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RESEARCH ARTICLE

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Impact of infiltration parameters and Manning roughness on the advance trajectory and irrigation performance for closed-end furrows

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Abstract

Evaluation of furrow irrigation systems requires accurate estimation of soil infiltration parameters and Manning roughness, and the impact of variations of those parameters should be considered. The objectives of this paper were to verify the reliability of the infiltration parameters and Manning roughness estimated with SIPAR_ID software, and to analyze the impacts of different combinations between soil infiltration parameters and Manning roughness on the water trajectory and irrigation performance for closed-end furrows. The study consisted of field experiments and numerical simulation. Field experiments using Fuji apple trees were conducted in three villages of the Yangling district in October 2007. Infiltration parameters and Manning roughness were estimated with SIPAR_ID software. The estimated values were input into the WinSRFR software, and the advance trajectory and flow depths in the upstream were simulated on each furrow. The results show that the simulated values with WinSRFR software were in good agreement with measured data. Thus, the infiltration parameters and Manning roughness estimated with SIPAR_ID software were reliable. It was found that the water advance trajectory and the irrigation performance were not sensitive to variations of Manning roughness, but they were very sensitive to the variation of soil infiltration parameters laterally across the field between the furrows. Therefore, the average of Manning roughness on the whole field can be used as a representative value to simulate the advance trajectory and irrigation performance for every furrow. However, during the simulations, the variations of the soil infiltration parameters for different furrows across the field must be taken into account. Otherwise, significant errors can be produced in the simulated water advance trajectory and irrigation performance.

Additional key words: SIPAR_ID software; numerical simulation; furrow irrigation.

Introduction

Furrow irrigation, a method of crop irrigation, is widely used because of its low cost and energy demand. However, furrow irrigation systems are often inefficient due to over-irrigation and poor application uniformity (Upadhyaya & Raghuwanshi, 1999; Schwankl & Frate, 2004). Advanced simulation models of surface irrigation have been proved to be effective for the evaluation of system design and management, and to improve furrow irrigation performance. Soil infiltration parameters and Manning roughness coefficient are essential input parameters for surface irrigation simulation models (Raghuwanshi & Wallender, 1998; Wohling *et al.*, 2004; Mailapalli *et al.*, 2008). Therefore, it is very important to obtain the realistic infiltration parameters and Manning roughness at field scales. The application of these models depends on how the field data for describing infiltration parameters have been collected and how representative the values of Manning roughness are. Since model operation needs a lot of measured data and the data measurements are

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Abbreviations used: AAE (average absolute error); ARE (average relative error); DE (differential evolution); Du (distribution uniformity); Ea (application efficiency); Es (storage efficiency); KW (kinematic-wave); RE (relative error); ZI (zero-inertia).

time-consuming, adequate measurements are always lacking. An alternative method developed over the last 40 years is to characterize infiltration and possibly Manning roughness parameters from the observed behavior of the surface irrigation. Walker (2005) developed an optimization method using the advance time, runoff hydrograph, and recession time to calculate the infiltration parameters and Manning roughness based on the ZI (zero inertia) model. The advantages of this method are simplicity, stability, and ease of implementation, but the problem may exist in the longer execution time and the requirement for water recession data. Another estimation of the infiltration parameters using the optimization method may be carried out using the measured advance data (Elliott *et al.*, 1983; McClymont & Smith, 1996) or by using a combination of the advance and runoff hydrograph (Scaloppi *et al.*, 1995; Gillies & Smith, 2005). But most of the above studies often use some unreasonable assumptions that may lead to the violations of mass conservation. For example, if the cross-sectional area of flow at the field inlet is constant, the shape of flow profile downstream will be assumed constant. The assumption of a constant cross-sectional area is known to introduce substantial errors. Rodríguez & Martos (2010) developed a software tool called SIPAR_ID, to estimate field values of infiltration and roughness parameters using the measured advance and hydrograph of depth based on the volume balance principle. SIPAR_ID tries to avoid most typical violations of the mass conservation principle through a hybrid model, and it is capable of accurately simulating the advance trajectory and flow depth compared with the zero-inertia model. However, SIPAR_ID has been developed in Spain; whether or not the software is suitable for closed-end furrow irrigation in China, and the reliability of estimating the infiltration and roughness parameters must be verified.

Meanwhile, many researchers clearly demonstrated that soil infiltration parameters and Manning roughness vary considerably between the furrows within the same field (Schwankl *et al.*, 2000; Oyonarte & Mateos, 2003; Mateos & Oyonarte, 2005; Wang *et al.*, 2009; Zhu *et al.*, 2009; Gillies *et al.*, 2011), and indicated that the variations between furrows are significant factors for the advance trajectory and performance of surface irrigation. Previous researches have often used representative values of infiltration parameters and roughness to simulate the advance trajectory and performance for the whole field scale, thereby ignore the inter-furrow variability (Álvarez, 2003; Eldeiry *et al.*, 2005; Sánchez *et al.*, 2009; Reddy *et al.*, 2013). However, whether or not the simulated values correspond well to the real field performance must be analyzed, particularly the uniformity terms. Evaluation of furrow irrigation systems requires a high accuracy of infiltration parameters and Manning roughness. Considerable savings in the cost of field data collection can be achieved if efforts are concentrated on ensuring accuracy of those variables to which the dependent parameters are most sensitive, but not the variables with little or no impact which are even kept constant at certain typical values. Therefore, it is necessary to conduct a comprehensive analysis of the impact of dependent infiltration parameters and the Manning roughness on the advance trajectory and irrigation performance of closed-end furrows, which can help design and manage the furrow irrigation systems.

Although soil conditions may vary considerably along the length of a single furrow, surface irrigation simulations typically require furrow-averaged infiltration parameters. Therefore, this study was conducted under the conditions of the uniform soil infiltration parameters and Manning roughness along the same furrow, and those soil parameters and the Manning roughness may vary across different furrows. The objectives of this paper were: (1) to verify reliability of the infiltration parameters and Manning roughness estimated with the SIPAR_ID software; (2) to analyze the impact of different combinations between the infiltration parameters and Manning roughness on the water trajectory and irrigation performance of the closed-end furrows.

Material and methods

Furrow irrigation experiments

The furrow irrigation experiments for Fuji apple (Malus × domestica) trees were conducted in Guan, Wang Shang and Fa Xi villages in Yangling district in October 2007. These villages were selected depending on the soil textural. Table 1 presents the details of the furrow irrigation events. The furrow lengths used in the experiment varied from about 60 m to 80 m. The spaces of typical furrows were 1 m in the Fa Xi (sandy loam), and 0.9 m in the Guan, and Wang Shang villages (clay loam). The trapezoidal section was adopted for every furrow, the maximum depth was 150 mm,

Table 1. Specification of furrow irrigation experiments

Experiment spots	Discharge *q* (m^3 min^{-1})	Cut-off time *t* (min)	Furrow length *L* (m)	Width *W* (m)	Slope S_0	Soil texture	Down-stream condition
Guan village							
G1	0.123	21.50	60	0.9	0.006	Clay loam	Closed end
G2	0.117	35.80					
G3	0.096	45.50					
G4	0.168	11.65					
G5	0.264	8.50					
G6	0.150	22.52					
G7	0.168	23.50					
G8	0.180	11.00					
Wang Shang village							
W1	0.189	26.15	80	0.9	0.006	Clay loam	Closed end
W2	0.143	32.48					
W3	0.172	31.96					
W4	0.149	42.50					
W5	0.142	58.65					
W6	0.171	42.85					
W7	0.194	24.32					
Fa Xi village							
F1	0.136	29.50	60	1.0	0.004	Sandy loam	Closed end
F2	0.174	15.50					
F3	0.150	17.00					
F4	0.131	29.50					
F5	0.124	31.00					

bottom width was 200 mm and side slope was 1:1. The required application water depth was 80 mm. Inflow discharge measurements of every furrow were collected by the triangle weir. Measuring stations were set every 10 m along the furrow length, where advance times were recorded. Flow depths in the upstream were recorded every 2 or 5 minutes throughout the irrigation process. Soil moisture for one day prior to and two days after irrigation were collected down to 1 m in depth, at intervals of 0.2 m for the profile, where 5-8 measuring points were selected with soil auger along the furrow.

Infiltration parameters and Manning roughness identification

SIPAR_ID (Rodríguez & Martos, 2010), is a software for estimating the infiltration parameters of the Kostiakov equation and the roughness value of the Manning's equation in a surface irrigation event under both steady and variable inflow conditions. The basic features of SIPAR_ID are:

— Robust multi-objective inverse modeling for surface irrigation parameter identification.

— Hybrid model that combines a volume-balance approach with four artificial neural networks for simulating the surface irrigation advance phase.

— Fast and efficient evolutionary optimization algorithm known as Differential Evolution (DE). DE is a simple and efficient heuristic for global optimization over continuous spaces derived from the genetic algorithm. Despite DE usually converged faster, especially in the more difficult cases, but it is still in its infancy and can most probably be improved (Storn & Price, 1997; Mayer *et al.*, 2005).

— Advance distance and flow depth data can be used for defining the objective function based on the aggregation procedure (Madsen, 2003). The following equations are used as the objective functions:

$$\min \sum_{i=1}^{m} (x_{is} - x_{im}) \qquad [1]$$

$$\min \sum_{j=1}^{p} (h_{js} - h_{jm}) \qquad [2]$$

where x_{is} is the simulated advance distance (m); x_{im} is the measured advance distance (m); h_{js} is the simulated flow depth data (m); h_{jm} is the measured flow depth data (m); and m and p are the number of advance distances and flow depth of the single furrow, respectively.

The basic data of field length, bottom slope, cross-section parameters, inflow discharge, advance trajectory and flow depth in the upstream obtained in field experiments were input in SIPAR_ID software estimate the infiltration parameter and Manning roughness. Compared with the conventional optimization, the SIPAR_ID tries to avoid most typical violations of the mass conservation principle. For example, the volume balance methods use a uniform flow equation, like Manning equation to describe the cross-sectional area of flow at the field inlet and then an assumption regarding the shape of the flow profile downstream, generally assuming the cross-sectional area is constant. The assumption of a constant cross-sectional area is known to introduce substantial errors.

Advance trajectory and irrigation performance simulation

Advance trajectory and irrigation performance were simulated with the WinSRFR software. WinSRFR, proposed by USDA-Agricultural Research Service, is an integrated software package for analyzing surface irrigation systems. It consists of two models: the zero-inertia (ZI) model and the kinematic-wave (KW) model (Bautista *et al.,* 2009a). The above mentioned experiments were closed-end, so the ZI model was chosen to simulate the irrigation performance on each test furrow. The ZI model used in these procedures is

$$\frac{\partial A}{\partial t} + \frac{\partial q}{\partial x} + \frac{\partial Z}{\partial t} = 0 \quad [3]$$

$$\frac{\partial h}{\partial x} = S_0 - S_f \quad [4]$$

where A is the cross-sectional area of flow (m^2); q is the inflow rate ($m^3\ min^{-1}$); Z is the infiltrated volume per unit of length ($m^3\ m^{-1}$); x is distance from the field inlet (m); t is elapse time (min); h is the surface-flow depth (m); and S_0 and S_f are the bottom slope of the furrow and friction slope, respectively.

Indices of irrigation performance were analyzed by WinSRFR. The indices were application efficiency (Ea), distribution uniformity (Du) and storage efficiency (Es) (Bautista *et al.,* 2009b). The mathematical expressions for these indices were:

$$Ea = \frac{W_s}{W_f} \times 100\% \quad [5a]$$

$$Du = \frac{Z_{Lq}}{Z_{av}} \times 100\% \quad [5b]$$

$$Es = \frac{W_s}{W_n} \times 100\% = \frac{W_f - D_p - R_O}{W_n} \times 100\% \quad [5c]$$

where W_s is the infiltrated depth contributing to the irrigation target; W_f is the average depth of applied water; Z_{lq} is the low quarter average infiltrated depth; Z_{av} is the average depth of infiltration water; W_n is the required or target application water depth; D_p is the depth of deep percolation; and R_o is the depth of surface runoff. If closed-end, then $R_o = 0$.

In the simulation process, the infiltration parameters and Manning roughness input in the software were grouped in three combinations: Sim1, infiltration parameters of each furrow + Manning roughness of each furrow; Sim2, infiltration parameters of each furrow + average value of Manning roughness in the whole field; and Sim3, average value of infiltration parameters in the whole field + Manning roughness of each furrow.

The other input parameters are all the measured values adopted in the experiment spots.

Evaluation index of simulation results

The average absolute error (AAE) and the average relative error (ARE) are taken as the evaluation index of simulation in advance trajectory. A quantitative evaluation is conducted between simulated and measured values of advance trajectory under the three combinations, which is used to analyze the impact of variability of infiltration parameters and Manning roughness on advance trajectory. The AAE and ARE are shown as below:

$$AAE = \frac{\sum_{i=1}^{m} \left| t_{is} - t_{im} \right|}{m} \quad [6]$$

$$ARE = \frac{\sum_{i=1}^{m} \frac{\left| t_{is} - t_{im} \right|}{t_{im}} \times 100\%}{m} \quad [7]$$

where t_{is} (min) and t_{im} (min) are the simulated and measured time of the water flow reached the i-th measured point; and m is the number of water trajectory measurement of the single furrow. Similarly, in order to analyze the impacts of the combination between the variability of infiltration parameters and Manning roughness on advance trajectory, the relative error (*RE*) of the simulated and measured irrigation performance values of each furrow is taken as the evaluation index, that is

$$RE = \frac{\left|IP_{rs} - IP_{rm}\right|}{IP_{rm}} \times 100\% \qquad [8]$$

where IP_{rs} and IP_{rm} are the simulated and the measured indices of irrigation performance (*Ea*, *Du* or *Es*) for the *r*-th furrow, respectively.

Results

The reliability analysis of the infiltration parameters and the Manning roughness

Infiltration parameters and Manning roughness values were estimated with SIPAR_ID software. The results in Table 2 show the infiltration parameters and Manning roughness were significantly different between test furrows. The reasons were that the cross sectional area (or wetted perimeter) varied with inflow discharges, and the spatial variability of soil characteristics contribute to the differences of the infiltration parameters and Manning roughness for each furrow. For example, G4 and G7 had the same inflow discharge in the Guan village, but they were significantly different in the estimated values of the infiltration parameters and Manning roughness, so were the W2 and W5 in the Wang Shang village.

Here, the accuracy of the infiltration parameters and Manning roughness values estimated with SIPAR_ID software was given more concern. The estimated values (Table 2) were input into the WinSRFR software, and the advance trajectory and flow depths in the upstream were simulated for every furrow to ensure the reliability of the estimated parameters. Then, the simulated values were compared with the measured values. The results are presented in Fig. 1 and Table 2, which show that the simulated water advance trajec-

Table 2. The infiltration parameters and Manning roughness estimated by the SIPAR_ID in furrow irrigation

Experimental spots	Kostiakov equation		Manning's *n*	*ARE*[1] (%)	
	k (m² min^{-a})	a		Advance distance	Flow depth
G1	0.00448	0.698	0.121	3.19	3.78
G2	0.01143	0.492	0.115	4.02	4.93
G3	0.00643	0.657	0.100	2.70	13.64
G4	0.00377	0.742	0.082	2.25	3.27
G5	0.00373	0.598	0.088	6.35	9.66
G6	0.00712	0.643	0.088	7.83	11.53
G7	0.00679	0.725	0.087	3.04	10.87
G8	0.00386	0.704	0.084	3.14	6.88
Average value	0.00595	0.657	0.096	4.07	8.07
W1	0.00636	0.698	0.085	5.30	11.10
W2	0.00556	0.687	0.100	4.26	8.80
W3	0.00656	0.688	0.110	7.23	6.54
W4	0.00575	0.705	0.111	7.30	9.77
W5	0.01023	0.597	0.099	6.63	14.43
W6	0.00939	0.627	0.088	6.76	7.67
W7	0.00887	0.580	0.085	3.72	13.40
Average value	0.00753	0.655	0.097	5.89	10.24
F1	0.00908	0.598	0.089	4.94	10.57
F2	0.00860	0.520	0.104	3.25	8.13
F3	0.00626	0.647	0.096	3.01	7.86
F4	0.00987	0.545	0.108	3.85	10.83
F5	0.00613	0.692	0.114	6.32	3.47
Average value	0.00799	0.600	0.102	4.27	8.17

[1] *ARE* is average absolute value of relative error, *ARE* of advance distances = $|(x_{is} - x_{im})|/xim \times 100\%$, *ARE* of flow depth = $|(hjs - h_{jm})|/h_{jm} \times 100\%$.

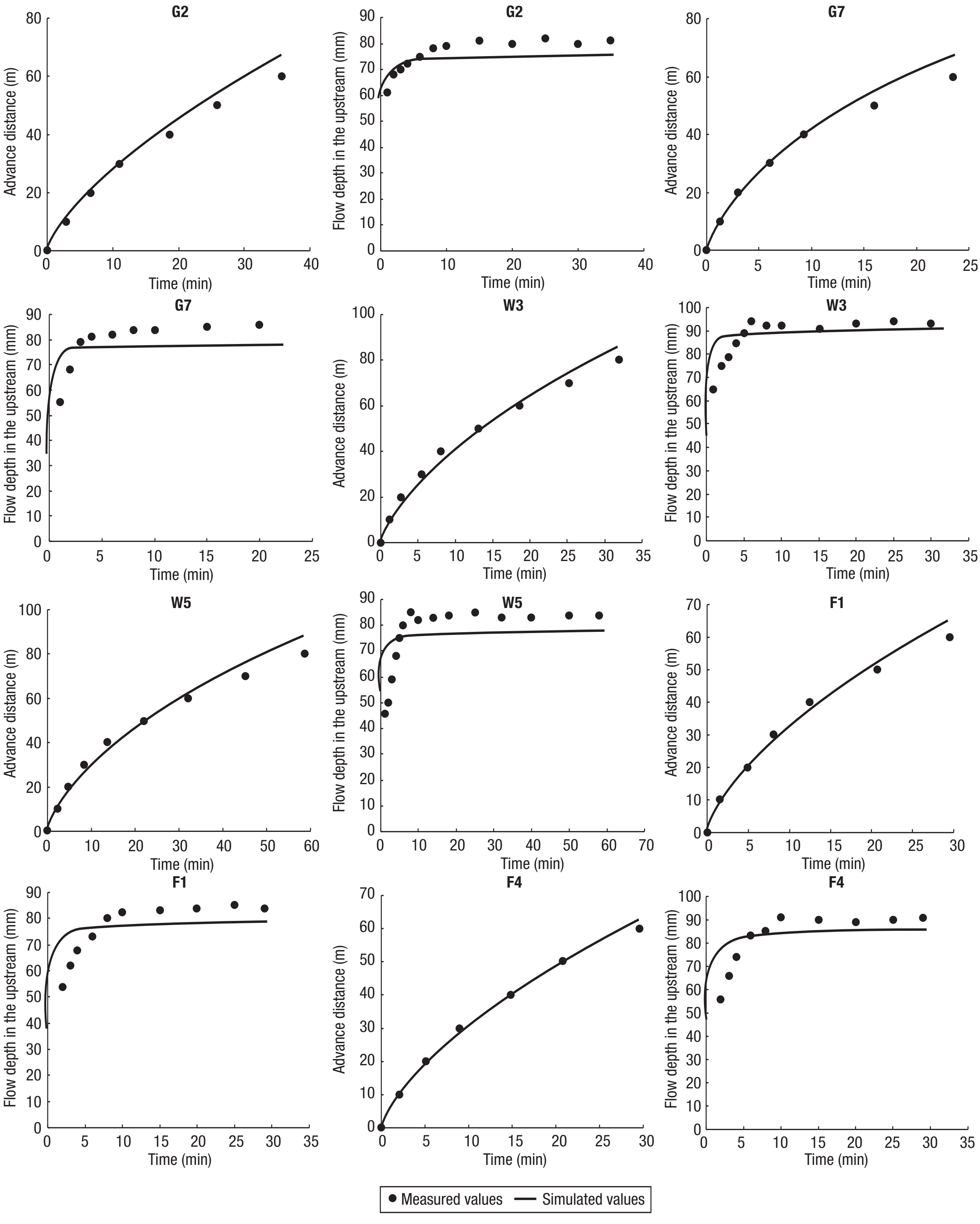

Figure 1. Comparison of simulated and measured advance trajectories and flow depth in the upstream by the WinSRFR software at the different experimental spots.

tory by using the WinSRFR software were in good agreement with measured data. The absolute error average values of advance distance between measured and simulated were 4.07%, 5.89%, and 4.27% in the Guan, Wang Shang, and Fa Xi villages, respectively. The simulated and measured flow depth in the upstream showed acceptable agreement, the average absolute error values of 8.07%, 10.24%, and 8.17% in the Guan, Wang Shang, and Fa Xi villages, respectively. This is probably because the flow depth in the upstream had not yet become steady enough at the beginning of the irrigation (Fig. 1), or in furrow irrigation, maximum flow velocity was realized closely to the inlet and gradually declines over the furrow length, and hence soil erosion generally increases throughout the first quarter of the field length and steadily declines over the second half of the field (Trout, 1996), which led to the uncertainty of flow depth data collected in the irrigation process. However, the error of flow depth bet-ween measured and simulated values were within the reasonable range based on the actual situations of furrow irrigation. Therefore, the validity of the infiltration parameters and Manning roughness estimated with SIPAR_ID software was reliable.

The impacts on advance trajectory

The advance trajectory under three different combinations (Sim1, Sim2, and Sim3) was simulated with the WinSRFR software. The simulated advance trajectory values were compared with the measured values, and the results are presented in the Fig. 2. Meanwhile, the measured and simulated values under Sim1, Sim2 and Sim3 were input into Eq. [6] and Eq. [7], respectively, to calculate the *AAE* and the *ARE*. The results are listed in Table 3.

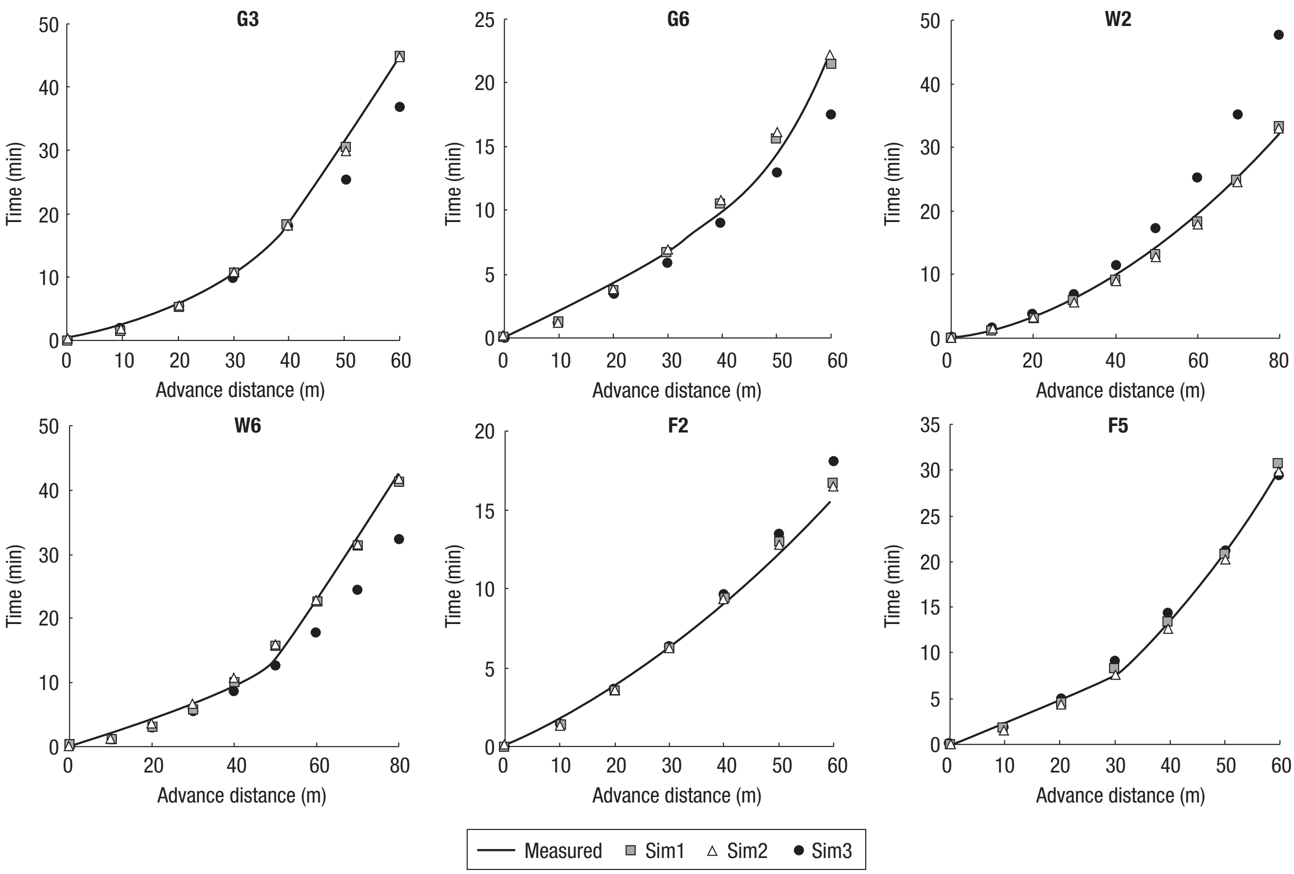

Figure 2. Comparison of measured and simulated advance trajectories under the different simulation conditions at the different experimental spots. Sim1: infiltration parameters of each furrow + Manning roughness of each furrow. Sim2: infiltration parameters of each furrow + average value of Manning roughness in the whole field. Sim3: average value of infiltration parameters in the whole field + Manning roughness of each furrow.

Table 3. Errors analysis of measured and simulated the advance trajectory under the different simulation conditions

Experimental spots	Cutoff time (t, min)				AAE[1] (min)			ARE[2] (%)		
	Measured	Sim1[3]	Sim2[4]	Sim3[5]	Sim1	Sim2	Sim3	Sim1	Sim2	Sim3
G1	21.50	22.05	19.87	26.12	0.32	0.92	1.89	5.71	10.28	16.92
G2	35.80	34.57	33.03	27.40	0.57	1.11	4.32	6.11	9.10	28.97
G3	45.50	44.90	44.52	36.73	0.49	0.52	3.00	4.89	5.14	12.97
G4	11.65	12.02	13.12	14.81	0.36	0.91	1.53	7.39	17.07	25.03
G5	8.50	8.59	9.04	10.14	0.23	0.41	0.79	8.33	10.54	16.36
G6	22.52	21.48	22.17	17.48	0.67	0.73	1.48	10.12	10.47	16.53
G7	23.50	23.50	24.28	15.22	0.22	0.51	2.50	4.76	7.24	17.26
G8	11.00	11.28	12.16	13.89	0.31	0.73	1.35	3.88	5.66	12.59
W1	26.15	24.92	26.03	26.57	0.35	0.61	0.84	4.85	7.08	9.31
W2	32.48	33.05	32.75	47.68	0.56	0.57	5.10	7.94	7.75	32.69
W3	31.96	32.55	31.37	34.12	0.49	0.74	0.84	5.44	6.37	8.44
W4	42.50	39.65	38.32	45.18	0.61	1.15	2.01	3.74	6.22	15.03
W5	58.65	56.88	56.70	48.45	0.75	0.81	4.56	5.75	5.97	21.02
W6	42.85	40.88	41.72	32.32	0.73	0.74	3.52	8.66	8.69	21.17
W7	24.32	23.67	24.73	25.43	0.31	0.52	0.55	4.94	8.30	5.93
F1	29.50	28.67	29.73	23.72	0.44	0.56	1.96	3.88	5.66	12.59
F2	15.50	16.52	16.65	18.02	1.02	1.15	2.52	6.58	7.42	16.26
F3	17.00	18.40	18.88	21.20	0.30	0.48	1.36	3.46	5.59	13.96
F4	29.50	28.73	28.25	26.60	0.38	0.42	1.30	4.61	4.79	11.67
F5	31.00	30.72	29.73	29.23	0.35	0.60	0.95	6.15	7.82	10.04
Average value					0.47	0.71	2.12	5.86	7.86	16.24

[1] AAE: average absolute error of measured and simulated values. [2] ARE: average relative error of measured and simulated values. [3] Sim1: infiltration parameters of each furrow + Manning roughness of each furrow. [4] Sim2: infiltration parameters of each furrow + average value of Manning roughness in the whole field. [5] Sim3: average value of infiltration parameters in the whole field + Manning roughness of each furrow.

The simulated advance trajectory values by the WinSRFR software were in good agreement with measured values (Fig. 2), and the average values of *AAE* and *ARE* between the measured and simulated values were 0.47 min and 5.86% under the Sim1 (Table 3), respectively. The results show that the variability of soil infiltration parameters and Manning roughness was ignored along the length of a single furrow, there were insignificant differences between the simulated and the measured of advance trajectory. The study shows that the adoption of the uniform soil infiltration parameters and Manning roughness in the same furrow does not lead to significant errors in the simulated water advance trajectory.

The simulated advance trajectory values were in good agreement with measured values (Fig. 2), and the average values of *AAE* and *ARE* between the measured and simulated values were 0.71 min and 7.86% under the Sim2 (Table 3). The reasons were not only because the variations of the soil infiltration parameters and Manning roughness were ignored along the length of a single furrow, but also the variation of Manning roughness was ignored laterally across the field between the furrows. Compared with the Sim1, the average values of *AAE* and *ARE* under the Sim2 increased by 0.24 min and 2.00% (Table 3), respectively. The results showed that the water advance trajectory was not sensitive to the variation of Manning roughness laterally across the field between the furrows, and the average of the Manning roughness in the whole field can be used as the representative values of every furrow to simulate the advance trajectory.

However, significant differences were found between the measured and simulated advance trajectory under the Sim3 (Fig. 2), and the average values of *AAE* and *ARE* between the measured and simulated values were 2.12 min and 16.24% under the Sim3 (Table 3). The significant differences between simulated and measured advance trajectory were mainly caused by ignoring the variation of soil infiltration parameters and

Manning roughness along the length of a single furrow and the variation of soil infiltration parameters laterally across the field between the furrows. Compared with the Sim1, the average values of *AAE* and *ARE* under the Sim3 increased by 1.65 min and 10.38% (Table 3), respectively. The results show that the water advance trajectory is very sensitive to variations of soil infiltration parameters laterally across the field between furrows, which must be considered when simulating the advance trajectory.

Impacts on the irrigation performance

The irrigation performance under three different combinations (Sim1, Sim2 and Sim3) was simulated with the WinSRFR software. Simulated values of irrigation performance were compared with the measured values, and the results were presented in Fig. 3. Meanwhile, the measured and simulated values under the Sim1, Sim2 and Sim3 were input into Eq. [8], to calculate the *RE*. The results are listed in Table 4.

The simulated irrigation performance values by the WinSRFR software were in good agreement with measured values (Fig. 3), and the average values of *RE*, between the measured and simulated values, were 7.74%, 8.58%, and 6.52% under the Sim1 (Table 4), for *Ea*, *Du* and *Es* respectively. The results showed that the variability of soil infiltration parameters and Manning roughness was ignored over the furrow length, which led to insignificant differences between the simulated and measured values of irrigation performance.

The simulated irrigation performance values were in good agreement with measured values (Fig. 3), and the average values of *RE* between the measured and simulated values were 7.98%, 9.16%, and 7.46% under the Sim2 (Table 4). There was only small difference between simulated and measured values of irrigation performance because of the ignoring of the variation of soil infiltration parameters and Manning roughness along the length of a single furrow and the variations of Manning roughness laterally across the field between furrows. Compared with the Sim1, the average values of *RE* of *Ea*, *Du* and *Es* under the Sim2 were increased by 0.24%, 0.58%, and 0.94% (Table 4), respectively. The results showed that the irrigation performance was not sensitive to the variation of Manning roughness laterally across the field between furrows, and the average of Manning roughness on the whole field can be used as representative value of every furrow to simulate the irrigation performance.

Significant differences were found between the measured and simulated irrigation performance under the Sim3 (Fig. 3), and the average values of *RE* between the measured and simulated values were 10.25%, 19.64%, and 15.90% under the Sim3 (Table 4). The significant differences were caused by ignoring the variations of soil infiltration parameters and Manning roughness along the length of a single furrow, and the variation of soil infiltration parameters laterally across the field between furrows. Compared with the Sim1, the average values of *RE* of *Ea*, *Du* and *Es* under the Sim3 increased by 2.51%, 11.06%, and 9.38% (Table 4), respectively. The results show that the irriga-

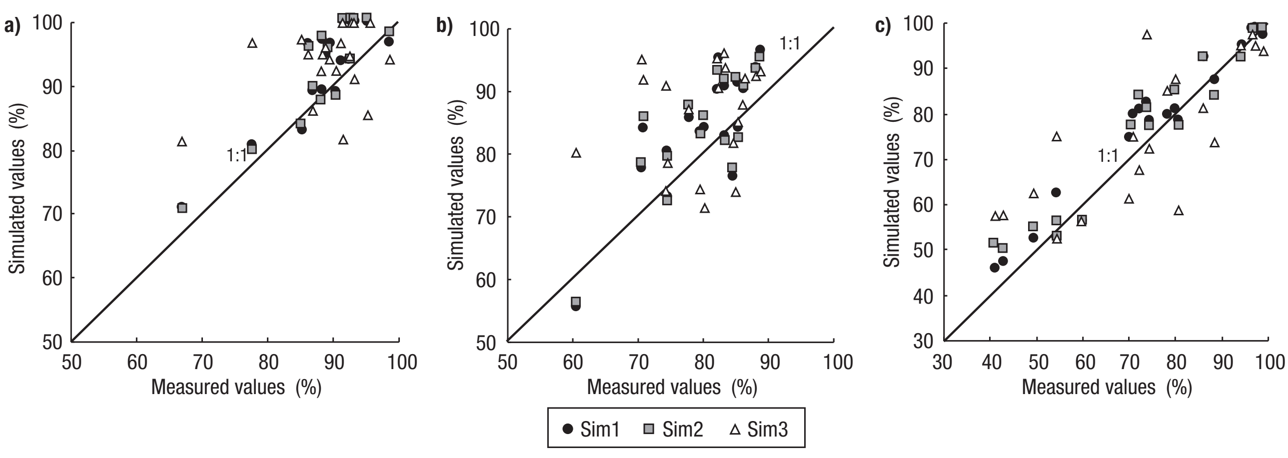

Figure 3. Comparison of measured and simulated values of the irrigation performance under the different simulation conditions: (a) application efficiency, *Ea;* (b) distribution uniformity, *Du;* and (c) storage efficiency, *Es*. Sim1: infiltration parameters of each furrow + Manning roughness of each furrow. Sim2: infiltration parameters of each furrow + average value of Manning roughness in the whole field. Sim3: average value of infiltration parameters in the whole field + Manning roughness of each furrow.

Table 4. Error analysis of measured and simulated the irrigation performance values under the different simulation conditions

Experimental spots	Measured irrigation performance (%)			*RE*[1] (%)								
				Sim1[5]			Sim2[6]			Sim3[7]		
	Ea[2]	*Du*[3]	*Es*[4]	*Ea*	*Du*	*Es*	*Ea*	*Du*	*Es*	*Ea*	*Du*	*Es*
G1	88.74	88.76	54.32	15.06	8.55	17.71	15.17	7.35	5.94	15.17	5.01	41.25
G2	91.25	82.31	88.47	9.48	15.82	5.96	9.48	13.57	1.72	9.48	9.88	16.64
G3	85.21	74.54	86.16	2.65	6.67	1.41	3.09	9.16	1.41	10.85	14.77	10.92
G4	90.56	82.12	41.03	5.65	9.80	7.96	5.65	9.32	19.63	5.65	15.85	34.22
G5	95.31	60.59	49.51	4.92	19.34	6.04	4.92	20.88	11.09	4.82	72.05	26.24
G6	89.57	83.26	70.04	11.53	9.27	7.08	11.53	10.32	10.65	11.53	15.40	12.55
G7	88.28	70.54	80.68	9.88	10.26	11.55	11.46	11.44	14.65	13.16	34.80	27.18
G8	93.41	83.35	42.81	6.95	8.63	10.95	6.95	7.69	16.79	6.95	22.78	34.31
W1	93.21	77.82	79.98	7.18	10.55	1.59	7.18	12.53	6.28	7.18	27.55	15.40
W2	91.45	79.54	73.74	9.24	5.07	11.88	9.24	4.76	10.18	10.55	26.31	32.22
W3	98.64	85.47	94.14	0.24	1.58	0.92	1.87	3.56	1.74	4.40	8.46	8.92
W4	86.89	80.21	97.50	2.77	5.11	1.28	3.23	6.97	1.28	0.91	11.11	2.56
W5	66.89	74.26	96.72	5.99	0.51	2.10	6.14	0.83	2.10	21.39	15.30	10.81
W6	77.59	84.50	98.75	4.14	9.44	1.27	2.85	8.14	0.00	24.76	13.29	5.06
W7	95.64	86.06	78.34	4.45	5.14	2.12	4.45	5.59	6.91	4.45	22.05	15.5
F1	86.23	70.86	72.07	15.85	18.88	12.73	15.89	21.34	16.20	16.24	29.48	6.35
F2	91.61	86.49	59.83	9.05	5.05	5.98	9.05	6.71	5.98	9.05	8.44	5.98
F3	92.71	85.12	54.32	7.76	7.39	3.35	7.76	7.75	3.35	7.76	13.11	3.35
F4	92.56	88.21	74.52	9.23	6.41	5.68	10.83	8.80	4.00	7.93	4.85	2.71
F5	88.54	74.35	70.91	12.83	8.15	12.83	12.83	6.52	9.30	12.83	22.25	5.77
Average value				7.74	8.58	6.52	7.98	9.16	7.46	10.25	19.64	15.90

[1] RE: relative error of the simulated and measured irrigation performance. [2] *Ea:* application efficiency. [3] *Du:* distribution uniformity. [4] *Es:* storage efficiency. [5] Sim1: infiltration parameters of each furrow + Manning roughness of each furrow. [6] Sim2: infiltration parameters of each furrow + average value of Manning roughness in the whole field. [7] Sim3: average value of infiltration parameters in the whole field + Manning roughness of each furrow.

tion performance is very sensitive to the variation of soil infiltration parameters laterally across the field between furrows, and it must be consideration when simulating the irrigation performance. Meanwhile, the results also show that the most significant factor with the variation of soil infiltration parameters is *Du*, followed by *Es*, and the less important for determination was *Ea*.

Discussion

Although the recognized Kostiakov equation has provide a poor description of the infiltration characteristic and limits the accuracy of the simulations for many soils, this may be satisfactory for surface irrigation with short ponding times when the expression adequately estimates accuracy where the opportunity time does not exceed 3 to 4 hours (Walker *et al.,* 2006). This is confirmed by the good agreement between the simulated and measured advance trajectory values for each furrow (Fig. 1). Meanwhile, the Kostiakov equation is the only option when the SIPAR_ID software is adopted.

In the process of estimating the infiltration parameters and Manning roughness with the SIPAR_ID software, data of recession trajectories were not collected because soil infiltration characteristics has spatial variability, *i.e.* in some experimental spots water may totally infiltrate, but in some other may not, which makes the recession time non-continuous. Therefore, there is not a universal criterion to measure the recession time. Fortunately, data of flow depth in the upstream and advance trajectories are collected to estimate the infiltration parameters and Manning roughness with the SIPAR_ID software, which can compensate the disadvantage caused by the spatial variability of soil infiltration characteristics. The results were sufficiently satisfactory to fulfill to the objectives of this study. This is confirmed by the excellent agreement between the simulated and measured advance curves for each of the field evaluations (Fig. 1 and Table 2).

The Manning roughness presented in Table 2 had high values for G1, G2, W3, W4, F2, F4, and F5. The reasons were that the bottom was unsmoothed and many clods of the side slope of the furrows had been manually excavated, and the infiltration parameters and Manning roughness interacted with each other when the SIPAR_ID software was used to perform the inverse solution. Fortunately, the data of flow depth in the upstream were collected to help sort the competing influence. Therefore, the accuracy of estimation depends upon how accurate the data of flow depth in the upstream were collected (Clemmens, 2009).

The impact of the soil infiltration parameters and Manning roughness on water trajectory and irrigation performance was analyzed under the closed-end furrow conditions. The infiltration parameters and Manning roughness values were estimated with the SIPAR_ID software for closed-end furrows, and the reliability of estimated values were verified. The absolute error average values of measured advance distance and flow depth values in the upstream in the Guan, Wang Shang, and Fa Xi villages, respectively, were 4.07%, 5.89%, and 4.27%, and the simulated values were 8.07%, 10.24%, and 8.17%. The results show that the infiltration parameters and Manning roughness estimated with the SIPAR_ID software were reliable. The water advance trajectory and irrigation performance are not sensitive to the variations of the Manning roughness, but they are very sensitive to the variations of soil infiltration parameters laterally across the field between furrows. Therefore, the average of Manning roughness of the whole field can be used as representative value to simulate the advance trajectory and irrigation performance of every furrow, and during the procedure of simulation the variations of the soil infiltration parameters across the field between the furrows must be considered.

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