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Assessment of the Effect of Irrigation with Treated Wastewater on Soil Properties and on the Performance of Infiltration Models

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Abstract: An alternative strategy for saving limited water resources is using treated wastewater (TWW) originating from wastewater treatment plants. However, using TWW can influence soil properties owing to its characteristics compared to conventional water resources. Therefore, assessing the effect of TWW on soil properties and soil water infiltration is crucial to maintain sustainable use of TWW and to increase the water use efficiency of the precious irrigation water. Moreover, several studies were carried out to assess the performance of infiltration models. However, few studies evaluate infiltration models under the use of treated wastewater. Therefore, this study aims to assess the effect of TWW irrigation on soil properties after 2 and 5 years and to evaluate five classical infiltration models with field data collected from soil irrigated by treated wastewater for their capability in predicting soil water infiltration. This study revealed that using TWW for irrigation affects significantly on soil properties after 2 and 5 years. The soil irrigated with TWW had significantly higher electrical conductivity, organic matter, sodium adsorption ratio, cation exchange capacity, and lower soil bulk density compared to control. The basic infiltration rate and cumulative infiltration decreased significantly compared to control (60.84, 14.04, and 8.42 mm hr^{-1} and 140 mm, 72 mm, and 62 mm for control, 2, and 5 years' treatments, respectively). The performance of the infiltration models proposed by Philip, Horton, Kostiakov, Modified Kostiakov, and the Natural Resources Conservation Service was evaluated with consideration of mean error, root mean square error, model efficiency, and Willmott's index. Horton model had the lowest mean error (0.0008) and Philip model had the lowest root mean square error (0.1700) while Natural Resources Conservation Service had the highest values (0.0433 and 0.5898) for both mean error and root mean square error, respectively. Moreover, Philip model had the highest values of model efficiency and Willmott's index, 0.9994 and 0.9998, respectively, whereas Horton model had the lowest values for the same indices, 0.9869 and 0.9967, respectively. Philip model followed by Modified Kostiakov model were the most efficient models in predicting cumulative infiltration, while Natural Resources Conservation Service model was the least predictable model.

Keywords: evaluation; infiltration models; model efficiency; treated wastewater; Willmott's index agreement

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1. Introduction

Arid and semi-arid regions are characterized by a short period and low amount of rainfall; therefore, water is a scarce commodity and considered as a limiting factor for agricultural production. This water shortage has compelled the decision-makers to look for other water sources. One of these sources is the treated wastewater (TWW) [1]. Under these conditions, persistent monitoring of the TWW and soil properties are required due to the variation in the TWW properties because of the raw water source as well as advancement of the treatment plant. In comparison to fresh water, TWW has higher content of organic matter as well as nutrients that are required for plant growth especially in arid soils [2]. However, depending on the source and treatment type, TWW may contain some elements that could affect soil and plant adversely [3–5]. One of the main problems of using TWW is the physical clogging by suspended solids and bioclogging facilitated by dissolved organic matter [6–8]. Therefore, understanding and quantifying water movement in the vadose zone is essential for identifying strategies of water conservation, flood or runoff control, erosion control, and assessment of potential aquifer contamination due to migration of water-soluble chemicals present in the vadose zone [9]. In irrigation science, infiltration is a vital and key dynamic process for agricultural activities to be considered for irrigation system design and optimization, irrigation scheduling, and irrigation management [10–12].

Infiltration models have been developed over the years ranging from empirical to physical-based models [13–15]. When these models are used to predict soil infiltration, only a few are satisfactory for field application; therefore, the presentation of variability of soil infiltration properties is a key problem [16]. In this context, new infiltration models have been developed by simplifying the assumptions of Richard's equation by Philip [14] and Green and Ampt [17]; however, the models have some strict restrictions such as soil distribution and ponding depth that imposed limitations on the practical applications [18–20]. Other limitations remain in the practical application of models developed by Horton [13] and Green and Ampt [17] because these models are applicable particularly when rainfall intensity is exceeding the initial water absorption capacity of the soil [21]. Such models will inaccurately predict soil infiltration characteristics in arid and semi-arid regions. On the other hand, multiple factors play a crucial role in the variation of soil infiltration, i.e., soil texture, topography, land use, bulk density, water content, biological activity, etc. [16]. Another factor playing a role in determination of the infiltration and its prediction is the suspended solid in the treated wastewater, which can clog the pores and reduce the infiltration [6,22]. This variation is not well presented by infiltration models. Moreover, the data used as an input for the infiltration models being obtained from field and laboratory experiments are affected by several conditions (soil texture, water quality, spatial heterogeneity, etc.). Hence, the effect of using TWW in irrigation on soil properties and the performance of infiltration models should be evaluated worldwide using field data to identify which infiltration model is best suited. Therefore, the objectives of this study were to (i) assess different infiltration models based on describing and predicting soil infiltration characteristics in areas irrigated with treated wastewater and (ii) evaluate the effect of using TWW in irrigation on soil properties at different periods.

2. Infiltration Models

Soil water infiltration models can be divided into three categories: (1) physically- based, (2) empirical, and (3) semi-empirical models. Physically-based models are approximate solutions of the Richards equation by Philip model. The derivation of these models depends on the considerations of flow dynamics, moisture content, hydraulic conductivity, and initial and boundary conditions [23]. Empirical models are built based on data obtained from field experiments such as Kostiakov model, and semi-empirical models that utilize the simple forms of the continuity equation such as Horton model. Horton and Green and Ampt models provide estimates of the infiltration capacities as a function of time, and they are the most commonly used models [12]. Furthermore, the popularity of these empirical models is due to their simplicity in various water resource applications and reliability in yielding satisfactory results [23]. Infiltration model parameters are typically determined before a rainfall-runoff model is used [24]. A brief description of each of these infiltration models that have been used in this study is given below.

2.1. Philip Model (PH)

Philip model [14] is based on a semi-analytical solution of Richards equation, which results in two term infiltration equation as:

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

where I is the cumulative infiltration at time t, S is the soil sorptivity, and A is constant; at long time, A is equal to soil saturated hydraulic conductivity (Ks).

2.2. Horton Model (HO)

Horton [13] presented an exponential infiltration model described as:

$$I = i_f t + \frac{i_o - i_f}{\beta}\left(1 - e^{-\beta t}\right) \quad (2)$$

where i_f is final infiltration rate, i_o is the initial infiltration rate at time (t = 0), and β is constant for soil and initial condition.

2.3. Kostiakov Model (KO)

Among the empirical models, Kostiakov model [15] was the first to propose an infiltration model in which cumulative infiltration can be described as:

$$I = kt^a \quad (3)$$

where k and a are constants and can be evaluated using the measured infiltration data. The limitation of this model is that it predicts zero infiltration rate at long time. However, it is more effective under a relatively short period of water application [9].

2.4. Modified Kostiakov Model (MK)

Due to the limitation of Kostiakov model at long time, it was modified by Smoth [25] through accounting for the final infiltration rate, described as:

$$I = kt^a + i_f t \quad (4)$$

The logic for adding the i_f is that the infiltration rate decreases as more water infiltrates into soil until a constant rate, known as ultimate infiltration capacity, is achieved.

2.5. NRCS Model (SCS)

Natural Resources Conservation Services (NRCS) modified Kostiakov Model to include a term for cracking, commonly known as SCS Model, described as:

$$I = kt^a + d \quad (5)$$

where d is equal to 0.6985 [26].

3. Materials and Methods

3.1. Experimental Site

The experiments were carried out at Jordan University of Science and Technology (JUST) in the province of Irbid, Jordan (32 27′ 57.4′′ N latitude, 35 57′ 54.4′′ E longitude). The soil is classified as fine, mixed, thermic Typic Calcixerert with 15% $CaCO_3$ content and clayey soil texture (clay 48%, silt 37 %, and sand 15%). Three plots (0.8 ha each) were placed under different experimental treatments. The first one was non-irrigated plot and served as control, referred to as 0 YR. The second plot was irrigated with treated wastewater (TWW) for two years, referred to as 2 YR. The third plot was irrigated with TWW for five years, referred to as 5 YR. Flood basin irrigation was used to irrigate the alfalfa planted in the plot at 2 days' interval, each plot received a total amount of 172 m^3 per week (equivalent to

21.5 mm per week). Soil bulk density (BD) was determined using the core method. Soil alkalinity (pH) and electrical conductivity (EC) were measured in saturated paste extract, respectively. Cation exchange capacity (CEC) and sodium adsorption ratio (SAR) were determined by ammonium acetate method. Organic matter (OM) was measured using the loss on ignition. Particle size analysis was measured using the hydrometer method.

3.2. Irrigation Water Quality

The TWW used in this study was provided from a wastewater treatment plant located in the JUST campus. TWW samples were analyzed for various physicochemical characteristics following the standard methods described by the American Public Health Association (APHA) [27] and the average values are presented in Table 1. Overall, most of the measured parameters were below the recommended maximum concentrations and within guidelines for irrigation of agricultural crops (JS893/2006).

Table 1. Mean values of selected properties of the used TWW.

Parameter	Value	TWWS	Unit
pH	7.8	9	-
EC	1.6	2.5	dSm^{-1}
Na	359.4	230	
K	37.7		
Ca	97.0	230	
Mg	24.8	100	
Cl	297.8	400	mgL^{-1}
DOM	70		
TSS	30	300	
TDS	1050	1500	
COD	25	100	

TWWS: Treated wastewater standard (JS 893/2006); EC: electrical conductivity; DOM: Dissolved organic matter; TSS: Total suspended solid; TDS: Total dissolved solid.

3.3. Infiltration Measurements

In situ soil infiltration tests were performed following Schwärzel and Punzel [28] using the Hood infiltrometer (IL-2700, Umwelt-Gerate-Technik GmbH, Muncheberg, Germany). Using the Hood infiltrometer does not require any preparation of the soil prior to the measurements. The soil infiltration measurements were performed in five replicates per each treatment at a random location within each site. The infiltration measurements started by applying 0 mm tension and increased by 20 mm steps after that, until reaching the bubbling point of the soil. Each infiltration measurement took approximately 8 min to reach the steady rate, after which the tension was increased to the next level.

3.4. Model Parameter Estimation

In order to compare the infiltration models, parameter values for each model needed to be determined. The model parameters were estimated using iterative non-linear regression procedure of Solver tool, which is a component of the Excel software for Microsoft office for MAC version 14.5.5. This method can best fit the model to the experimental data while the sum of squared error (SSE) is minimized. Squared differences between measured and predicted data of cumulative infiltration can be calculated as:

$$\mathrm{SSE} = \sum_{i=1}^{n} (I(m)_i - I(p)_i)^2 \tag{6}$$

where $I(m)_i$ and $I(p)_i$ are measured and predicted cumulative infiltration for i-th measurement, respectively, and n is the number of cumulative infiltration measurements. Note that we used the same method to estimate the parameters of the physical model instead of determining those parameters by field measurements due to the violation of the assumptions such as uniform soil properties and uniform initial water content [29,30].

3.5. Model Performance Evaluation

The goodness of fit of each model was tested by several performance indices to evaluate how closely each model describes the measures and predicts infiltration. Models that best fit the data according to many goodness of fit indices were considered superior to the others. The commonly used, accepted, and recommended indices in published literature [29,31–36] are addressed below.

3.5.1. Mean Error (ME)

The ME statistic shows whether the selected model overestimates or underestimates the measured data of cumulative infiltration. ME can be calculated as:

$$ME = \sum_{i=1}^{n} \frac{I(p)_i - I(m)_i}{n} \tag{7}$$

Its absolute value should be as small as possible, the closer to zero, the better the model.

3.5.2. Root Mean Square Error (RMSE)

RMSE is used as an index of absolute error, it is always positive. It can be calculated as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left(I(p)_i - I(m)_i\right)^2}{n}} \tag{8}$$

The smaller the RMSE (close to zero), the better the agreement between the predicted and measured data.

3.5.3. Model Efficiency (EF)

EF proposed by Nash and Sutcliffe [37] is defined as one minus the sum of the absolute squared differences between the measured and predicted cumulative infiltration values normalized by the variance of the measured values during the period of the experiment. It can be calculated as:

$$EF\% = 1 - \frac{\sum_{i=1}^{n} \left(I(m)_i - I(p)_i\right)^2}{\sum_{i=1}^{n} \left(I(m)_i - \overline{I(m)}\right)^2} \tag{9}$$

where $\overline{I(m)}$ is the mean of the measured data. EF equal to 1 means the predicted cumulative infiltration values are in perfect agreement with the measured cumulative infiltration values.

3.5.4. Willmott's Index Agreement (W)

W index reflects the degree to which the data measured are accurately estimated by the data predicted [38]. It can be calculated as:

$$W = 1 - \frac{\sum_{i=1}^{n} \left(I(p)_i - I(m)_i\right)^2}{\sum_{i=1}^{n} \left(\left|I(p)_i - \overline{I(m)}\right| + \left|I(m)_i - \overline{I(m)}\right|\right)^2} \tag{10}$$

W equal to 1 means the predicted cumulative infiltration values are in perfect agreement with the measured cumulative infiltration values.

Finally, the mean values of ME, RMSE, EF, and W have been calculated to compare the models' performances for all the different TWW irrigated soils tested. Lower values of mean ME and RMSE, and higher values of EF and W are expected for the better infiltration models of the TWW irrigated soils in this research.

4. Results and Discussion

4.1. Effect of TWW on Soil Properties

Table 2 shows that the soil irrigated with TWW had significantly higher EC values, OM, SAR, and CEC. However, soil bulk density decreased under TWW irrigation (Table 2). The basic infiltration rate and cumulative infiltration were 60.84, 14.04, and 8.42 mm hr^{-1} and were 140, 72, and 62 mm for the 0 YR, 2 YR, and 5 YR treatments after 90 min experiments' period, respectively. These results propose that using TWW in irrigation could lead to a significant decrease in soil infiltration rate and cumulative infiltration, which may lead to higher runoff and soil erosion vulnerability. The infiltration rate and cumulated infiltration rate were significantly lower in the case of 2 YR and 5 YR treatments compared to control. This reduction in infiltration could be explained by the changes in pore size distribution (higher micropore content and lower macrospore) (Table 2) as a result of the total suspended solid and salts existing in the TWW [29,31–36] (Table 2). The soil irrigated with TWW had relatively higher total porosity (56.7, 55.7, and 59% for 0 YR, 2 YR, and 5 YR, respectively) as a result of increasing the organic matter content in the treated soil (Table 2). However, it had significantly lower wide coarse pores (wCP), and narrow coarse pores (nCP) at 2 YR treatment than that of control (0 YR). Even though the total porosity (TP) increased significantly and insignificant difference of wCP and nCP at 5 YR treatment compared to control (0 YR) (Table 3), the decrease in infiltration rate and cumulative infiltration at 5 YR treatment can be related to soil surface sealing, and accumulating of organic material and grease on the upper thin layer of soil surface [39,40].

Table 2. Mean values of soil chemical properties, infiltration rate, and accumulated infiltration for the three treatments.

Treatment	pH	ECe (dS m^{-1})	OM (%)	CEC (cmole$_{(+)}$ kg^{-1})	SAR	i_r (mm hr^{-1})	I_{cu} (mm)	TP (%)	wCP (>50 µm) (%)	nCP (50 to 10 µm) (%)
0 YR	6.9 b	0.7 b	2.77 c	32.49 b	0.75 c	60.84 a	140 a	56.7 b	3.6 a	8.3 a
2 YR	7.7 a	1.68 a	4.37 b	31.16 b	3.85 b	14.04 b	72 b	55.7 b	1.8 b	6.5 b
5 YR	7.4 a	2.09 a	7.19 a	33.44 a	6.39 a	8.42 c	62 c	59.0 a	4.1 a	9.0 a

ECe: saturated paste extract electrical conductivity; OM: organic matter; CEC: cation-exchange capacity (CEC); i_r: basic infiltration (90 min experiment); I_{cu}: accumulated infiltration at the end of the 90-min; TP: total porosity; wCP: wide coarse pores; nCP: narrow coarse pores. Values followed by the same letter are not significantly different.

Table 3. The estimated parameters of the five evaluated soil infiltration models for TWW irrigated soils at JUST.

		KO		MK			PH		HO			SCS	
		k	A	k	a	i_f	S	A	i_f	i_o	β	k	a
0 YR	Mean	0.3016	0.4287	0.5372	0.2236	0.0020	0.1010	0.0012	0.0023	0.1581	0.0786	0.2106	0.4656
	SE	0.0192	0.0060	0.0950	0.0123	0.0001	0.0084	0.0000	0.0001	0.0293	0.0077	0.0263	0.0086
2 YR	Mean	0.1214	0.4796	0.5237	0.2169	0.0007	0.0903	0.0001	0.0010	0.1535	0.0775	0.3439	0.6103
	SE	0.0224	0.0210	0.0628	0.0024	0.0000	0.0069	0.0001	0.0000	0.0343	0.0091	0.0878	0.0375
5 YR	Mean	0.1032	0.4796	0.4961	0.2132	0.0006	0.0854	0.0000	0.0009	0.1085	0.0617	0.0755	0.5005
	SE	0.0136	0.0131	0.0449	0.0028	0.0001	0.0075	0.0000	0.0001	0.0124	0.0027	0.0121	0.0278
	Overall Max	0.3449	0.5482	0.8999	0.2458	0.0023	0.1299	0.0020	0.0026	0.2709	0.1067	0.6719	0.7050
	Overall Min	0.0571	0.4145	0.3431	0.1779	0.0005	0.0657	0.0000	0.0008	0.0710	0.0544	0.0324	0.4200

KO: Kostiakov; MK: Modified Kostiakov; PH: Philip; HO: Horton; NRCS: Natural Resources Conservation Service; k, A, a, are constants; if: final infiltration rate; S: soil sorptivity; io: initial infiltration rate; β: constant for soil and initial condition; SE: standard Error; 0 YR: non-irrigated plot (control); 2 YR: plots irrigated with treated wastewater (TWW) for two years; 5 YR: plots irrigated with TWW for five years; R: replicate number.

4.2. Model Parameter

The values of the estimated parameters are listed in Table 3 for the selected infiltration models in this study. In addition, Table 3 shows the mean and standard error for each treatment, and for each model used in this study.

In most publications, Modified Kostiakov model is basically the Kostiakov model plus i_f t term [41,42]. However, the results presented in Table 3 showed that these parameters of the above-mentioned models are completely different. Similar conclusion was drawn by Dashtaki et al. [29] who recommended to not use similar parameters when these two models are used. Regarding the discussed models, one may expect that the values of i_f in Modified Kostiakov and Horton models, and A in Philip model would be essentially equal to the measured final infiltration rates. However, based on the results presented in Table 2, they are not comparable and this could be explained by the fact that these parameters are empirical in nature [29].

The estimated parameter value for each model was different for each measurement in each treatment. This could be caused by the heterogeneity of soil properties (initial soil water content, soil and water temperature, etc.) under field condition. Moreover, there is a clear decreasing trend in the values of the estimated parameters for each model with increasing the TWW irrigation period. For example, the k parameter in the KO model decreased from 0.3016 for the 0 YR treatment to 0.1214 and 0.1032 for the 2 YR and 5 YR treatments, respectively. Similarly, the i_f parameter in the MK model decreased from 0.0020 for the 0 YR treatment to 0.0007 and 0.0006 for the 2 YR and 5 YR treatments, respectively. These decreases in the infiltration parameters suggest that long-term application of TWW results in a decrease in the cumulative infiltration which could be explained by clogging of the small pores by the suspended materials loaded in the TWW [6,22,43]. In general, the reported values of the estimated parameter are different from those reported in the literature because of the differences in soil and water quality. In a study conducted by Fan et al. [44] to analyze the influence of soil texture, initial water content, film hole diameter, and water depth on cumulative infiltration, numerical simulations carried out with HYDRUS-2D showed that cumulative infiltration from a film hole was affected by each of soil texture, film hole diameter, and water depth. Sorptivity, (S) parameter in Philip model, increases with the film hole diameter for the same soil texture, and the relationship is a power function [44]. Wang et al. [45] stated that the capillary suction sometimes can be approximated by sorption, can control the early stage of infiltration process in Philip model. However, gravity plays a bigger role as time goes, and the second term in Philip model will have greater values [45].

4.3. Model Performance

The performance of each infiltration model was evaluated based on the value of mean error (ME), root mean square error (RMSE), model efficiency (EF), and Willmott's index agreement (W). The results of the evaluation indices for the five selected soil infiltration models are presented in Table 4. Horton model had lowest ME followed by Philip model where NRCS model had the highest ME, and was found to be the worst in describing the infiltration in clayey soil irrigated by treated wastewater. Similar to the results presented by Li et al. [46], Horton model ranked number 1 with the lowest ME value compared to other models. Note that all models over-estimated the cumulative infiltration since the means of ME were positive (Table 4).

The theoretically-based Philip model was ranked number 1 and found to be the most predictive model considering RMSE followed by Modified Kostiakov model. As Machiwal et al. [11] concluded from a number of experiments conducted in a wasteland of Kharagpur, the best model to describe variability of infiltration process was Philip model [16]. NRCS model had the highest RMSE as the poorest model in predicting infiltration. In agreement to these predictions, Duan et al. [31] reported that NRCS model was the poorest in predicting the infiltration considering the RMSE. In contrast to our results, Zolfaghari et al. [35] reported that Modified Kostiakov model results in lowest RMSE and ranked as the best model to describe the soil infiltration. Additionally, Nie et al. [16] concluded that according to RMSE and R^2 results, Kostiakov–Lewis model was the best in predicting cumulative infiltration, and Philip model was the worst in prediction. These overall rankings are similar to within the treatments' ranking except that for Kostiakov model. It has an overall ranking of 4 considering both ME and RMSE but for the third treatment (soil irrigated with TWW for five years), it ranked number 2 and 1 considering ME and RMSE, respectively.

Table 4. Evaluation indices of the five evaluated soil infiltration models for TWW irrigated soils at JUST.

Model	Index	0 YR			2 YR			5 YR				
		Mean	SE	Rank	Mean	SE	Rank	Mean	SE	Rank	Overall Mean	Overall Rank
KO	ME	0.0866	0.0491	5	0.0305	0.0239	5	0.0034	0.0036	2	0.0402	4
	RMSE	1.1747	0.0455	4	0.1782	0.0356	2	0.1851	0.0186	1	0.5127	4
	EF	0.9011	0.0085	4	0.9879	0.0048	2	0.9850	0.0017	1	0.9959	2
	W	0.9656	0.0035	4	0.9967	0.0014	2	0.9960	0.0005	1	0.9990	2
MK	ME	0.0223	0.0132	3	0.0268	0.0028	3	0.0196	0.0066	4	0.0229	3
	RMSE	0.3108	0.0216	2	0.2906	0.0178	4	0.3236	0.0313	3	0.3083	2
	EF	0.9932	0.0004	2	0.9711	0.0030	4	0.9545	0.0031	3	0.9946	3
	W	0.9983	0.0001	2	0.9923	0.0008	4	0.9876	0.0009	3	0.9986	3
PH	ME	0.0206	0.0021	2	-0.0035	0.0142	2	0.0037	0.0079	3	0.0069	2
	RMSE	0.1438	0.0154	1	0.1737	0.0203	1	0.1925	0.0192	2	0.1700	1
	EF	0.9985	0.0003	1	0.9891	0.0026	1	0.9835	0.0025	2	0.9994	1
	W	0.9996	0.0001	1	0.9973	0.0006	1	0.9958	0.0006	2	0.9998	1
HO	ME	0.0004	0.0001	1	0.0006	0.0001	1	0.0013	0.0002	1	0.0008	1
	RMSE	0.4695	0.0307	3	0.4378	0.0385	5	0.4588	0.0434	5	0.4554	3
	EF	0.9846	0.0007	3	0.9334	0.0102	5	0.9083	0.0071	5	0.9869	5
	W	0.9961	0.0002	3	0.9824	0.0028	5	0.9753	0.0021	5	0.9967	5
NRCS	ME	0.0555	0.0403	4	0.0271	0.0022	4	0.0472	0.0277	5	0.0433	5
	RMSE	1.2261	0.0623	5	0.2099	0.0097	3	0.3334	0.0382	4	0.5898	5
	EF	0.8943	0.0032	5	0.9849	0.0016	3	0.9434	0.0188	4	0.9881	4
	W	0.9627	0.0014	5	0.9960	0.0004	3	0.9815	0.0074	4	0.9969	4

KO: Kostiakov; MK: Modified Kostiakov; PH: Philip; HO: Horton; NRCS: Natural Resources Conservation Service; ME: mean error; RMSE: root mean square error; EF: model efficiency; W: Willmott's index; SE: standard Error; 0 YR: non-irrigated plot (control); 2 YR: plots irrigated with treated wastewater (TWW) for two years; 5 YR: plots irrigated with TWW for five years; R: replicate number.

The results of model efficiency (EF) and Willmott's index agreement (W) evaluation for the five selected soil infiltration models are presented in Table 4. The overall ranking of both parameters (EF and W) were similar for each model of the evaluated models. Philip model had highest model efficiency (EF) as well as Willmott's index agreement (W), where the values was 0.9994 and 0.9998, respectively. Kostiakov model followed Philip model, and Horton model was the worst in prediction cumulative infiltration with lowest EF and W values (Table 4).

Similar to ME and RMSE evaluation indices, Kostiakov model had the highest EF and W values and ranked number 1 for the third treatment (soil irrigated with TWW for five years). In agreement with our results, Li et al. [46] had drawn a similar conclusion where both indices, EF and W, had similar ranking for all evaluated models. However, for the three models they evaluated, the superior model was Kostiakov model followed by Horton model, and the worst model in predicting soil infiltration was Philip model, whereas our ranking for the same models was Philip model followed by Kostiakov model and then Horton model. In another study, Jejurkar and Rajurkar [12] found that the models of Kostiakov and modified Kostiakov provide better fit to the measured cumulative infiltration in clayey soil with R^2 values 0.959 and 0.964 for Kostiakov and modified Kostiakov models, respectively.

In order to evaluate the overall performance of the five selected soil infiltration models considering all indices used in this study, the model ranking was summed up as final scores (Table 5).

Table 5. Overall ranking of the evaluated soil infiltration models for TWW irrigated soils at JUST.

Model	KO	MK	PH	HO	NRCS
Final Scores	12	11	5	14	18
Final Ranking	3	2	1	4	5

KO: Kostiakov; MK: Modified Kostiakov; PH: Philip; HO: Horton; NRCS: Natural Resources Conservation Service.

The final scores presented in Table 5 are the sum of the ranking number for each index (ME, RMSE, EF, and W) of each model. Philip model was superior over all models to describe and predict cumulative infiltration followed by Modified Kostiakov model, and the worst model was the NRCS model in predicting cumulative infiltration for the soil irrigated by treated wastewater. In contrast to these results, Dashtaki et al. [29] reported a superior performance for Horton model whereas Mirzaee et al. [36] reported a superior performance for Modified Kostiakov model. In another study, field experiments were conducted on a sandy soil to test the predictability of four infiltration models (Horton, Kostiakov, Philip, modified Kostiakov) for cumulative infiltration under local conditions by Ogbe et al. [24]. In terms of accuracy, the researchers found that cumulative infiltration was accurately predicted by Horton, followed by Kostiakov, then Philip and modified Kostiakov models. In agreement to our conclusion, Zolfaghari et al. [35] reported that NRCS model had the lowest ranking between all models to predict and describe soil infiltration. However, Al Maimuri [21] stated that Horton model has the least predictability and applicability among other three models tested in arid region. This result was attributed to the fact that Horton model is inefficient in predicting infiltration characteristics in regions where initial rainfall intensities are less than initial infiltration capacity of soils.

Based on the results of Table 5, Philip model was ranked number 1. Therefore, it has been used to plot the cumulative infiltration (Figure 1) based on the estimated parameters (Table 3). The results showed that at the end of the 90 min experiments, the cumulative infiltrations were 140 mm, 72 mm, and 63 mm for the 0 YR, 2 YR, and 5 YR treatments, respectively. These results suggest that long-term application of TWW results in significant decrease in the cumulative infiltration which may lead to susceptibility of more runoff and soil erosion [6,22,43]. This conclusion can be supported by the decrease in the sorptivity (S) parameter (Table 3), with increase in the TWW irrigation period which could be explained by clogging of the small pores.

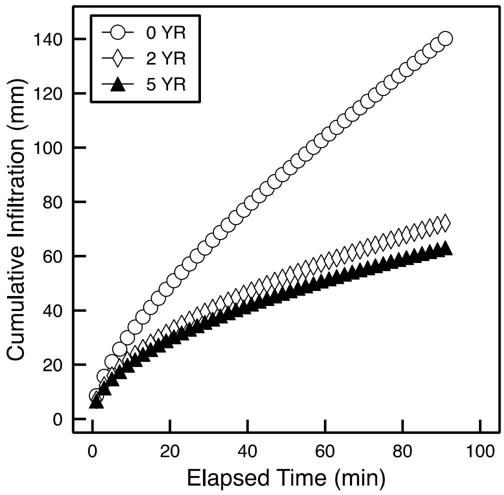

Figure 1. Cumulative infiltration curves fitted to Phillip's model parameters for the three experimental plots subjected to different irrigation treatments (0YR, 2YR, and 5YR).

5. Conclusions

Infiltration data of clayey soil irrigated with treated wastewater (TWW) were fitted to assess and evaluate Philip, Horton, Kostiakov, Modified Kostiakov, and NRCS models. Among the five selected infiltration models, Philip model and Modified Kostiakov models performed the best fitting results based on mean error, root mean square error, model efficiency, and Willmott's index of agreement. Philip model performed consistently well in all treatment, whereas the performance of Kostiakov model varied within the treatments, while NRCS model was the least predictable model. Moreover, using treated wastewater significantly decreased soil infiltration via accumulation of suspended solids and clogging of soil pores. Philip model captured best the adjustment to real field conditions and therefore, it could be recommended for the prediction of TWW infiltration in clayey soil.

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