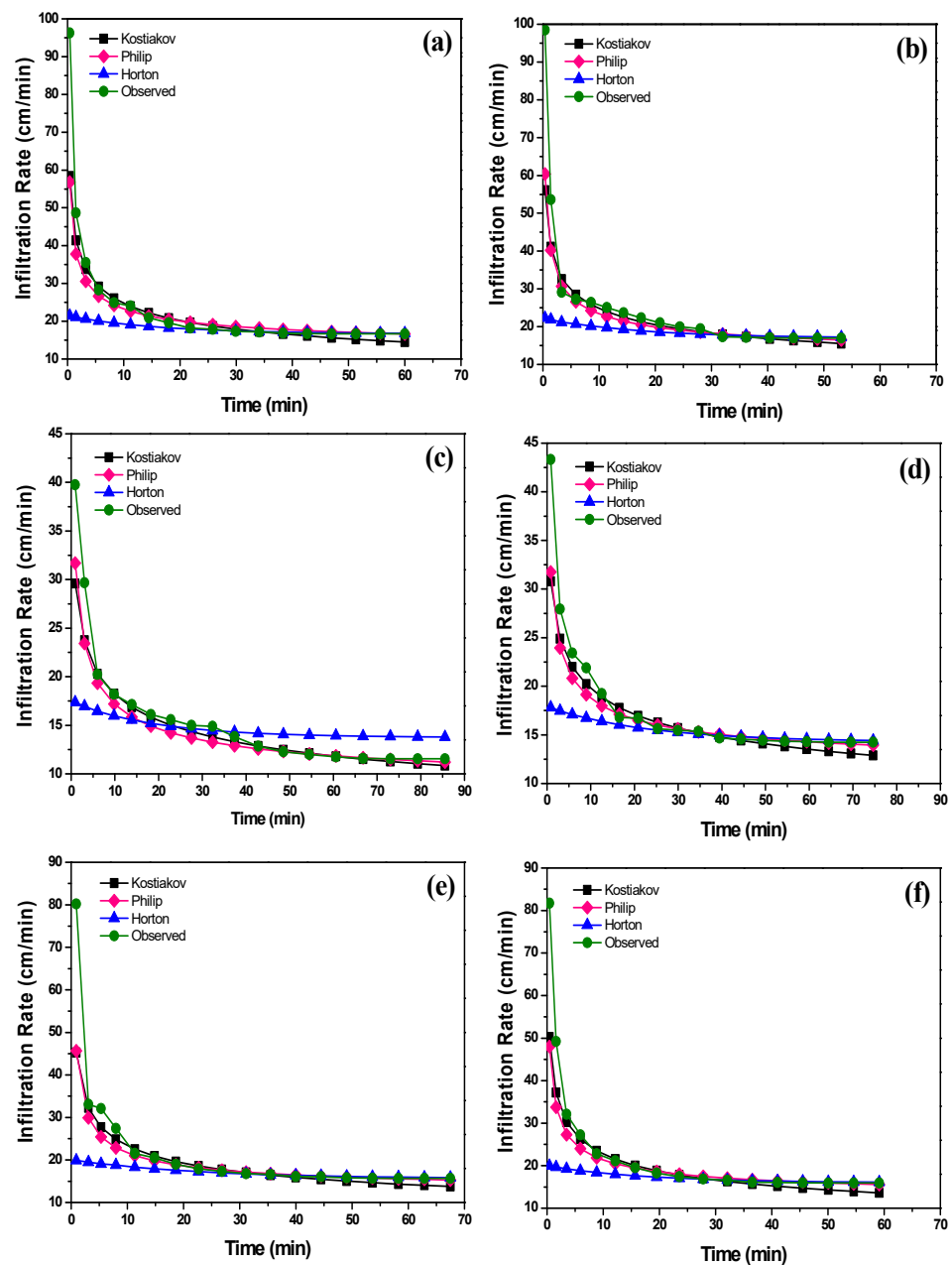
The correspondence between observed and fitted infiltration for selected replicates of tillage treatments (MP (P6, P8), NT (P2, P4) and TC (P3, P5)) indicated by the R<sup>2</sup> value revealed a higher value for the Philip model and a lower value for Horton model (Figure 4). There are several possible explanations for these findings where the empirical models (Philip and Kostiakov) predict infiltration data better than the Horton model because the calibration of empirical models is done with field experiments data without any presumptions about the hydrologic process. Thus, it should be considered that the theoretical models are mainly predictive, whereas the empirical models are only adjustment models, which reduce the accuracy of the estimation of the infiltration rates. It was concluded in research that one of the major drawbacks in adopting theoretical models is the need to measure certain soil properties, which are either unavailable or difficult to obtain [62].



**Figure 4.** Comparison between observed and estimated infiltration rates for different models in different treatments: no-tillage; (a) Plot 4, (b) Plot 2; moldboard plow; (c) Plot 8, (d) Plot 6; tine cultivator; (e) Plot 3 and (f) Plot 5.

#### 4. Effect of Tillage on Soil Water Infiltration Characteristics by Model Analysis

Figure 5 shows a schematic description of the progress of infiltration rate with time based on different infiltration models and observed values. At the startup stage within the first 10–15 min (10 min for tilled plots and 15 min for untilled plots), the infiltration rate overtime was always less for the experimental values than for modeled values. The predicted infiltration curves of the selective plots of untilled soil (NT: P2, P4), tilled soil with a moldboard plow (MP: P6, P8) and tilled soil with a tine cultivator (TC: P3, P5) are examples of the validation results by visually assessing the performance of the model. From Figure 5, it is possible to see that our curves show a high-quality presentation of the fit of the models, with the exception of the NT. However, each infiltration curve obtained after the infiltration test revealed a similar trend and showed that after 20 min of the beginning of the experiment, the infiltration rate for both Philip and Kostiakov models and observed values are identical. These findings are supported by the literature [63,64].



**Figure 5.** Variations in the infiltration rate  $f_p$  over time for different selected tillage treatments plots: moldboard plow; (a) P6, (b) P8; no tillage; (c) P2, (d) P4; tine cultivator; (e) P3 and (f) P5.

In addition, it is also apparent that the infiltration rate of each model decreases over time. As put forward by a study [65], we found the evidence points to all similar values at the end of the infiltration test, which can be attributed to the increase in soil surface compaction increased following a decrease in its porosity or crust formation.

## 5. Conclusions

In conclusion, the capacity of infiltration in the studied sandy clay loam soil increased in the order of no-tillage, tine cultivation and moldboard plowing. Furthermore, the saturated hydraulic conductivity ( $K_{sat}$ ) varied in the order of MP > TC > NT, with the big mean  $K_{sat}$  at the steady-state is 0.0471, 0.0466 and 0.03104 cm/s for MP, TC and NT, respectively. This trend suggested that infiltration capacity increased with increased soil disturbance. Furthermore, three commonly used infiltration models (Kostiakov, Philip, Horton) were applied to the field measured data to predict infiltration rates under tilled

and untilled conditions. The Philip model was better at predicting the measured infiltration rates compared to the Horton and Kostiakov models under all tillage treatments ( $R^2$  ranged between 0.967 and 0.981, and RMSE ranged between 3.359 and 9.21). Hence, this model is useful for the measured field data and can be applied for better tillage management in the study site or other areas with similar soil conditions. These topics are reserved for future work to investigate the relationship between structural variables of the soil such as aggregate stability, bulk density and hydraulic properties by using traditional statistical methods or physical-based models. Future studies on the current topic are therefore required to understand the processes of infiltration under tillage practices in this region that should be based on long-term field experiments with additional soil types.

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## Abbreviations

EC	Electrical conductivity
Ksat	Saturated hydraulic conductivity
S	soil sorptivity
A	stable infiltration rate
a	Kostiakov's time Coefficient
b	Kostiakov's time exponent
fp	Infiltration rates at time t (min)
fc	Final infiltration rate
f0	Infiltration rate at t = 0
pi	Mean observed cumulative infiltration
p	Observed cumulative infiltration
mi	Mean simulated cumulative infiltration
m	Simulated cumulative infiltration
n	Total numbers of samples
I (t)	Cumulative infiltration rate
i (t)	Infiltration rate
t	Time
NT	No-tillage
MP	Moldboard plow
TC	Tine cultivation
$R^2$	Coefficient of determination
RMSE	Root mean square error

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