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Characterising Vertical Redistribution on Irrigated Furrows in the Tukulu Soil

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Abstract: Subsurface soil water redistribution on the South African Tukulu, also referred as the Cutanic Luvisols in other countries, was evaluated following single run irrigation (20, 40, 80 and 160 L/min inflow rates) in 90 m furrows. Changes in soil water content (SWC) at three horizons were monitored using neutron water meter. Measurements were made every 10 m starting 5 m from the furrow inlet for 455 h. HYDRUS-2D software was used to estimate soil hydraulic parameters through inverse optimization algorithms for redistribution at the inlet, midpoint and furrow end. Optimized model parameters compared with initial estimates recorded satisfactory agreement between measured and predicted soil water content, despite spatial variability. Effective hydraulic conductivity (K_{eff}) for 0-600 mm and 0-850 mm profile flow domains demonstrated linearity with SWC although inconsistencies under field conditions were inevitable. The underlying layer restricted gravity and augmented redistribution with K_{eff} assuming a steeper gradient than normal. Conversion of K_{eff} and soil water content into a ratio assisted in quantifying rate of redistribution at 0-600 mm and 0-850 mm profile depth. Vertical redistribution was found to be limited within the upper 600 mm depth thus providing the opportunity to develop furrow irrigation with confidence that water productivity is optimized.

Key words: Soil water redistribution, inflow rates, effective unsaturated hydraulic conductivity, infiltrated depth, HYDRUS-2D.

1. Introduction

Redistribution is an important soil physical property that if properly exploited can enhance soil water storage and productivity of flood irrigation methods, especially furrow irrigation. Given the growing water scarcity in the semi arid areas of the Free State province of South Africa, farmers without adequate energy supplies can still achieve greater water use efficiency (WUE) from furrow irrigation by selecting layered soils with adequate water storage properties.

Layered soils occupy more than 10% of the provincial landscape and because of low and erratic rainfall, high runoff and evaporation losses are susceptible to a dry soil water regime. In-field rainwater harvesting (IRWH) was developed by Hensley et al. [1] to improve WUE by converting runoff to deep infiltration; however, during prolonged dry spells water reserves in the root zone are severely depleted. To stabilize crop yields, micro-flood irrigation (MFI) [2] was proposed for farmers practising IRWH with access to irrigation water [3]. Furrow irrigation efficiencies are estimated to be 25% to 60% compared to the sprinkler (60% to 95%) and drip (80% to 95%) irrigation systems [4]. The MFI is more effective because small inflow rates that approach the soils basic intake are used and wetted surface area is reduced. Consequently, water lost through surface evaporation and deep drainage is remarkably reduced while subsurface redistribution between and below furrows is promoted. Distribution efficiency as high as 95% has been reported for MFI [2].

Optimal furrow irrigation design and management

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rely on soil infiltration and redistribution properties. The two dimensionality and complexity of infiltration and redistribution on furrows is acknowledged by Ref. [5-7]. Infiltrated water depth and distribution are primary efficiency indicators and are well researched in furrow irrigation [7-9]. This is not surprising because infiltration is usually rapid and last for a short time compared to redistribution that could persist for many days, especially in layered soils [10]. Despite the fact that software programs for redistribution analysis on furrows have increased in recent times [5, 6, 9], its importance and meaningful application is often overlooked, especially under frequent irrigation. However, where controlled deficit irrigation or increased retention capacity of rainfall is the primary objective; the functional role of redistribution on soil water storage cannot be ignored.

Characterising and simulating water movement during redistribution requires accurate description of soils unsaturated hydraulic properties that serve as inputs in the governing flow equation. These are the soil water characteristics curve (SWCC) and the unsaturated hydraulic conductivity (*K*-coefficient). The SWCC represents the unique relationship between the soil water content and matric suction of a particular soil while the *K*-coefficient can be expressed in terms of matric suction (h) or volumetric water content (θ). The *K*-coefficient is the most difficult hydraulic property to measure [10] and usually varies with depth because the upper and lower soil profile layers desorbs and wets monotonically. In addition, soil textural and structural spatiality across the flow domain has serious implication on the extent and rate of redistribution across the flow domain. Therefore, redistribution is generally characterised by a unique relationship of infiltrated depth, matric suction and *K*-coefficient [10-12].

Numerical methods with varying levels of complexity are available for estimating the *K*-coefficient along partially wetted furrows. One such method is the spatial moments technique that describes water movement and spread of water plume from drip and furrow irrigation using zeroth moment, first moment and second moments [13-16]. In layered soils the spatial heterogeneity of the flow domain can be viewed as a homogeneous medium by characterising spatial average of hydraulic properties [16]. This concept was successfully used to calculate average or effective *K*-coefficient from spatial moments [16] and has since become popular in soil water related studies [17-20].

The South African Tukulu which is similar to the Cutanic Luvisols of the World Reference Soil Group represents layered soils common in IRWH fields and covers an estimated 500 to 600 million hectares [21]. An experimental study on how Tukulu soil profile layers affected redistribution on irrigated furrows was carried with the following objectives. Firstly, the soil hydraulic properties pertaining to the water movement during redistribution from irrigated furrows of the Tukulu soil were estimated. Secondly, the relationships between the rate of redistribution and infiltrated depth along irrigated furrows were described.

2. Material and Methods

2.1 Experimental Design and Measurement

The field experiment was carried out at Parady's Experiment Farm (29°13'24.69"S, 26°12'40.93"E, altitude 1,422 m) of the University of the Free State, South Africa. The selected site was predominately of the Tukulu soil form according to the Soil Classification Working Group [22]. A soil profile pit was opened on the representative site and diagnostic horizons are illustrated in Fig. 1. Soil samples were also taken for textural analysis and dry bulk density determination, summarised in Table 1.

Redistribution of soil water in the Tukulu soil was characterised with furrows of 90 m that were irrigated in a single run. Because the study was part of the broader aim to establish the optimum inflow rate for micro flood irrigation, four inflow rate treatments

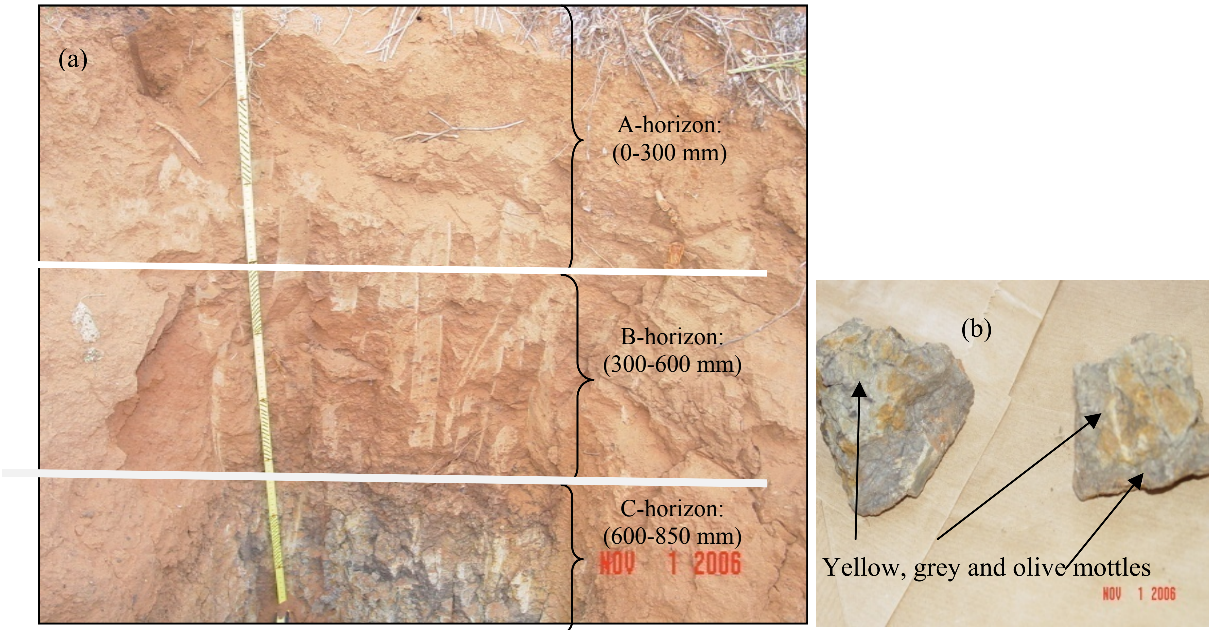

Fig. 1 Representation of an opened soil profile pit for the (a) Tukulu soil and (b) hydromorphic mottles present in the prismacutanic C-horizon.

Table 1 Summary of the measured soil physical properties of the Tukulu soil form.

Physical properties	Master horizons		
	A	B1	C
Coarse sand (%)	5.3	9.2	2.1
Medium sand (%)	9.3	8.8	3.8
Fine sand (%)	41.2	31	28.3
Very fine sand (%)	25.3	21	8.4
Coarse silt (%)	2.1	2	3
Fine silt (%)	4.6	2.5	6.5
Clay (%)	11.3	26.4	47.9
Bulk density (kg/m)	1670	1597	1602
Porosity (%)	34.0	33	32.4
Ks (mm/h)	36.1	40	9.6

Ks = saturated hydraulic conductivity.

were used: 20, 40, 80 and 160 L/min. Each plot had three furrow replications with 1.2 m long neutron access tubes installed only in the central furrow at 10 m intervals starting 5 m from the furrow inlet. An area of 2 m by 2 m around each access tube was covered with plastic to minimize the influence of evaporation on subsurface water redistribution (Fig. 2).

A site calibrated neutron soil water meter was used to monitor the change in soil water content during the redistribution period that commenced immediately after the depletion-recession phase of irrigation. Measurements were taken twice a day, in the morning and afternoon, for the first week and then daily for a fortnight at depths of 150, 450 and 725 mm.

2.2 Description of the Soil Hydraulic Properties

The SWCC corresponding to the diagnostic A-, B- and C-horizons of the Tukulusoil was determined by using a combination of the hanging water column method and the pressure chamber plate desorption technique. The hanging water column measured the suction (h) and soil water (θ) relationship for a suction range of 0 to 1,000 mm, while suctions from 1,000 mm (10 kPa) to 150,000 mm (1,500 kPa) were measured using chambers of various pressure sizes. The hydraulic parameters of the resulting θ-h relationship were determined using the closed-form equation of van Genuchten [23] where m is given by m = 1–1/n. The model is expressed as:

$$\theta(h) = \theta_r + \frac{\theta_{s-}\theta_r}{\{1+|\alpha h|^n\}^m} \quad (1)$$

where, θ_s and θ_r are the respective saturated and residual values of the volumetric soil water content, θ (mm/mm), h is the matrix suction (mm), while α and n are the shape and pore size distribution parameters,

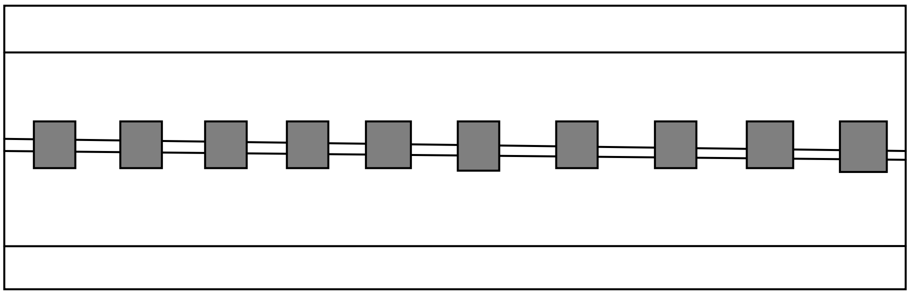

Fig. 2 Plot layout of three 90 m furrow length with covered 2 m × 2 m sections at 10 m distance intervals along the central furrow.

respectively. Parameters related to pore-size distribution (*n*) and shape (α) of the SWCC were estimated from the Rosetta pedo-transfer [24] in agreement with the field measured saturated hydraulic conductivity (*Ks*). Table 2 summarises the initial estimates of soil hydraulic parameters for the Tukulusoil horizons before optimisation.

Table 2 Estimated soil hydraulic parameters from ROSETTA, Schaap et al. [24].

Parameters	A	B	C
θ_s (mm/mm)	0.34	0.33	0.32
θ_r (mm/mm)	0.13	0.12	0.26
α	0.00116	0.00094	0.005
n	1.773	1.617	1.226
Ks (mm/h)	36.1	40	9.6

2.3 Simulation of Redistribution with HYDRUS-2D

A two-dimensional soil water movement during redistribution on irrigated furrows was predicted using the software HYDRUS-2D [9]. This model numerically solves the two dimensional form of the Richard flow equation and minimizes the objective function for parameter optimization by using the Levenberg-Marquardt non linear-squares approach [25]. The HYDRUS-2D code is successfully employed in simulation studies of subsurface soil water distribution during furrow irrigation and redistribution [18, 26, 27].

In this paper the soil water movement during redistribution was inversely predicted using soil water content measurement versus time as the objective function. To improve the model's predictions, the laboratory based SWCC hydraulic parameters had to be optimized [27]. Any parameter that improved predictions was selected, but a combination of more than three parameters was not considered given the instability of the inverse optimization method [9, 28].

The HYDRUS-2D uses the Galerkin finite element method to simulate water flow in porous media and for this exercise a soil profile flow domain of 2,000 mm by 850 mm with a trapezoidal furrow shape at the symmetric position was used (Fig. 3). The flow domains were described by a finite element mesh of 50 mm and discretised into three layer materials. Final pressure head from the irrigation phase were exported as the initial pressure condition for the redistribution phase. The zero flux boundary condition was assigned at the soil surface inside the furrow, and along the vertical sides of the flow domain. Free drainage boundary conditions were selected for the bottom of the soil profile. Three sections of furrow at pre-determined distances from inflow were used for model predictions for each inflow rate. The distances of 5, 35 and 55 m from the 20 L/min inflow rate furrow were chosen because the advancing stream could not reach the end of the 90 m furrow. For the 40, 80 and 160 L/min inflow rate furrows, the three chosen distances were 5, 55 and 85 m, respectively.

2.4 Experimental Data Analysis

The measured and predicted soil water content was used to characterise the spatio-temporal redistribution process. Firstly, the measure of dispersion (*D*) between the measured (*M*) and predicted (*P*) soil water content (*θ*) from the various soil profile horizons

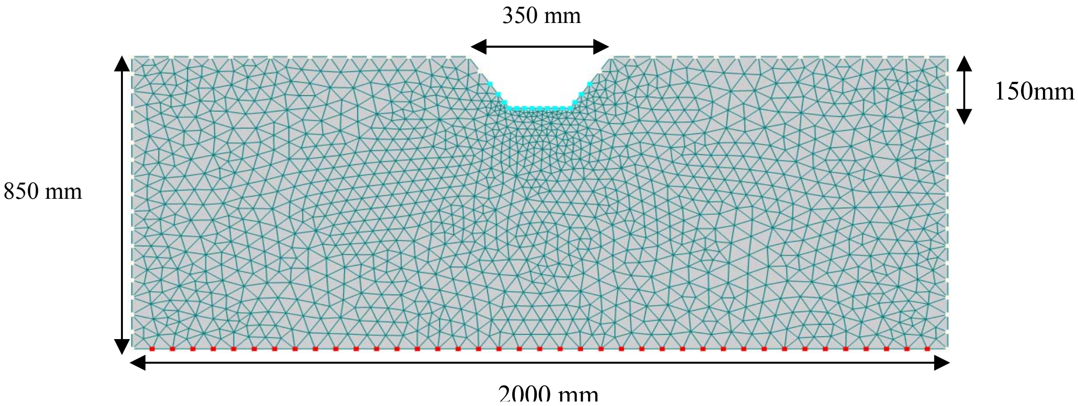

Fig. 3 Fine element mesh and boundary conditions assigned inside the furrow (constant head), zero flux at the surface and vertical sides and free drainage at the bottom of the profile.

of the three respective furrow distance sections were determined. The following mathematical expression was found to be convenient for this purpose:

$$D = \left|\frac{\Delta\theta_P}{\Delta\theta_M}\right| \quad (2)$$

wherever, the predicted and measured variations of soil water content were similar, the ratio would be in the order of one. Soil water content measurements at 150, 450 and 725 mm depths allowed the profile to be discretised into two flow domains, 0-600 mm and 0-850 mm, and could be applied to describe redistribution under different soil water regimes. The redistribution flux across these flow domains was quantified using the unsaturated hydraulic conductivity (*K*-coefficient) and the hydraulic gradient that operated between the upper nearly saturated layers and the lower less infiltrated layer. The inter block or effective *K*-coefficient (K_{eff}) was appropriate for the Tukulu soil profile. Given the assumption that furrow irrigation usually leaves the upper layer nearly saturated compared to the lower unsaturated layers, the Darcian flux expression for redistribution from Gasto et al. [30] was simplified to become:

$$q_{eff} = K_{eff}\left[\frac{h_L - h_U}{Z_L - Z_U} + 1\right] \quad (3)$$

where, q_{eff} is the average flux between the lower (*L*) and upper (*U*) horizons, h_L and h_U. Z_L and Z_U represent the corresponding matrix suctions and depths of the horizons in question. A unit value was assigned to the gravitational gradient (Δz/Δz) with a positive sign for downward water flow. The horizon thickness was also considered to be large enough for the redistribution process to be consistent with the principles of K_{eff}. Before irrigation and at the onset of redistribution the assumption was made that profile layers not infiltrated to near saturation approached residual soil water content. Thus the redistribution flux was a function of K_{eff} and infiltrated depth. The geometric mean as described by Warrick [19] was used to estimate the effective soil water content and *K*-coefficient for the 0-600 mm and 0-850 mm selected soil profile flow domains.

The rate of distribution was therefore represented by the ratio of the estimated K_{eff} and soil water content of the flow domain (0-600 mm or 0-850 mm) derivatives. This analogy was similar to that of Yeh et al. [16] who described the rate of change for the first spatial moments in the z direction (*Vz*) as:

$$\frac{dK_z}{d\theta} = Vz(\theta) \quad (4)$$

The resulting derivatives from the three furrow distant sections were then plotted against the corresponding measured infiltrated depth to obtain a linear relationship between redistribution and infiltrated depth. If available data were sufficient this function could have been extended to determine the moisture diffusivity length (*λ*) described by Yeh et al. [16] as follows:

$$\lambda(\theta) = \frac{D(\theta)}{\frac{dK(\theta)}{d\theta}} \quad (5)$$

2.5 Statistical Analysis

The quality of fit between the measured and estimated soil water during the redistribution period was evaluated using the 1:1 line. The coefficient of determination (R^2), root mean square error (RMSE) and the index of agreement or D-index as proposed by Willmot et al. [31] were also calculated. The Bartletts test [29] was preferred for evaluating the homogeneity of the error variances between *K*-coefficients calculated from averages of measured and predicted soil water content.

3. Results

3.1 Parameter Optimisation and HYDRUS-2D Inverse Solution

Table 3 is a summary of the parameters optimised at various furrow points that received different inflow rates. The quality of fit is also shown. A comparison between the measured and predicted soil water content was drawn on a 1:1 line presented in Fig. 4 along with the coefficient of determination (R^2).

Model solutions converged readily to the optimisation of the θ_s, θ_r and n compared to that of the α and Ks parameters. Optimised θ_s were highly variable at the inlet, midpoint and furrow end with the exception of the 20 L/min inflow rate furrow where values were similar for both 5 m and 35 m distances. Comparable initial estimates were recorded for the A- and B-horizons at the 80 L/min inflow rate furrow. Similar initial estimates and optimised θ_s values were observed at the 160 L/min inflow rate furrow at 85 m. Only the 160 L/min inflow rate furrow recorded optimized θ_r at all three distance points and for all cases. All values for the 160 L/min inflow rate were variable, except the 5 m point where almost the same value was assigned to the soil horizons. Similarly, the n assumed different values along the furrow length and depth, which differed from the initial estimates with the exception of the 80 L/min inflow rate furrow C-horizon at 55 m. The α and Ks were optimised once in the 40 L/min inflow rate furrow at the 85 m and 5 m points, respectively. The α value showed similarities with the initial estimates especially in the A- and C-horizons while the Ks values were not comparable at any depths.

The quality of fit from the optimised parameters when the HYDRUS-2D was initialised exhibited variability along the furrow distance points from the four inflow rate treatments. The R^2 ranges were calculated for 20 L/min (0.57 to 0.77), 40 L/min (0.68 to 83), 80 L/min (0.63 to 0.88) and 160 L/min (0.52 to 0.58). The corresponding RMSE ranged from 0.013 to 0.008, 0.027 to 0.012, 0.25 to 0.008 and 0.019 to 0.007 while the *D*-index ranged from 0.85 to 0.93, 0.57 to 0.84, 0.295 to 0.96 and 0.788 to 0.925, respectively.

3.2 Changes in Soil Water Content during Redistribution

The changes in SWC depth of the inlet, mid and furrow end with the different inflow rates at different times of redistribution are summarised in Fig. 5. Results are given by means of a XY one dimensional curve to provide a simple comparison between the measured and predicted soil water content. The change in measured and predicted volumetric soil water content and the dispersion between the measured and predicted soil water content at the different horizon layers from the four inflow rate treatments are given in Table 4. For simplicity the time intervals of 0, 45 and 455 h from the onset of redistribution were assumed to be applicable to all the four inflow rates furrow treatments. Changes in soil water content were indicated by the prefix (-) if a loss in volumetric SWC from the flow domain was recorded while the prefix (+) represented a gain.

3.3 Estimated Effective K-coefficient during Redistribution

Figs. 6-9 illustrates the variation in the estimated *K*-coefficient from the measured and predicted SWC from the 20, 40, 80 and 160 inflow rate furrows. Redistribution at soil profile depths ranging from 0-600 mm and 0-850 mm were characterised using average *K*-coefficient (K_{eff}). Homogeneity tests calculated from measured and predicted SWC are illustrated in Table 5.

The calculated K_{eff} from the measured and model prediction values showed considerable variations along the 20 L/min inflow rate furrow. However, the K_{eff} estimated from measured and model predictions was found to be homogeneous for the 0-850 mm profile domain at 35 m and 55 m furrow sections. The estimated K_{eff} from the 40 L/min passed the homogeneity test at 5 m and 55 m furrow sections at respective profile flow domain of 0-600 mm and 0-850 mm. At the 85 m furrow the estimated K_{eff} were homogenous at 0-600 mm and 0-850 mm profile domains.

Table 3 Optimised parameters to improve HYDRUS-2D model prediction.

Inflow rate (L/min)	Distance (m)	Horizons	Hydraulic parameters						
			θ_s	θ_r	α	*n*	*Ks*	RMSE	*D*-index
		A	0.331	-	-	1.522	-	0.008	0.905
	5	B	0.319	-	-	-	-	-	-
		C	0.313	-	-	1.297	-	-	-
		A	0.331	-	-	1.522	-	0.014	0.853
20	35	B	0.319	-	-	-	-	-	-
		C	0.313	-	-	1.297	-	-	-
		A		0.160	-	-	-	0.013	0.931
	55	B		0.206	-	-	-	-	-
		C		0.199	-	-	-	-	-
		A	0.327	0.271	-	-	139	0.012	0.57
	5	B	0.329	0.303	-	-	266	-	-
		C	0.330	0.267	-	-	4	-	-
		A	0.346	-	0.001	-	-	0.027	0.565
40	55	B	0.349	-	1.222	-	-	-	-
		C	0.294	-	0.005	-	-	-	-
		A	0.275	-	0.001	-	-	0.022	0.844
	85	B	0.381	-	0.0004	-	-	-	-
		C	0.276	-	0.012	-	-	-	-
		A	0.337	-	-	1.570	-	0.025	0.295
	5	B	0.333	-	-	1.290	-	-	-
		C	0.306	-	-	1.342	-	-	-
		A	0.340	-	-	1.525	-	0.022	0.800
80	55	B	0.343	-	-	1.223	-	-	-
		C	0.274	-	-	1.182	-	-	-
		A	0.324	0.241	-	-	-	0.008	0.957
	85	B	0.286	0.259	-	-	-	-	-
		C	0.323	0.318	-	-	-	-	-
		A	0.328	0.260	-	-	-	0.007	0.925
	5	B	0.278	0.261	-	-	-	-	-
		C	0.307	0.261	-	-	-	-	-
		A	0.326	0.225	-	-	-	0.012	0.922
160	55	B	0.280	0.240	-	-	-	-	-
		C	0.332	0.318	-	-	-	-	-
		A	0.340	0.181	-	-	-	0.019	0.788
	85	B	0.330	0.167	-	-	-	-	-
		C	0.320	0.308	-	-	-	-	-

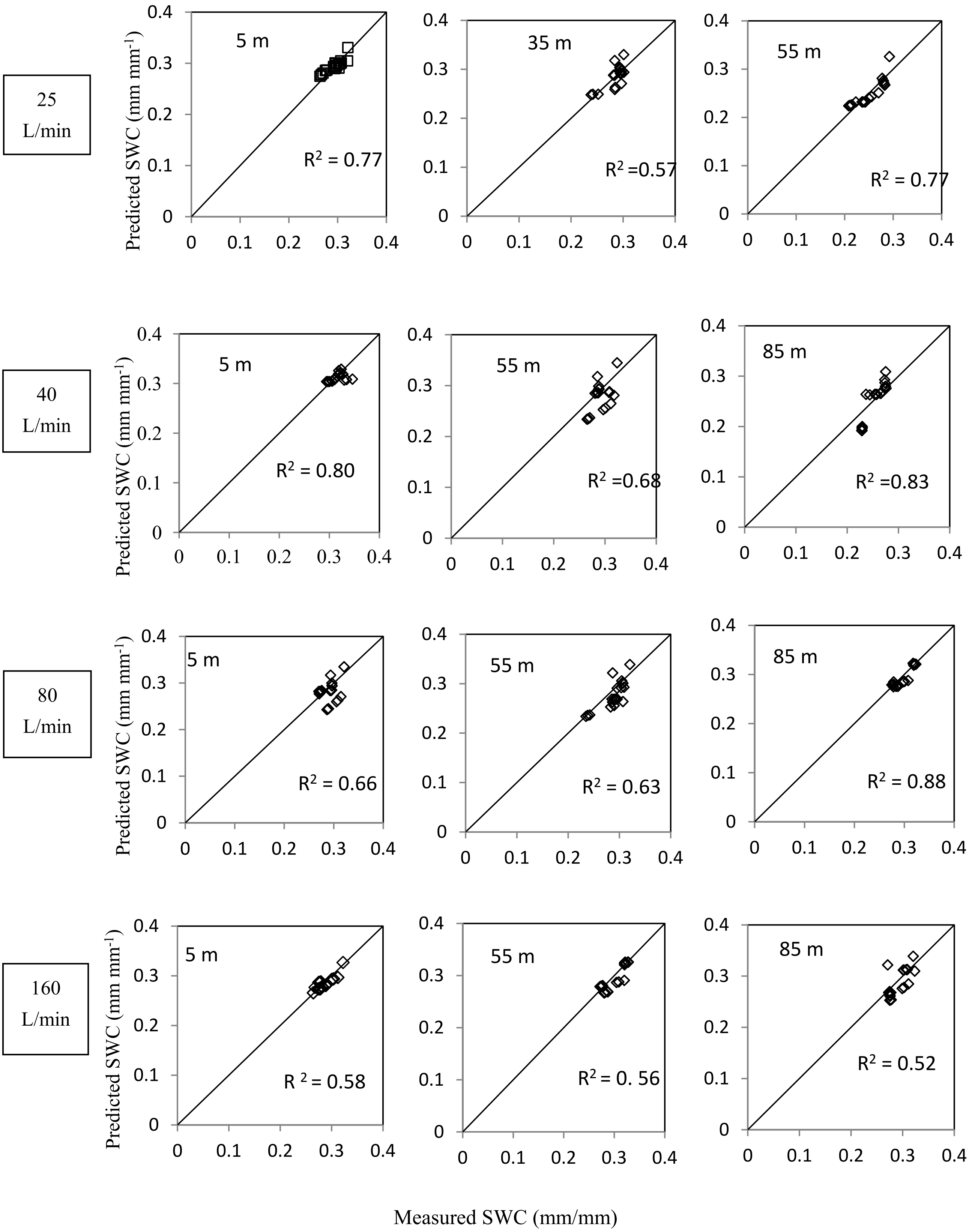

Fig. 4 Measured and predicted soil water content (SWC) of the soil profile during redistribution from the 20, 40, 80 and 160 L/min inflow rates at various furrow distances covered by the advance stream.

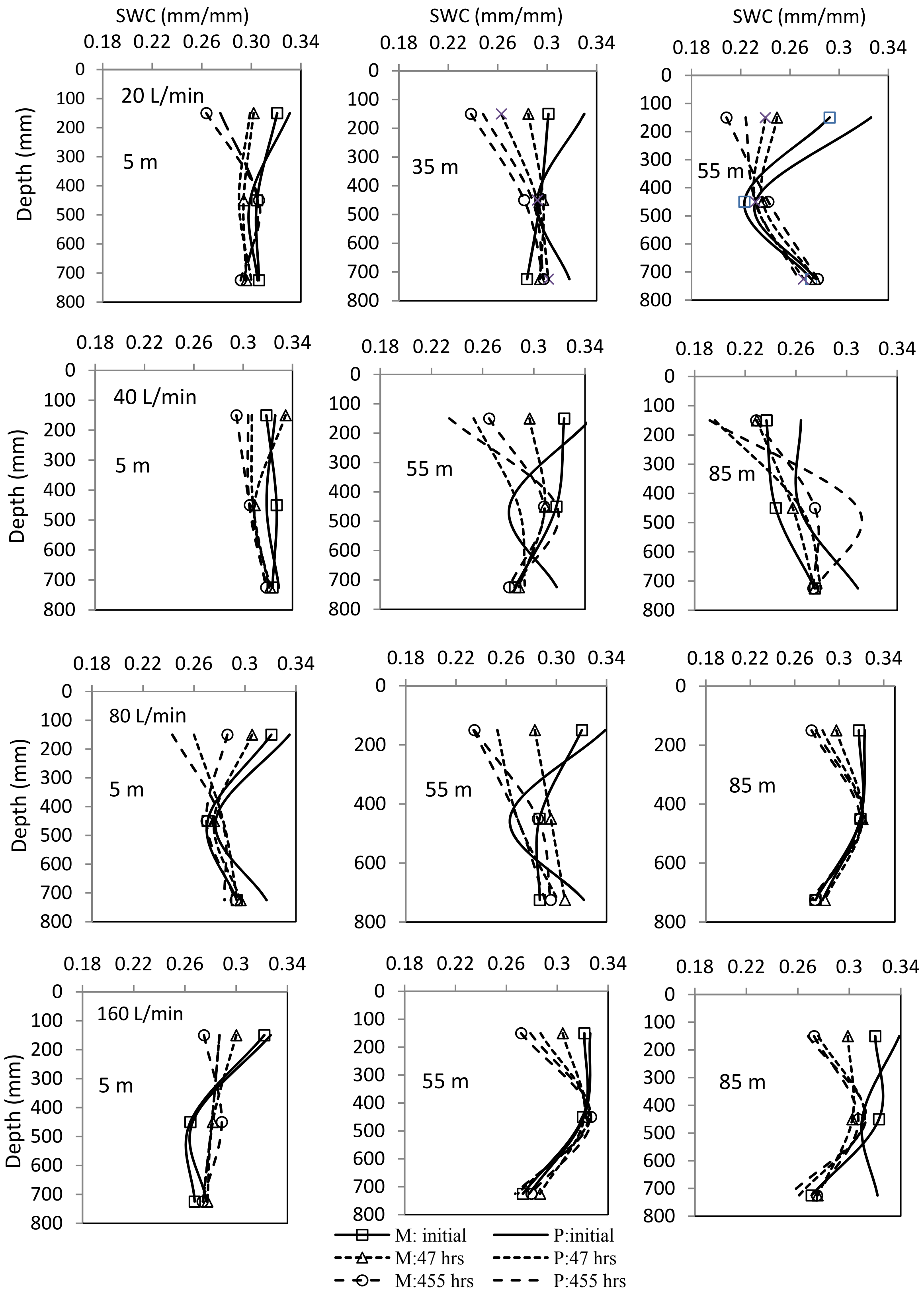

Fig. 5 Measured and predicted soil water content (SWC) for the initial and selected time intervals during redistribution at different furrow distances and soil profile depths from the 20, 40, 80 and 160 L/min inflow rates.

Table 4 Measure of dispersion between the measured and predicted soil water content (mm/mm) after 455 h of redistribution.

Inflow rate (L/min)	Distance (m)	Horizons								
		A			B			C		
		Measured SWC	Predicted SWC	Dispersion*	Measured SWC	Predicted SWC	Dispersion*	Measured SWC	Predicted SWC	Dispersion*
	5	-17	-16	0.98	-9	+2	3.90	-4	-3	0.75
20	35	-19	-24	1.31	-4	-1	0.31	+3	-5	1.55
	55	-25	-31	1.22	+6	0	0.00	+1	-4	2.60
	5	-7	-7	0.91	-7	-4	0.64	-1	-3	1.95
40	55	-18	-33	1.89	-3	+11	3.81	-1	-8	7.05
	85	-2.5	-22	8.80	+9	+14	1.48	-8	-8.3	25.15
	5	-10	-28	2.67	-0.24	+1.5	6.17	-0.23	-8.3	36.28
80	55	-26	-32	1.22	-0.4	+2	4.36	+2.2	+8	3.55
	85	-13	-13	1.03	-0.13	+0.6	4.72	+0.1	-3	24.41
	5	+14	+12	0.85	+7	+5	0.61	+2	+1	0.49
160	55	-15	-14	0.95	+2	-2	0.78	+2	+3	1.64
	85	-14	-21	1.49	-5	-1	0.19	+1	-17	16.67

SWC = soil water content (mm/h); *calculated.

Substantial variations in estimated K_{eff} were also observed in the 80 L/min inflow rate furrow. The estimated K_{eff} from measured and model predictions passed the homogeneity test at 0-600 mm and 0-850 mm profile flow domains at the 5 m furrow section and at the 0-850 mm profile flow domain of the 55 m section. Variable spatiality was also noticeable at the 160 L/min inflow rate furrow. However, the estimated K_{eff} from measured and models predictions passed the homogeneity test at depths of 0-850 mm from the 5 m and 55 m furrow sections.

3.4 The Rate of Soil Water Redistribution

In this paper the rate of redistribution is represented by the ratio of $\frac{dK_{eff}}{d\theta}$ in relation to infiltrated depth (mm) as illustrated in Fig. 10. For simplicity only the K-coefficient calculated from the measured soil water content were used, and the semi log linear regression functions for vertical redistribution (Vz) and the corresponding coefficient of determination (R^2) are summarised in Table 6.

4. Discussion

Soil water movement characterisation during redistribution is a difficult exercise because the interactions of gravity and matric suction gradients across a flow domain exhibit differing physical properties. Monitoring subsurface soil water content changes and the use of the HYDRUS-2D to predict changes in soil water content along short furrows, however, provided insight on the effect of horizon layering in Tukulu soil on redistribution.

Parameter optimisation under field scale conditions was critical in improving the model's prediction. No strict format was followed when selecting the hydraulic parameters for optimisation, except that no more than three parameters were selected per optimization [9, 32]. The θ_s and θ_r were among the most frequently optimised parameters irrespective of the depth or inflow rate furrow regime. Although the field and laboratory derived θ_s was fairly comparable [33], the θ_r exhibited remarkable inconsistencies that could partly be due to upper horizon soil mixing with the C-horizon clay-rich soil during deep ploughing or ripping operations. The general differences among parameters within the profile and along the furrows were to be expected given the considerable spatial variability in this soil. Interestingly, the simultaneous optimisation of α and n parameters either reduced the model's prediction or the inverse solution failed to converge.

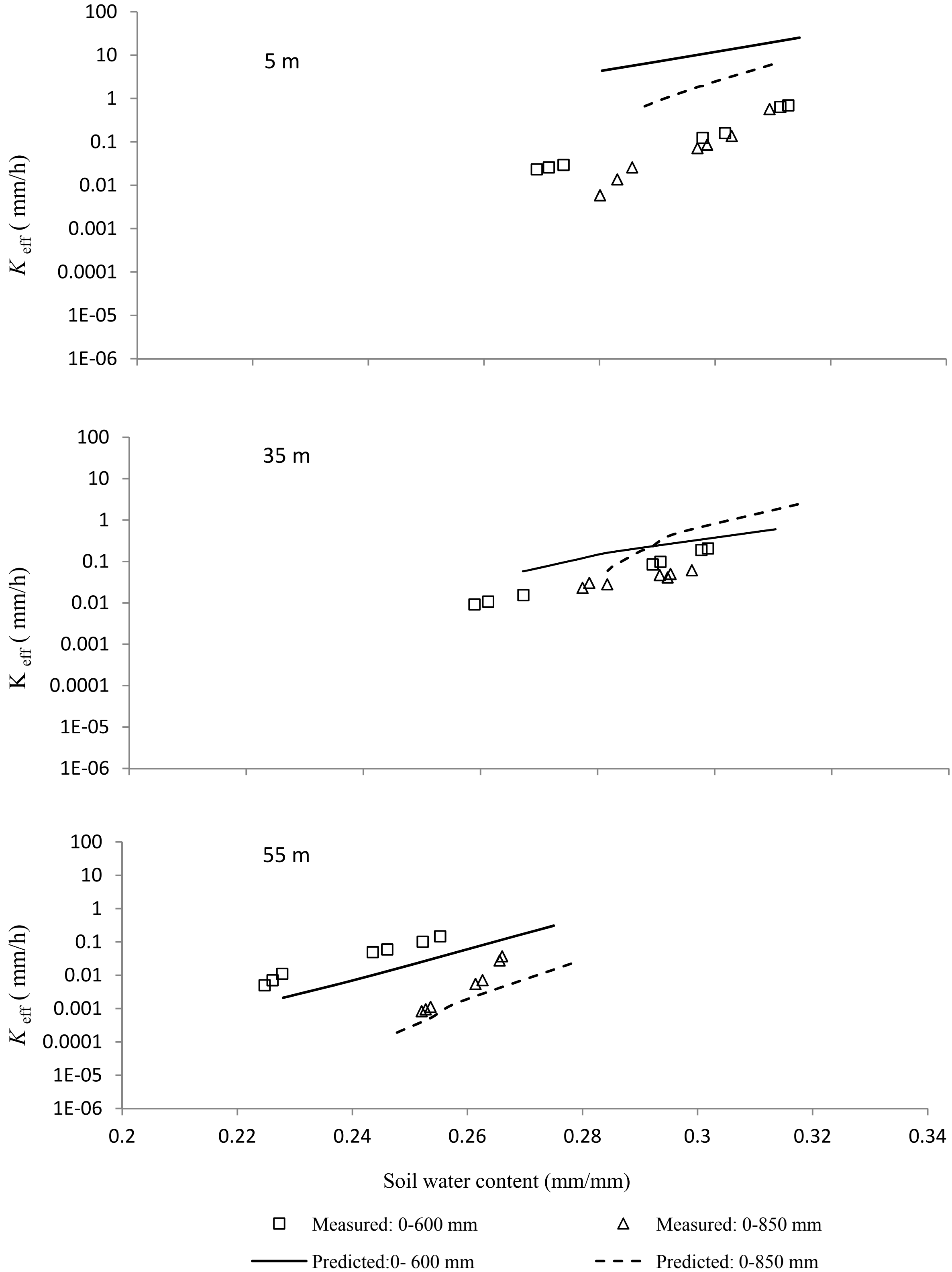

Fig. 6 Effective *K*-coefficient from the furrow treated with 20 L/min inflow rate for the 0-600 mm and 0-850 mm infiltrated depths at 5, 35 and 55 m distances.

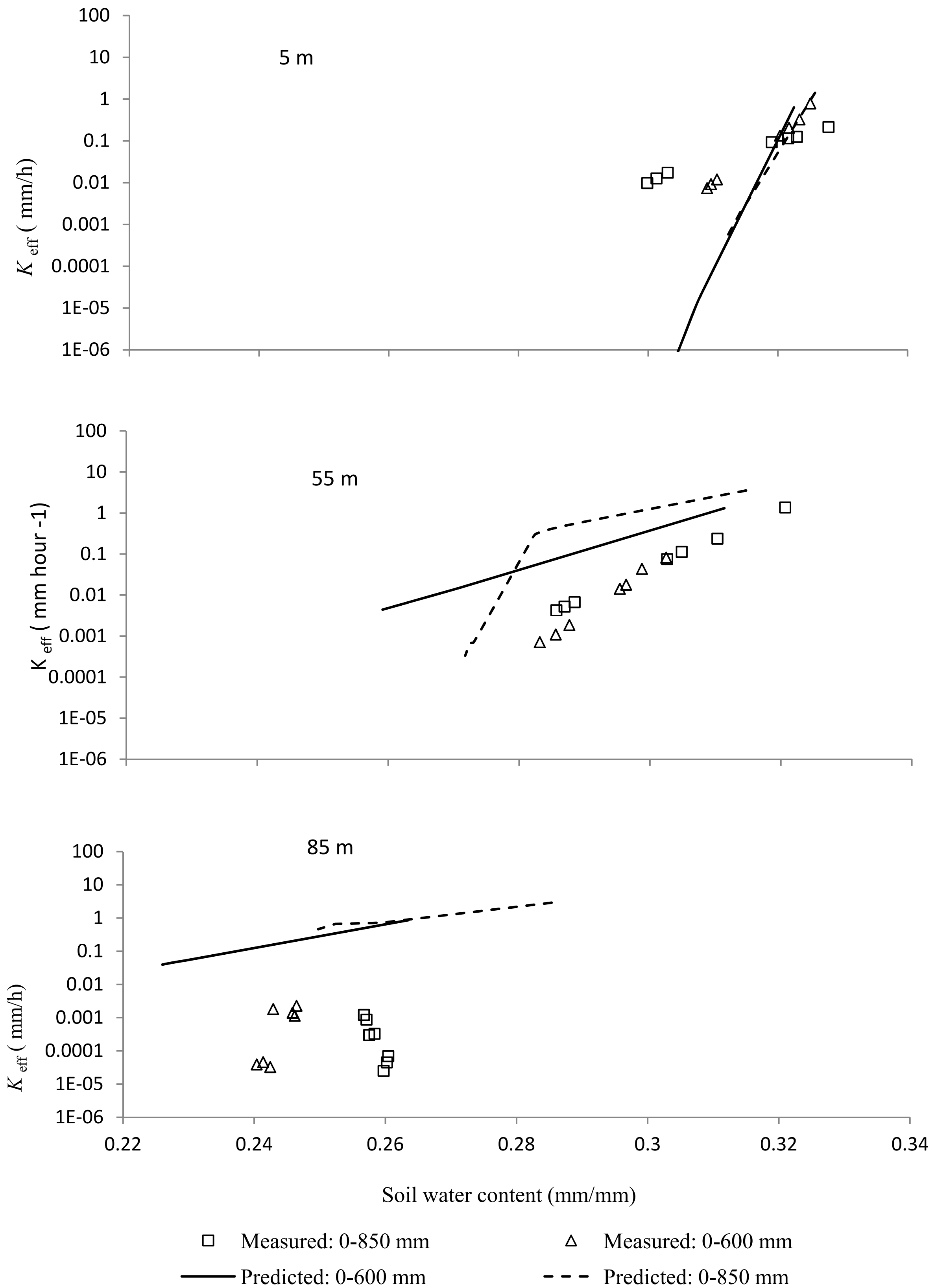

Fig. 7 Effective *K*-coefficient from the 40 L/min inflow rate at 0-600 and 0-850 mm infiltrated depths at 5, 55 and 85 m furrow distances.

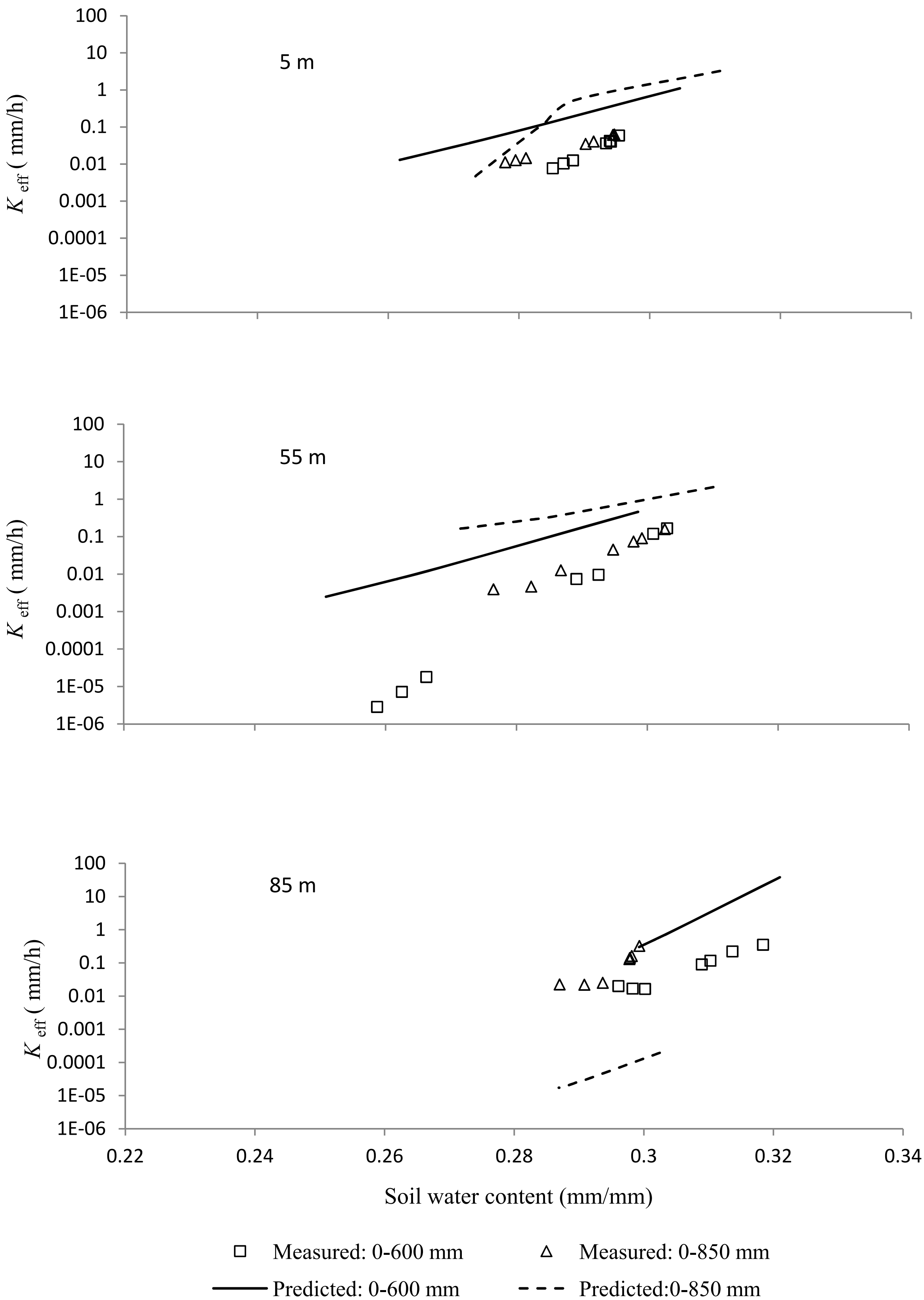

Fig. 8 Effective *K*-coefficient from the 80 L/min inflow rate at 0-600 and 0-850 mm infiltrated depths at 5, 55 and 85 m furrow distances.

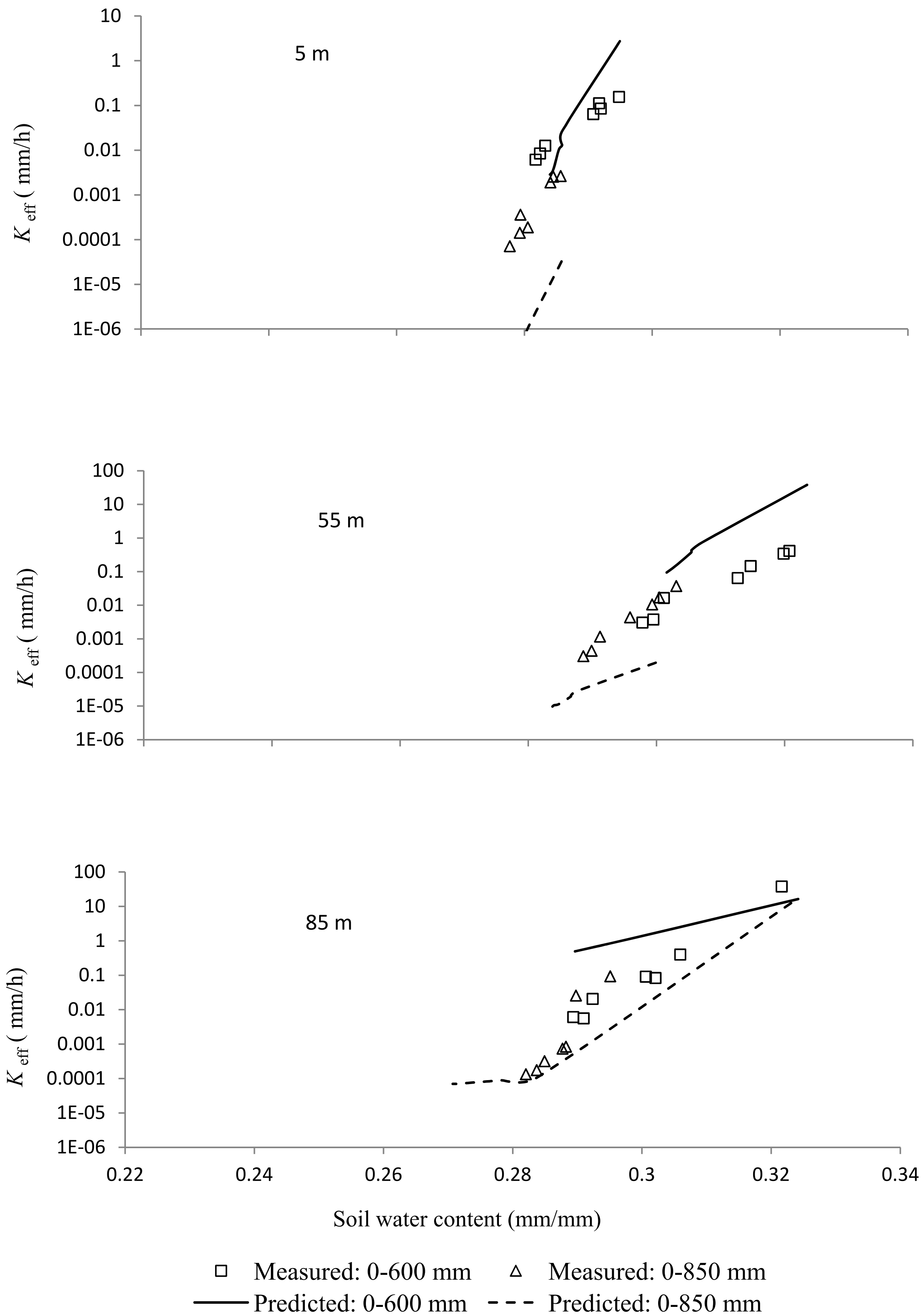

Fig. 9 Effective *K*-coefficient from the 160 L/min inflow rate at 0-600 and 0-850 mm infiltrated depths at 5, 55 and 85 m furrow distances.

Table 5 Homogeneity test for the effective *K*-coefficient calculated from measured and predicted soil water contents.

Inflow rate (L/min)	Distance (m)	K_{eff} range			Barttlet's test	
		Profile depth (M)	Measured SWC (mm/h)	Predicted SWC (mm/h)	Computed χ^2	Tabular χ^2 (0.05, 2)
20	5	0-600	0.7-0.023	25-4.4	28.16	3.84
		0-850	0.6-0.006	6-0.6	21.07	3.84
	35	0-600	0.2-0.009	0.6-0.06	9.53	3.84
		0-850	0.05-0.02	2.4-0.06	0.41	3.84
	55	0-600	0.15-0.005	0.31-0.002	9.96	3.84
		0-850	0.04-0.001	0.02-0.0002	0.02	3.84
40	5	0-600	0.13-0.01	0.63-0.00000083	2.10	3.84
		0-850	0.33-0.007	1.41-0.0004	34.00	3.84
	55	0-600	1.4-0.004	1.31-0.004	46.70	3.84
		0-850	1.4-0.004	3.5-0.0003	**3.44**	3.84
	85	0-600	0.002-0.00004	0.9-0.04	**0.02**	3.84
		0-850	0.001-0.00003	2.9-0.46	**2.37**	3.84
80	5	0-600	0.06-0.01	1.1-0.013	**0.59**	3.84
		0-850	0.04-0.008	3.25-0.004	**1.55**	3.84
	55	0-600	0.17-0.0000029	0.46-0.002	8.68	3.84
		0-850	0.05-0.004	2.1-0.15	**0.50**	3.84
	85	0-600	0.35-0.02	38-0.3	24.59	3.84
		0-850	0.3-0.0002	0.0002-0.0000173	5.83	3.84
160	5	0-600	0.11-0.01	2.73-0.003	10.31	3.84
		0-850	0.004-0.0001	0.00003-0.00000017	**0.0003**	3.84
	55	0-600	0.4-0.0003	38-0.09	29.28	3.84
		0-850	0.004-0.0003	0.0002-0.0000096	**0.00004**	3.84
	85	0-600	38-0.006	16.4-0.5	106.34	3.84
		0-850	0.09-0.0001	12.5-0.0000702	4.11	3.84

Bold = passed homogeneity test at 0.05 χ^2 test.

Agreement between the measured and predicted soil water content was fairly satisfactory with R^2 varying from 0.52 to 0.88. In most cases the model predictions overestimated soil water content, especially in the upper horizons. This was to be expected because the model predictions did not consider entrapped or dissolved air, which lowered field measured soil water content [10]. There was a pronounced dispersion between observed and predicted soil water content near the soil surface. The varied dispersion could partly be due to imposed flow domain conditions that did not represent the actual redistribution environment. The model's redistribution diffusive flux could have also contributed to the dispersion at deeper profile layers [26]. Dispersion between measured and predicted SWC from the small and large inflow rates generally increased and decreased with furrow length, respectively.

Despite some noticeable discrepancies between the measured and predicted SWC, the changes in SWC on the XY line reflected the redistribution process. The upper layers demonstrated remarkable soil water release to the lower horizons even though substantial amounts of soil water content were retained, far above the θ_r as a result of hysteresis. However, the recorded gains from the lower layers were less than the losses from the upper layers suggesting that soil water content measurements from the single neutron access tube could not capture the complete redistribution pattern across the furrow section domain [34]. Lack of precision of the neutron water meter near the soil surface could also have contributed to the discrepancies in soil water content measurements. Nevertheless, the change in the volumetric soil water

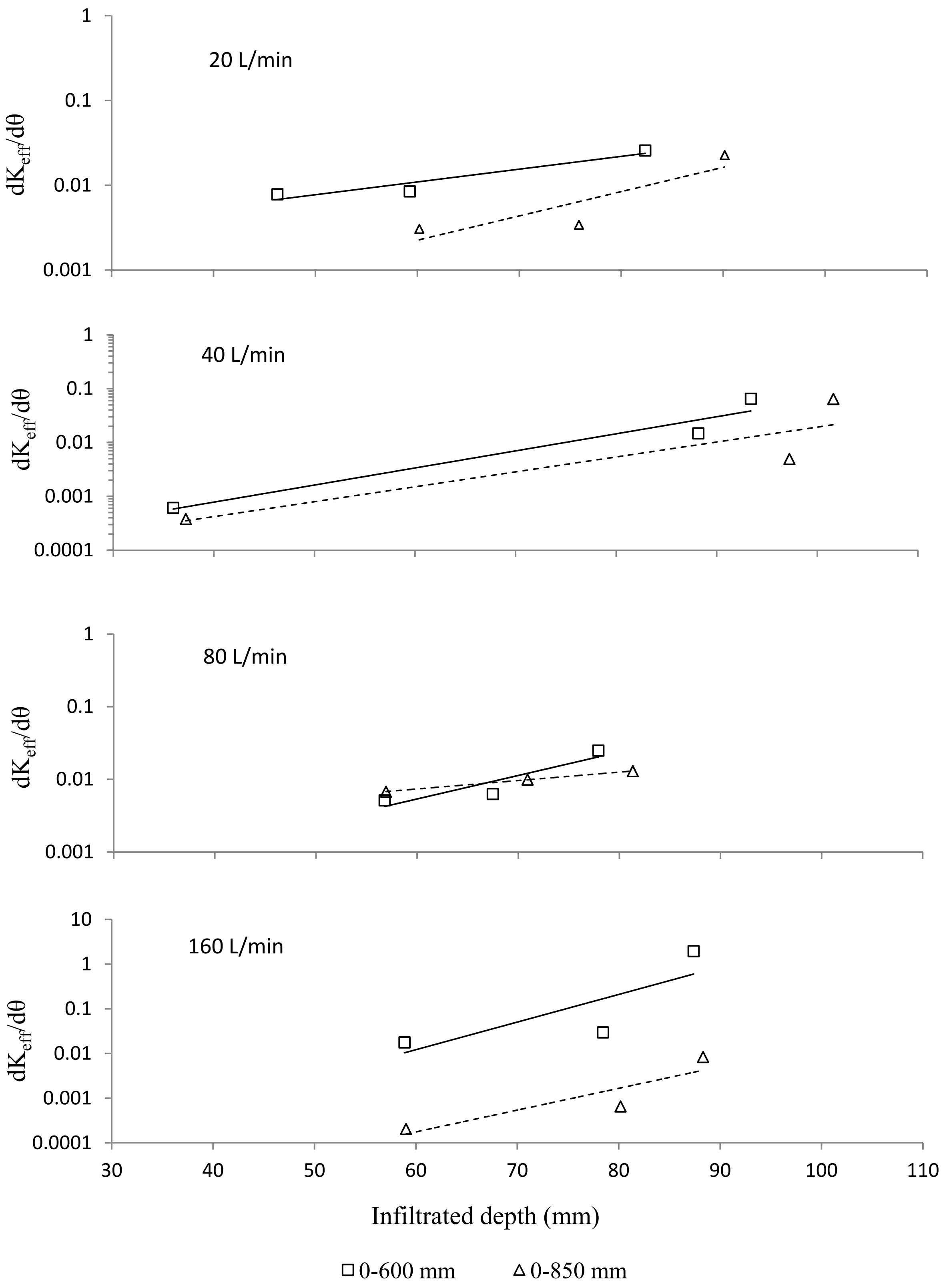

Fig. 10 Relationship between the rate of redistribution and infiltrated depth at 0-600 and 0-850 mm profile depth from the 20, 40, 80 and 160 L/min inflow rate furrows.

Table 6 Rate of vertical redistribution (*Vz*) expressed as a function of infiltrated depth (*θz*).

Inflow rate (L/mm)	Depth (mm)	Regression Log *Vz*	R^2
20	0-600	0.015 (θz)-2.866	0.91
	0-850	0.028 (θz)-4.368	0.77
40	0-600	0.031 (θz)-4.375	0.95
	0-850	0.027 (θz)-4.484	0.80
80	0-600	0.032 (θz)-4.208	0.84
	0-850	0.011 (θz)-2.827	0.99
160	0-600	0.061 (θz)-5.626	0.65
	0-850	0.048(θz)-6.682	0.80

content with time and space within the flow domain was able to show the variations in soil water storage in a meaningful and similar manner to that of the zeroth moment described by Yeh et al. [16] and Lazarovitch et al. [18]. Changes in soil water storage were the greatest in orthic A-horizon and least in the underlying C-horizon, irrespective of the inflow rate. Strong matric suction from less infiltrated lower horizons could be attributed to this phenomenon given that evaporation at the soil surface was controlled. Remarkable changes in C-horizons soil water content were associated with the deeply wetted profiles zones especially at the furrow inlet of the 20 L/min and 40 L/min inflow rates and furrow end of the 80 L/min and 160 L/min furrows. Under these circumstances, it is reasonable to suggest that deep infiltration augmented gravity driven redistribution, a phenomenon that was also noted by Hillel [10].

The permeability of the infiltrated domain during soil water redistribution was illustrated by the variability of the K_{eff}. Agreements between the measured and predicted K_{eff} was generally unsatisfactory especially at the furrow inlets and ends where overestimates from the model was pronounced. Spatial variability within and along the furrow length could be the reason for these discrepancies [27]. Nevertheless calculated K_{eff} from measured and predicted values showed homogeneity further away and nearer the furrow inlet from the respective small and large inflow rates. Within the upper 0-600 mm soil profile depth, the K_{eff} was generally higher for both measured and predicted values indicating that this section of the profile was wetted to near saturation compared to the 0-850 mm domain. The high K_{eff} in the upper strata of the profile was consistent with the loose structure and the smooth transition between the A and B horizons. At 0-850 mm, the K_{eff} exhibited a steeper gradient irrespective of furrow length suggesting that the underlying prismacutanic C-horizon could have played a major role in augmenting strong matric suction against gravity driven redistribution. Similar sentiment was shared by various internal drainage studies on layered soils [1, 33]. Despite spatial variability within the soil profile a general linear relationship could be drawn between the K_{eff} and the respective average soil water content's. Such linearity was also demonstrated by the K_{eff} values between 0-600 mm and 0-850 mm profile domain at each furrow section. In the 0-600 mm profiles depth the K_{eff} fell in the range of 10 mm/h to 0.001 mm/h while in the 0-850 mm depth ranged between 1 mm/h to 0.0001 mm/h. This was not surprising since the hydraulic conductivity of the infiltrated depth decreased with increasing soil profile depth. Inferences to the linearity between K_{eff} and infiltrated depth were also made by other researchers including the works of Rubin [11] and Yeh et al. [16].

The linear relationship between K_{eff} and infiltrated depth was extended to determine the rate of redistribution (*Vz*) within a specified profile flow domain (0-600 or 0-850 mm depth). This analogy found its validity on the convective term representing the rate of change of the first spatial moments in the downward (z) direction as described by Yeh et al. [16]. In this soil an infiltrated depth of 100 mm would be expected to augment a redistribution rate of 0.1 mm/h to 0.01 mm/h. An infiltrated depth of 500 mm of soil water content would fall in a range 0.01 mm/h to 0.001 mm/h within the profile depth of 600 mm and 0.01 mm/h to 0.0001 mm/h for the 850 mm depth. The decline in *Vz* with depth is not surprising given that the underlying prismacutanic C-horizon was of low permeability and that vertical water movement was restricted [33, 35]. In this regard, the higher permeability of the upper horizons could be well posed to encourage deep infiltration and redistribution during and after furrow irrigation. On the other hand, the low vertical redistribution of the underlying C-horizon gives the Tukulu and other soil types with a similar restrictive layer a high retention and soil water storage capacity, necessary to prevent deep drainage losses from furrow irrigation systems.

5. Conclusions

Vertical redistribution along 90 m distant irrigated furrows with different inflow rates (20, 40, 80 and 160 L/min) was characterised on the Tukulu soil, which is similar to the Cutanic Luvisols of the World Reference Base Group. During the 455 h redistribution period remarkable changes in soil water content were observed within the 0-600 mm soil profile depth compared to depth up to 850 mm. Effective hydraulic conductivity (K_{eff}) for the 0-850 mm soil profile depth was less than one order of magnitude compared to the 0-600 mm depth at all furrow distant sections. For soils with an underlying restrictive layer, it means that vertical redistribution below irrigated furrows is limited within the upper layers constituting the root zone of most stable crops. Rate of redistribution expressed by the relationship between the ratio $\frac{dK_{eff}}{d\theta}$ and infiltrated depth also showed steeper gradients for the infiltrated depth of 0-850 mm than the 0-600 mm, irrespective of inflow rate. This proved that near the surface and underlying horizons for the Tukulu soil or similarly layered Cutanic Luvisols had respective high and low redistribution regardless of infiltrated depth. Furrow irrigation, therefore, can be developed with confidence that soil water storage up to the depth of 850 mm can be exploited to enhance water productivity.

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