Water Practice & Technology

 Water Practice & Technology Vol 17 No 11, 2435 doi: 10.2166/wpt.2022.142

Simplified approach for determination of parameters for Kostiakov's infiltration equation

Mekonen Ayana Gebul

Department of Water Resources Engineering, School of Civil Engineering and Architecture, Adama Science and Technology University, Adama, Ethiopia

E-mail: mekonen.ayana24@gmail.com

ABSTRACT

Knowledge of soil infiltration characteristics is required increasingly for the proper design and efficient management of irrigation. Various empirical and physically based infiltration models have been used for several years, but the practical use of many is limited by parameter determination problems, which, in turn, are influenced by factors acting at the surface and within the soil, initial and boundary conditions, etc. In this study, a simplified approach for determining parameters for the Kostiakov equation was tested and validated. The equation's linearized form, using logarithmic transformation and field data collected from five sites, was employed. The results show that cumulative infiltration can be described well using the approach. Its quality is also confirmed by performance indices like R^2 and standard error, whose values ranged from 0.985 to 0.999 and 0.020 to 0.005, respectively, suggesting that the simplified approach described is sufficient for practical purposes, when data are too scarce to apply other, complex methods to predict cumulative infiltration.

Key words: cumulative infiltration, infiltration, Kostiakov equation, simplified approach

HIGHLIGHTS

- Knowledge of soil infiltration is needed for practical applications.
- Infiltration models involve complex processes of parameter determination.
- The modified Kostiakov equation (MKE) is widely used in irrigation.
- Other empirical approaches fail to describe infiltration over long periods.
- The simple approach explained here can accurately determine parameters of simplified MKE.

1. INTRODUCTION

Infiltration is important for crop growth and water resource management. Thus, understanding the infiltration characteristics of soils is fundamental in estimating effective rainfall and groundwater recharge, and the design, operation and management of irrigation (Parhi *et al.* 2007; Zakwan *et al.* 2016). Several equations have been developed to describe infiltration, including empirical, semi-physical and physically based models (Philip 1957; Van de Genachte *et al.* 1996; Parhi *et al.* 2007; Angelaki *et al.* 2013), and have been tested and applied in research (Bautista *et al.* 2009; Haghiabi *et al.* 2011; Angelaki *et al.* 2013; Mirzaee *et al.* 2014; Hasan *et al.* 2015).

Physically based models rely on the law of conservation of mass depicted by Richard's equation, which is the most commonly used model to describe steady-state soil infiltration. It attempts to describe flow dynamics based on soil hydraulic conductivity, moisture content and initial and boundary conditions. Determining the parameters required for Richard's equation, however, involves difficult processes that make finding the equation's analytical solution difficult (Lei *et al.* 2020). The practical application of physically based models is also limited by the restrictions and assumptions that they involve. Parhi *et al.* (2007) present some state-of-the-art infiltration models.

Empirical infiltration models are derived from field measurements involving cumulative infiltration as a function of time. Among empirical infiltration models, the Kostiakov equation is used by many researchers in surface irrigation design, operation and management (Fangmeier & Ramsey 1978; Blair & Smerdon 1988; Smerdon *et al.* 1988; Hartley 1992; Holzapfel *et al.* 2004; Bautista *et al.* 2009; Adamala *et al.* 2014; Seyedzadeh *et al.* 2020). In its original form, Kostiakov's equation relates cumulative infiltration to time as a power function. Because of its simplicity, Kostiakov's equation has been used widely in irrigation management (Van de Genachte *et al.* 1996).

Determining accurate infiltration characteristics leads to accurate design and management of irrigation systems but depends on the correct handling of model parameters. Different ways of parameter determination are available and range from graphical methods (Hartley 1992; Mirzaee *et al.* 2014; Zakwan *et al.* 2016; Vand *et al.* 2018) to combined furrow infiltrometry and surface irrigation advance trajectories (Holzapfel *et al.* 2004; Gillies & Smith 2005). Most methods are complex and time-consuming. A simple approach based on infiltration measurements, suggested by Davis (1943) and also described in Hasan *et al.* (2015), for determining parameters for Kostiakov-Lewi's equation was tested and validated in this study.

2. THEORETICAL BACKGROUND

Kostiakov empirical infiltration equation (Kostiakov 1932) takes a power form in an algebraic equation relating the cumulative infiltration depth, Z, explicitly to the infiltration time, t (Fok 1986). It is widely used because of its simplicity and ability to fit most infiltration data (Haghiabi *et al.* 2011). It is expressed in Equation (1):

$$Z = kt^{a} \tag{1}$$

where Z is the cumulative infiltration (cm), t the infiltration time (min); k is the soil infiltration coefficient (cm/min) and a is the infiltration index constant (dimensionless).

It is commonly accepted that the value of the power term a is between 0 and 1 ($0 < a < 1$). As a result, the infiltration rate is an exhaustion function, with infinite initial value and zero final value after long periods (Hartley 1992; Dashtaki *et al.* 2009; Zakwan 2019). In reality, infiltration rates will decline to a positive constant value – the infiltration capacity or final infiltration rate – not to zero. To overcome this limitation, a modification, widely known as the modified Kostiakov equation (Equation (2)), has been introduced:

$$Z = kt^{a} + f_{o}t \tag{2}$$

where f_o is the basic infiltration rate (cm/min) and the other terms are as defined in Equation (1). The first derivative of Equation (2) gives the infiltration rate (i) of the modified Kostiakov equation as Equation (3):

$$i = kat^{a-1} + f_{o} \tag{3}$$

3. MATERIALS AND METHODS

3.1. Infiltration test and data collection

Field data collection involved infiltration measurement at five sites and furrow irrigation monitoring at one, to enable a volume-balance approach for estimating parameters. The conceptual framework is shown in Figure 1.

Infiltration was measured using a standard, 20–30 cm deep, double-ring infiltrometer. Infiltration is high initially and decreases with time. Thus, measurements were taken at 2- to 5-min intervals initially but 10- to 20-min interval later. The tests were done on three fields in Wonji Showa irrigated sugarcane farm and Haramaya University's research farm in Ethiopia, during the second half of December 2021 and first week of January 2022. Infiltration data from other areas – e.g., Arba Minch University's demonstration farm, also in Ethiopia – were used as well. Datasets from five sites in total were used to test and validate the approach – Wonji Showa sugarcane farm (sites 1–3), Arba Minch University demonstration farm, AMU (site 4) and Haramaya University research farm, HrU (site 5). In terms of soil texture, site 1 is dominantly clay, sites 2 and 3 are silty clay, site 4 is sandy clay and site 5 sandy clay loam.

Cumulative infiltration values for all sites are given in Table 1.

3.2. Inflow–outflow and advance measurement

In parallel with the infiltration measurements at site 1, two 32-m long furrows were used to monitor inflow/outflow and the advance of water along them. This was intended to enable use of the volume-balance approach for estimating parameters for Kostiakov's modified equation, following procedures suggested by Walker & Skogerbboe (1987). Irrigation water was diverted from a farm ditch to the 32-m long furrows using siphons, after calibration for specific

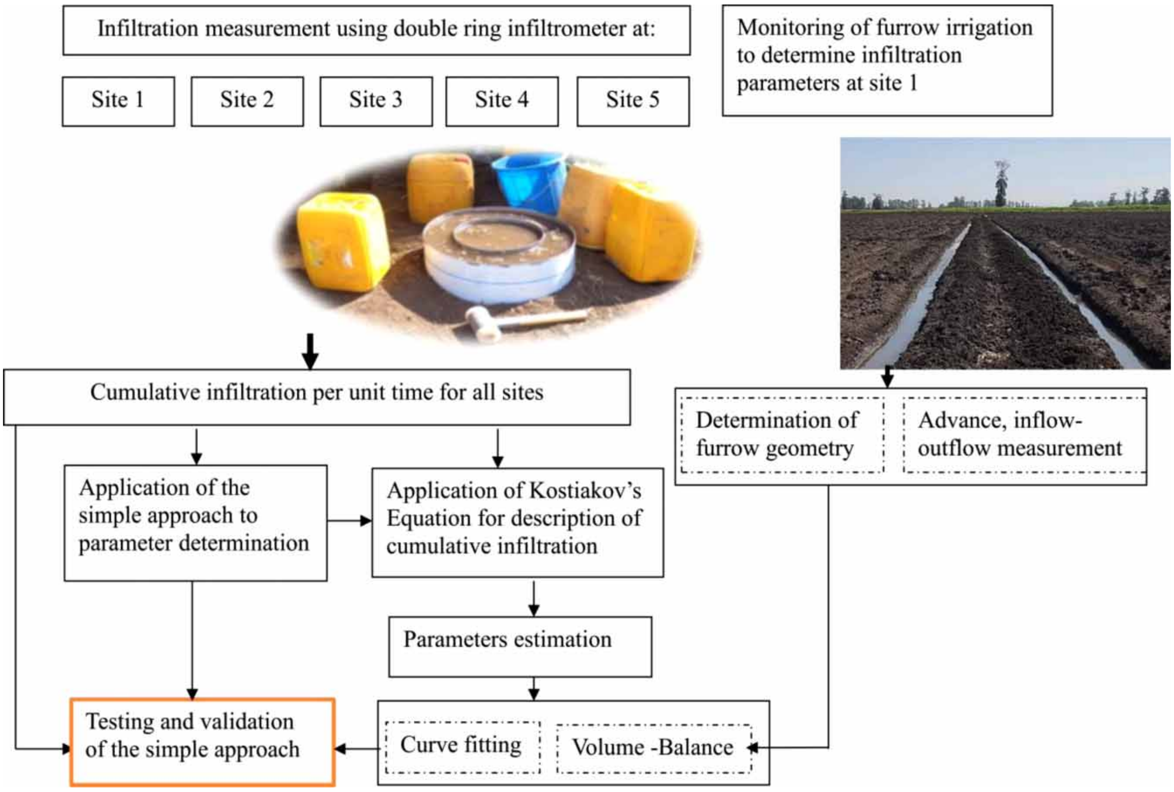

Figure 1 | Flowchart of study methodology.

Table 1 | Cumulative infiltration (all sites)

	Cumulative infiltration (cm)				
Time (min)	**Site 1 Clay**	**Site 2 Silty clay**	**Site 3 Silty clay**	**Site 4 Sandy clay**	**Site 5 Sandy clay loam**
2	2.0	1.6	2.7		3.0
5	3.5	2.4	3.8	1.8	
10	5.0			3.4	6.5
15	6.1	4.4	4.7	4.7	
20	7.1	5.7	5.0	5.6	10.0
25	8.1			6.4	
30	8.9	7.0	5.7		
35					15.0
40	10.4	8.1	6.2	7.0	
45		8.6	6.8		
55					20.5
60	13.5			9.8	
70		9.0	7.4		
80	16.2				26.1
85		9.4	8.0		
100	18.7				
105					31.7
120	20.7			14.6	
130	23.7				37.7

heads. This approach requires that the water's advance is measured at the middle and end of the furrow (in this case, 16 and 32 m along the furrow).

A 75-mm (3-inch) Parshall flume was used to measure outflow from the furrows, and measurement was taken when steady-state depth was established in the flume. The value of f_o was determined from the inflow–outflow data using Equation (4).

$$f_o = \frac{Q_{in} - Q_{out}}{L} \tag{4}$$

where Q_{in} and Q_{out} are the furrow inflow and outflow rates, respectively (m^3/min).

This approach is relatively complex and was considered in this study to see to what extent the simplified modified Kostiakov equation approach can produce results comparable to those from the volume-balance approach. Furrow geometry and other data required for the volume-balance application are given in Table 2.

Table 2 | Field data used for volume-balance computation

Parameter	Units	Value
Furrow length	m	32
Advance time to furrow mid-point, $L/2$	min	4.9
Advance time to furrow end, L	min	21.6
Furrow geometry (more or less parabolic)		
ρ_1	–	0.591
ρ_2	–	1.361
Slope	–	0.005
Roughness	–	0.04
Inflow, Q_{in}	l/s	2.0
Outflow, Q_{out}	l/s	1.18
Basic infiltration rate, f_o	m^3/min/m	0.00154
Surface storage shape factor, σ_y		0.77

3.3. Parameter determination

Different methods are available for determining the Kostiakov equation parameters. Of these, graphical methods are used widely to estimate the parameters for Equation (1), i.e., the original Kostiakov equation, and the volume-balance method for the modified version (Equation (2)).

3.3.1. Curve fitting

The most widely used method to determine parameters for Equation (1)) is transformation into linear form using logarithms:

$$\log(Z) = \log(k) + a\ \log(t) \tag{5}$$

The parameters in Equation (1) are determined from plotting log(Z) versus log(t). The best fit straight line is drawn through the plotted points, the line's slope being equal to 'a' and the intercept ordinate axis represents the value of log(k) (Zakwan *et al.* 2016).

3.3.2. Volume-balance (two-point)

In applying Equation (2) in surface irrigation, the two-point method and volume-balance approaches suggested by Walker & Skogerbboe (1987) are used to determine the infiltration parameters. Knowing the advance times corresponding to the two locations, the parameters 'a' and 'k' can be calculated for Equation (2) from the volume-balance equation using Equations (6)–(12):

$$a = \frac{\ln(V_L/V_{0.5L})}{\ln(t_L/t_{0.5L})} \quad (6)$$

$$k = \frac{V_L}{\sigma_z t_L^a} \quad (7)$$

where

$$V_L = \frac{Q_o t_L}{L} - \sigma_y A_o - \frac{f_o t_L}{1+r} \quad (8)$$

$$V_{0.5L} = \frac{2Q_o t_{0.5L}}{L} - \sigma_y A_o - \frac{f_o t_{0.5L}}{1+r} \quad (9)$$

$$A_o = \left[\frac{Q_o n}{60\rho_1 S^{1/2}}\right]^{1/\rho_2} \quad (10)$$

$$\sigma_y = \frac{a + (1-a) + 1}{(1+r)(1+a)} \quad (11)$$

$$r = \frac{\ln(L/0.5L)}{\ln(t_L/t_{0.5L})} \quad (12)$$

where a, k and f_o are empirical parameters (a = dimensionless, $k = m^3/m/min$ and $f_o = m^3/m/min^a$), A_o is the cross-sectional wetted area at the inlet (m^2), Q_o is the inflow rate (m^3/min), L is the furrow length (m), t_L is the advance time to the furrow end (min), $t_{0.5L}$ is the advance time to the mid-furrow length (min), V_L and $V_{0.5L}$ are the infiltrated volumes to the end and mid-furrow, respectively (m^3/m), and n, S and $\rho_{1,2}$, respectively, Manning's roughness coefficient, and field slope and furrow shape factors, σ_y is the surface profile shape factor and r is the empirical parameter of the advance equation. Determined parameters for the application of volume-balance approach are given in Table 3.

Table 3 | Parameters determined for the volume-balance approach

Volume-balance parameter (unit)	Value determined	Equation
A_o (m^2)	0.01356	(10)
V_L (m^3/m)	0.086035	(8)
$V_{0.5L}$ (m^3/m)	0.039256	(9)
σ_y (–)	0.77840	(11)
r (–)	0.46927	(12)

3.3.3. Simple approach to parameter estimation

The modified Kostiakov infiltration equation parameters are usually estimated from measurement data by: (1) logarithmic transformation and equation linearization (graphic method) (Haghiabi *et al.* 2011); or, (2) using volume-balance and advance measurements at two points. The latter involves several field measurements and is, thus, field and time specific. The simple method, suggested by Davis (1943) and described also by Hasan *et al.* (2015) involves the following steps:

Step 1: collect infiltration data using a standard, double-ring infiltrometer procedures, preparing the data as cumulative infiltration over time.

Step 2: find an equation of the form of Equation (13) – similar to the modified Kostiakov equation (Hasan *et al.* 2015) – to give a reasonable description of the cumulative infiltration (Z) to the soil.

$$Z = kt^a + b \quad (13)$$

where k is the soil infiltration coefficient (cm/min) as defined for Equation (1), b is the characteristic constant (cm).

Step 3: select two data points, near the beginning (t_1, Z_1) and end (t_2, Z_2) of the infiltration test data series, respectively. These points can also be obtained by interpolation from the cumulative infiltration versus time curve.

Step 4: calculate the third value, t_3, using Equation (14):

$$t_3 = \sqrt{t_1 \times t_2} \tag{14}$$

Step 5: take the value of t_3 from Equation (14), and read the corresponding cumulative infiltration depth (Z_3) from the curve or interpolate it from the data. The constant b in Equation (13) can now be calculated using Equation (15):

$$b = \frac{Z_1 \times Z_2 - Z_3^2}{Z_1 + Z_2 + 2Z_3} \tag{15}$$

Once b has been determined, Equation (13) can be linearized using logarithmic transformation – Equation (16):

$$\log(Z - b) = \log(k) + a\log(t) \tag{16}$$

Step 6: the unknown constants k and a in Equation (13) can be determined by rewriting Equation (16) for all time steps considered as Equation (17):

$$\log(Z_i - b_i) = \log(k_i) + a\log(t_i) \tag{17}$$

Thus, if there are n numbers of measurement points, then equal number of equations of the form Equation (17) are formulated for each cumulative infiltration (Z_i) and time step (t_i). In this process, it is best to select an even number of measurement points for simplicity. For example, if there are 12 measurement points during time (t_1–t_{12}) and correspondingly cumulative infiltration (Z_1–Z_{12}), Equation (17) is formulated for all 12. Equations are then grouped in time order into two equal sets, e.g. the first set for t_1–t_6 and second for t_7–t_{12}. An example of such a procedure is given in Table 4 for infiltration data at site 1. The equations are then

Table 4 | Derived Equation (17) for all rows and values (site 1)

Row 1: $\log(k) + 0.301a = 0.068$
Row 2: $\log(k) + 0.699a = 0.427$
Row 3: $\log(k) + 1.000a = 0.620$
Row 4: $\log(k) + 1.176a = 0.722$
Row 5: $\log(k) + 1.301a = 0.797$
Row 6: $\log(k) + 1.398a = 0.862$
Row 7: $\log(k) + 1.477a = 0.907$
Row 8: $\log(k) + 1.602a = 0.994$
Row 9: $\log(k) + 1.778a = 1.103$
Row 10: $\log(k) + 1.903a = 1.187$
Row 11: $\log(k) + 2.000a = 1.252$
Row 12: $\log(k) + 2.079a = 1.298$
Sum equations from rows 1 to 6: $6\log(k) + 5.875a = 3.495$
Sum equations from rows 7 to 12: $6\log(k) + 10.84a = 6.728$

summed to yield simultaneous equations of the forms of Equations (18a) and (18b):

$$\sum_{i=1}^{6} \log(k_i) + \sum_{i=1}^{6} alog(t_i) = \sum_{i=1}^{6} (Z_i - b_i) \tag{18a}$$

$$\sum_{i=7}^{12} \log(k_i) + \sum_{i=7}^{12} alog(t_i) = \sum_{i=7}^{12} (Z_i - b_i) \tag{18b}$$

Equations (18a) and (18b) must be solved simultaneously to determine k and a.

3.4. Performance evaluation

Two indices – the coefficient of determination and the standard error (SE) – were used to analyze the goodness of fit between the results of this simple approach and the measured data.

3.4.1. Coefficient of determination

$$R^2 = \frac{\left[\sum_i^n (M_i - \bar{M})(E_i - \bar{E})\right]^2}{\sum_i^n (M_i - \bar{M})^2 \times \sum_i^n (M_i - \bar{M})^2} \tag{19}$$

Coefficient of determination (R^2) can be in the range 0.0–1.0, values close to 1.0 show good agreement between measurement and estimation.

3.4.2. Standard error

$$SE = \frac{\sqrt{1/n \sum_{i=1}^{n} [M_i - E_i]^2}}{\bar{E}} \tag{20}$$

where M_i indicates measured values, $\overline{M}$ indicates average of measured values, E_i indicates estimated values, $\bar{E}$ indicates average of estimated values, and n indicates number of observations.
Values of SE closer to zero indicate better agreement between measured and estimated values.

4. RESULTS AND DISCUSSION

4.1. Parameter estimation

The value of the term 'b' in Equation (13) – calculated using Equation (15) – is 0.451. Applying Equation (17) to the time and cumulative infiltration in all rows in Table 1 for site 1 yielded the 12 equations and two simultaneous equations in Table 4.

Applying Equation (17) to data from site 1, the equations from rows 1 to 12 yield the last two Equations (18a) and (18b) in Table 4, with unknown values for a and k from Equation (13) that, when solved simultaneously, yield the values: $a = 0.651$ and $k = 0.881$.

With all three constants known, the cumulative infiltration for site 1 is described by Equation (21):

$$Z_{site\ 1} = 0.881t^{0.651} + 0.451 \tag{21}$$

Equations similar to Equation (21) can be developed for cumulative infiltration data from other sites. The infiltration parameters for all five sites, determined as described, are presented in Table 5.

4.2. Testing the simple approach

The simple approach described here represents a simplified version of the modified Kostiakov equation, which is said to be simplified as the second term on the right hand side does not involve time, unlike Equation (2). Its ability to predict cumulative infiltration was tested using: (1) cumulative infiltration data measured at the five sites; (2) cumulative infiltration estimated using Kostiakov's original equation (Equation (1)), with the parameters estimated by curve fitting; and (3) estimated cumulative infiltration in which the parameters were determined by the

Table 5 | Infiltration parameters determined using different approaches and performance indices

Site	Parameters and indices	Parameter values for Simple approach Equation (13)	Curve fitting Equation (1)	Volume-balance Equation (2)
1	k (cm/min)[a]	0.881	1.231	0.0.217 (m^3/m/min)[a]
	a (–)	0.651	0.582	0.531 (–)
	b (cm)	0.451		$f_o = 0.00154$ (m^3/min/m)
	R^2	0.999	0.997	0.9992
	SE	0.0209	0.055	0.126
2	k (cm/min)	1.285	1.56	
	a (–)	0.378	0.368	
	b (cm)	0.09		
	R^2	0.985	0.981	
	SE	0.005	0.005	
3	k (cm/min)	1.075	1.146	
	a (–)	0.536	0.510	
	b (cm)	0.216		
	R^2	0.993	0.981	
	SE	0.050	0.067	
4	k (cm/min)	0.807	0.611	
	a (–)	0.621	0.682	
	b (cm)	−0.37		
	R^2	0.991	0.973	
	SE	0.025	0.118	
5	k (cm/min)	1.348	1.745	
	a (–)	0.676	0.615	
	b (cm)	0.644		
	R^2	0.999	0.992	
	SE	0.012	0.065	

[a]This unit is valid for both the original Kostiakov Equation (Equation (1)) and the simple approach (Equation (13)). For the modified Kostiakov Equation (Equation (2)), k is expressed in m^3/m/min (as given in the last column of Table 5).

volume-the balance approach. The results are presented in Figures 2 and 3, and Table 5. Statistical analysis was carried out to determine performance indices like R^2 and SE – see Table 5.

The predicted cumulative infiltration results using the simple approach are very close to the measured data (Figure 2). However, with slight variations, the approach seems to overestimate cumulative infiltration as time proceeds at sites 3 and 4. The results obtained from the volume-balance method using Equation (2) at site 1 show increasingly greater values than the others (Equations (1) and (13)), probably because the second term on the right hand side of Equation (2) allows the cumulative infiltration to increase proportionally with time.

The test results indicate that the cumulative infiltration predicted using the simple approach is reasonably accurate and can be used to estimate cumulative infiltration over reasonable time for irrigation. The values of R^2, for instance, vary from 0.985 to 0.999, while SE varies from 0.02 to 0.005. There is a good agreement between measured and estimated cumulative infiltration at all five sites. Figure 4 compares the estimated values of cumulative infiltration with the measurement results obtained from site 1.

The results obtained using the simple approach described here and curve fitting lie on or close to the 1:1 line, showing good prediction. The results of the volume-balance method, however, deviate considerably with time from the measured data, although its scattered points fall within the $\pm 15\%$ error bands from the 1:1 line.

4.3. Parameter interpretation

As shown in Table 5, the values of parameters 'k' and 'a' estimated using the simple approach and curve fitting methods compare well. The parameter values ranged from 0.807 to 1.285 and 0.378 to 0.687, respectively. Fok (1986) interpreted the Kostiakov equation parameters and, fitting it to a physically based infiltration equation, derived five separate sets of values for 'k' and 'a', depending on time, initial moisture content, and hydraulic conductivity. The power constant 'a' has more physical meaning than other Kostiakov equation constants, as its magnitude depends on the interrelations and interactions of numerous infiltration abatement or augmentation factors (Dixon *et al.* 1978). According to Dixon, large 'k' values are associated with micro-rough and macro-

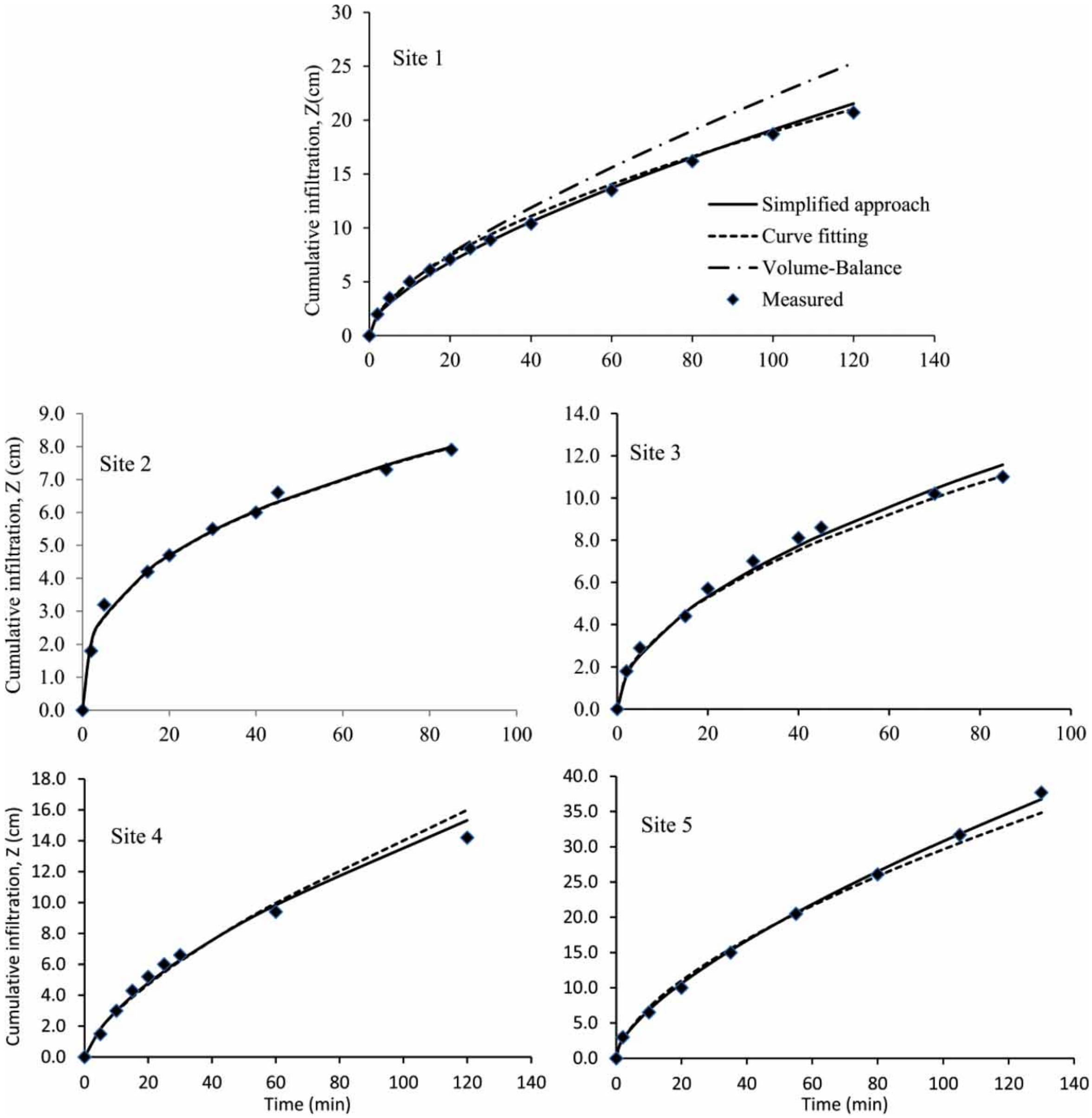

Figure 2 | Comparison of cumulative infiltration determined by different methods.

porous soil surfaces, or with conditions favoring a relatively large gravitational contribution to infiltration. On the other hand, small '*k*' values are associated with a smooth, micro-porous surface where capillarity is the major force driving infiltration.

The values of constant '*b*' varied from −0.37 to 0.644. As the values indicate, the constant '*b*' is simply an infiltration curve fitting coefficient. For empirical infiltration equations, it is generally understood that, while infiltration is described as a function of time, the remaining parameters are calibration constants representing the conditions under which the test was conducted, including initial moisture content and any other factors that may induce variations in infiltration (Guzmán-Rojo *et al.* 2019).

5. CONCLUSIONS

Reliable determination of cumulative infiltration is important for the proper design and management of irrigation systems. Although infiltration measurements often deliver only point information, they are irreplaceable for infiltration model validation and parameter determination. The study has successfully tested and validated a simple approach for determining parameters for the modified Kostiakov equation. As for all modeling inputs, it was found that infiltration measurements and the selection of extreme values, described above in steps 3–5 of this

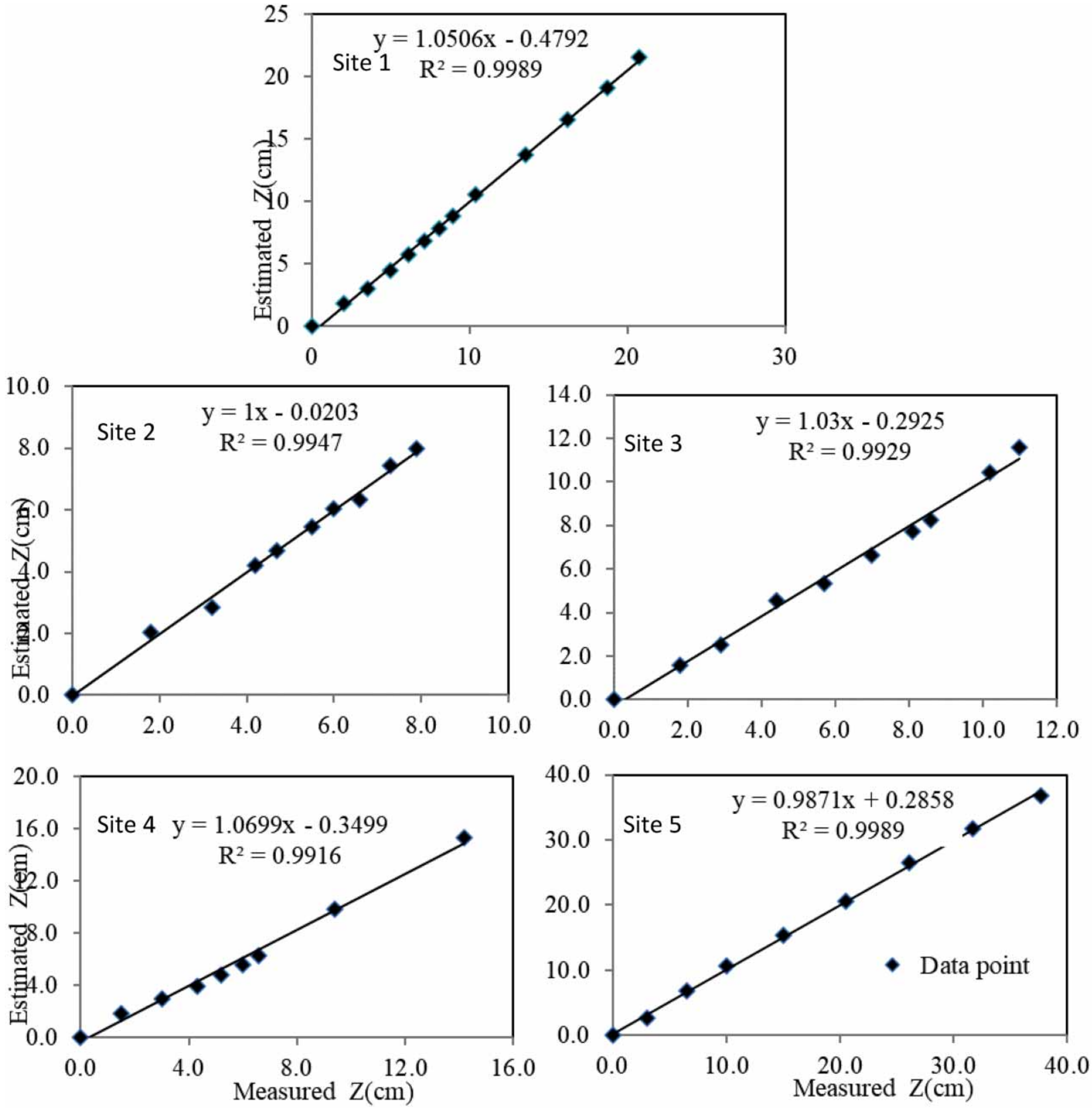

Figure 3 | Comparison of measured and estimated cumulative infiltration using the simple approach (all sites).

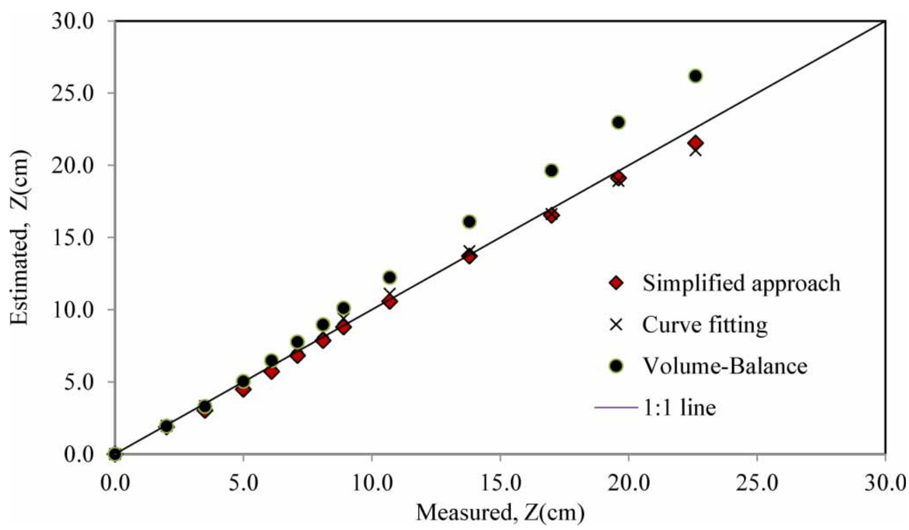

Figure 4 | Correlation between measured and estimated cumulative infiltration using different approaches at site 1.

approach, must be done carefully to get good results. The analyses by Fok (1986) and Hartley (1992) also indicated that calibrated optimum values of Kostiakov's parameters, '*a*' and '*b*', depend on both the experiment's duration and the data points selected for calibration. The approach's performance in describing soil infiltration characteristics at five sites was tested using two indices (R^2 and SE) and found to be highly acceptable. Although cumulative infiltration can be estimated over a reasonable time period for most irrigation practices with the simplified approach, however, it may not provide reliable estimates over longer periods. In surface irrigation, the two-term Kostiakov equation (Equation (2)) is commonly employed to account for longer infiltration periods.

The test and validation results show that this approach can adequately describe cumulative and helpful for irrigation management and other practical purposes.

ACKNOWLEDGEMENT

My graduate students who have participated in collection of the raw data are gratefully acknowledged. I am indebted to an anonymous reviewer for valuable comments and suggestions that substantially improved the quality of the paper.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Adamala, S., Raghuwanshi, N. S. & Mishra, A. 2014 Development of surface irrigation systems design and evaluation software (SIDES). *Computers and Electronics in Agriculture* **100**, 100–109.

Angelaki, A., Sakellariou-Makrantonaki, M. & Tzimopoulos, C. 2013 Theoretical and experimental research of cumulative infiltration. *Transport in Porous Media.* **100**, 247–257.

Bautista, E., Clemmens, A. J., Strelkoff, T. S. & Schlegel, J. 2009 Modern analysis of surface irrigation systems with WinSRFR. *Agricultural Water Management* **96**(7), 1146–1154.

Blair, A. W. & Smerdon, E. T. 1988 Infiltration from irrigation advance data. II: experimental. *Journal of Irrigation and Drainage Engineering* **114**(1), 18–30.

Dashtaki, S. G., Homamee, M., Mahdian, M. H. & Kouchakzadeh, M. 2009 Site-dependence performance of infiltration models. *Water Resources Management.* **23**, 2777–2790.

Davis, D. S. 1943 *Empirical Equations and Monography*, Vol. 200. McGraw Hill Book Co., New York.

Dixon, R. M., Simanton, J. R. & Lane, L. J. 1978 *Simple Time-Power Functions for Rainwater Infiltration and Runoff*. Arizona-Nevada Academy of Science. Available from: http://hdl.handle.net/10150/301042.

Fangmeier, D. D. & Ramsey, M. K. 1978 Intake characteristics of irrigation furrows. *Transactions of the ASAE* **21**, 696–700.

Fok, Y.-S. 1986 Derivation of Lewis-Kostiakov intake equation. *Journal of Irrigation and Drainage Engineering* **112**(2), 164–171.

Gillies, M. & Smith, R. J. 2005 Infiltration parameters from surface irrigation advance and run-off data. *Irrigation Science* **24**, 25–35.

Guzmán-Rojo, D. B., Bautista, E., Gonzalez-Trinidad, J. & Bronson, K. F. 2019 Variability of furrow infiltration and estimated infiltration parameters in a macroporous soil. *Journal of Irrigation and Drainage Engineering* **145**(2), 16.

Haghiabi, A. H., Jahangir, A. K., Manouchehr, H. & Jahanshir, M. H. 2011 A new method for estimating the parameters of Kostiakov and modified Kostiakov infiltration equations. *World Applied Sciences Journal* **15**(1), 129–135.

Hartley, D. M. 1992 Interpretation of Kostiakov infiltration parameters for borders. *Journal of Irrigation and Drainage Engineering* **118**(1), 156–165.

Hasan, M., Chowdhury, T., Drabo, M., Kassu, A. & Glenn, C. 2015 Modeling of infiltration characteristics by modified Kostiakov method. *Journal of Water Resource and Protection* **7**(16), 1309–1317.

Holzapfel, E. A., Jara, J., Zuñiga, C., Marino, M. A., Paredes, J. & Billib, M. 2004 Infiltration parameters for furrow irrigation. *Agricultural Water Management* **68**(1), 19–32.

Kostiakov, A. N. 1932 The dynamics of the coefficients of water percolation in soils and the necessity for studying it from a dynamic point of view for purpose of amelioration. Soil Science, Russian Part A, 17–21.

Lei, G., Fan, G., Zeng, W. & Huang, J. 2020 Estimating parameters for the Kostiakov-Lewis infiltration model from soil physical properties. *Journal of Soils and Sediments* **20**, 166–180.

Mirzaee, S., Zolfaghari, A. A., Gorji, M., Dyck, M. & Dashtaki, S. G. 2014 Evaluation of infiltration models with different numbers of fitting parameters in different soil texture classes. *Archives of Agronomy and Soil Science* **60**(5), 681–693.

Parhi, P. K., Mishra, S. K. & Singh, R. A. 2007 A modification to Kostiakov and modified Kostiakov infiltration models. *Agricultural Water Management* **21**, 1973–1989.

Philip, J. 1957 The theory of infiltration: 1. The infiltration equation and its solution. *Journal of Soil Science* **83**(5), 345–358.

Seyedzadeh, A., Panahi, A., Eisa, M., Singh, V. P. & Maheshwari, B. 2020 Developing a novel method for estimating parameters of Kostiakov–Lewis infiltration equation. *Irrigation Science* **38**, 189–198.

Smerdon, E. T., Blair, A. W. & Reddell, D. L. 1988 Infiltration from irrigation advance data. I: theory. *Journal of Irrigation and Drainage Engineering* **114**(1), 4–17. https://ascelibrary.org/doi/abs/10.1061/(ASCE)0733-9437.

Vand, A., Sihag, P., Singh, B. & Zand, M. 2018 Comparative evaluation of infiltration models. *KSCE Journal of Civil Engineering.* **22**, 4173–4184.

Van de Genachte, G., Mallants, D., Ramos, J., Deckers, J. K. & Feyen, P. 1996 Estimating infiltration parameters from basic soil properties. *Journal of Hydrological Processes.* **10**, 687–701.

Walker, W. & Skogerbboe, G. 1987 Surface Irrigation: Theory and practice. Englewood Cliffs, NJ, USA: Prentice-Halli, 386p.

Zakwan, M. 2019 Comparative analysis of the novel infiltration model with other infiltration. *Journal of Water and Environment* **33**, 620–632.

Zakwan, M., Muzzammil, M. & Alam, J. 2016 Application of spreadsheet to estimate infiltration parameters. *Perspectives in Science* **8**, 702–704.

First received 23 September 2022; accepted in revised form 30 October 2022. Available online 11 November 2022