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Applied Closed-end Furrow Irrigation Optimized Design Based on Field and Simulated Advance Data

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ABSTRACT

Closed-end furrows are commonly used to irrigate crop in northern part of China. The irrigation performance of furrow in this area is often low. The objectives of this paper are to verify reliability of infiltration parameters and Manning roughness estimated with SIPAR_ID software and present an optimized method for design of closed-end furrow system. The study consisted of field experiments and numerical simulation. Field experiments were conducted in two villages of Yangling district in October 2007. Infiltration parameters and Manning roughness values were estimated with SIPAR_ID software. The estimated values were put into the WinSRFR software, and then the advance trajectory, flow depths in the upstream, and irrigation performance were simulated on each test furrow. The results showed that the simulated values with the WinSRFR software were in excellent agreement with the measured data. Therefore, the infiltration parameters and Manning roughness estimated with SIPAR_ID software were reliable. Later, an optimized model for design of closed-end furrow irrigation system was proposed, based on field data and using the project of Uniform design and the WinSRFR software. Its solution required the use of optimized methodology with genetic algorithm (GA), and the inflow discharge and cutoff time were the independent variables. The results showed that adequate and efficient irrigations can be obtained using closed-end furrows through a proper selection of inflow discharge and cutoff time.

Keywords: Infiltration parameter, Irrigation performance, Genetic algorithm, Manning roughness, WinSRFR

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INTRODUCTION

Furrow irrigation is widely used because of its low cost and energy requirement. The pressurized irrigation systems i.e. sprinkler and drip irrigation systems, are usually more efficient than the furrow irrigation Therefore, the furrow irrigation system should be designed in such a way to ensure an adequate and uniform water application over the fields and to minimize the potential water losses.

Many researchers in this field have engaged in optimizing the design of furrow irrigation systems to improve irrigation performance. However, furrow irrigation performance is affected by a range of factors including the inflow discharge, soil infiltration characteristic, field length, required application volume, cutoff time, surface roughness, and field slope (Pereira and Trout, 1999; Eldeiry *et al.,* 2005). Dimensional sensitivity analysis technique has been employed to reduce the number of independent irrigation variables within a manageable range and empirical functions have been developed for a predictive performance and design of furrow irrigation systems (Zerihun *et al.,* 1997a,b; Navabian *et al.,*

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2009), but this technique is rather complex and tedious. Eldeiry *et al.* (2005) demonstrated that the furrow length and application discharge were the main factors affecting application efficiency in design of furrow irrigation in clay soil. Gillies *et al.* (2008) conducted a furrow irrigation experiment in a cotton filed, which evaluated and optimized the irrigation performance, and the results showed that the use of IrriProb software (Gillies, 2008) could optimize the field management to the maximum irrigation performance. However, the results of these studies were only adapted to the free-drainage furrow irrigation. Sanchez *et al.* (2009) developed management tools and guidelines for efficient irrigation of vegetables using closed-end level furrows. Results of the study indicated that adequate and efficient irrigations could be achieved through a proper selection of unit inlet flow rate and cutoff time. Ma *et al.* (2010) proposed a multi-objective optimized model for design of closed-end border irrigation system, in which a fuzzy relationship was analyzed and a fuzzy solution was presented. However, storage efficiency was not considered in their analysis.

The objectives of this study were (1) to verify reliability of infiltration parameters and Manning roughness estimated with SIPAR_ID software; (2) to present an optimized model for design of closed-end furrow irrigation system based on field data from Yangling district with clay loam and sandy loam soils.

MATERIALS AND METHODS

Field Experiments

The furrow irrigation experiments for apple trees were conducted in Wang Shang village and Fa Xi village in Yangling district in October 2007. The two villages were selected depending on the soil texture. 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. Typical furrows spacing were 1 m in Fa Xi village (soil texture was sandy loam) and 0.9 m in Wang Shang village (soil texture was clay loam). A trapezoidal section was adopted for each test furrow with the maximum depth of 150 mm, bottom width of 200 mm and a 1:1side slope. The required application water depth was 80 mm. The data of the inflow discharge, cutoff time,

Table1. Specification of furrow irrigation experiments.

Village	site No.	Inflow discharge. q $/ls^{-1}$	Cutoff time. t $/min$	Furrow length L $/m$	Furrow space W $/m$	Bottom slope S_0	Soil texture	Downstream condition
Wang Shang village	W1	3.15	26.2	80	0.9	0.006	Clay loam	Closed-end
	W2	2.38	32.5					
	W3	2.87	32.0					
	W4	2.48	42.5					
	W5	2.37	58.7					
	W6	2.85	42.9					
	W7	3.23	24.3					
Fa Xi village	F1	2.27	29.5	60	1.0	0.004	Sandy loam	
	F2	2.90	15.5					
	F3	2.50	17.0					
	F4	2.18	29.5					
	F5	2.07	31.0					

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depth hydrograph, and advance trajectory of each test furrow were collected in the irrigation process.

SIPAR_ID Software

SIPAR_ID, proposed by Rodriguez and Martos in 2007, is a software for estimating the infiltration parameters of the Kostiakov formula and the roughness value of the Manning's equation in a surface irrigation event under both steady and variable inflow conditions (Rodriguez and Martos, 2010). The basic features of SIPAR_ID are: (1) robust multi-objective inverse modeling for surface irrigation parameter identification, (2) hybrid model that combines a volume-balance approach with four artificial neural networks for simulating the surface irrigation advance phase, (3) 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. Although DE usually converges faster, especially in the more difficult cases, it is still in its infancy and can most probably be improved (Storn and Price, 1997; Mayer *et al*., 2005), and (4) 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:

$$\min\sum_{i=1}^{m}(x_{isim}-x_{iobs}) \tag{1}$$

$$\min\sum_{j=1}^{p}(h_{jsim}-h_{jobs}) \tag{2}$$

Where, x_{isim} is the simulated advance distance with SIPAR_ID software, x_{iobs} is the observed advance distance, h_{jsim} is the simulated flow depth data with SIPAR_ID software, h_{jobs} is the observed flow depth data, m and p are the number of advance distances and flow depth, 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 provided as input in SIPAR_ID software, then, the parameters were used to 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, to describe the cross sectional area of flow at the field inlet and then an assumption regarding the shape of the flow profile downstream, downstream, generally assuming the cross sectional area is constant. The assumption of a constant cross-sectional area is known to introduce substantial errors.

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). Closed-end furrows were used for apple trees in the above mentioned experiments, and the ZI model was chosen to simulate the irrigation performance of each test furrow. The ZI model used in these procedures was as follows:

$$\frac{\partial A}{\partial t}+\frac{\partial q}{\partial x}+\frac{\partial Z}{\partial t}=0 \tag{3}$$

$$\frac{\partial h}{\partial x}=S_0-S_f \tag{4}$$

Where, in Eq 3, A is the cross-sectional area of flow, q is the inflow discharge, Z is the depth of infiltrated water in unit length of furrow, x and t are the distance down the furrow and time, respectively. In Eq 4, h is the surface-flow depth; S_0 and S_f are the bottom slope of the furrow and friction slope, respectively.

Indices of irrigation performance were analyzed by WinSRFR, and the indices

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were application efficiency (*Ea*), distribution uniformity {*Du*), and storage efficiency (*Es*) (Bautista *et al.,* 2009b). The mathematical expressions for these indices were given as below

$$Ea = \frac{W_s}{W_f} \times 100\% \tag{5a}$$

$$Du = \frac{Z_{Lq}}{Z_{av}} \times 100\% \tag{5b}$$

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

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 infiltrated 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.

Optimized Model

The furrow length and field slope are commonly considered design factors that are not easily modified and often specified by farmers (Walker and Skogerboe, 1987). Similarly, the surface roughness and soil infiltration characteristic are essentially fixed factors over which the irrigator has limited, if any, control. However, inflow discharge and cutoff time are generally considered management factors which can be varied between events by the irrigator and, hence, used to improve irrigation performance (Wallender and Rayej, 1987; Alazba, 1997; Langat *et al.,* 2007; Ampas and Baltas, 2009). Therefore, the optimized model was proposed, and inflow discharge and cutoff time, as the critical factors, were selected to optimize the furrow irrigation systems. The modeling included factors such as irrigation application efficiency, distribution uniformity, and storage efficiency for design of furrow irrigation systems, and it can be written as below:

$$\max Y(q,t) = aEa(q,t) + bDu(q,t) + cEs(q,t) \tag{6}$$

Where, *Y(q,t)* is the objective equation, and it varies from 0 to 100; *a, b,* and *c* are the weight factors, and $a+b+c=1$.

The Eq. (6) solution requires the use of optimized methodology with the following constraint conditions:

$$q_{\min} \le q \le q_{\max} \quad t_{\min} \le t \le t_{\max} \tag{7}$$

Where, q_{min} and q_{max} are the lower boundary and the upper boundary of inflow discharge, respectively; t_{min} and t_{max} are the lower boundary and the upper boundary of cutoff time, respectively.

Optimized Method

The optimized model (Eq.6) is a complex problem that is difficult to solve using traditional technique, and its solution requires the use of optimized methodology. There are many kinds of optimization algorithm, such as evolutionary algorithm and genetic algorithm. Genetic algorithm (GA) is search algorithm based on the mechanism of natural selection and natural genetics. It originated in the mid 1970s (Holland, 1975) and emerged as a powerful optimization approach. GA is gaining importance because of its robust random search capability and near global optimal values (Azamathulla *et al*., 2008; Montesinos *et al*., 2001), and successfully used for the identification of optimal solutions in many hydraulic problems (Shin and Park, 2000; Babayan *et al*., 2005; Elferchichi *et al*., 2009, Haq and Anwar, 2010). Therefore, the GA was used to solve the optimized model (Eq.6) with the constraint conditions of Eq.7. The Flow chart of genetic algorithm is presented in Figure 1.

RESULTS

Estimation of Infiltration Parameters and Manning Roughness

Infiltration parameters and Manning roughness values were estimated with SIPAR_ID software. The results are listed in Table 2, which shows that the infiltration parameters and Manning roughness were significantly different in each test furrow. The reasons were that the cross sectional area (or wetted perimeter) varied with different inflow discharges and the spatial variability of soil characteristics caused the differences in the infiltration parameters and Manning roughness for each furrow. Meanwhile, the Manning roughness presented in Table 2 had high values for those furrows. The reasons were that the bottom was unsmoothed and many clods in side slope of furrow were manually excavated, and, also, the interaction between the infiltration parameters and Manning roughness when the SIPAR_ID software was used to perform the inverse solution. Fortunately, the data of flow depth in the upstream were collected, which can be used to help sort between these competing influences. The accuracy of estimation was dependent upon how accurate the data of flow depth in the upstream was collected (Clemmens, 2009).

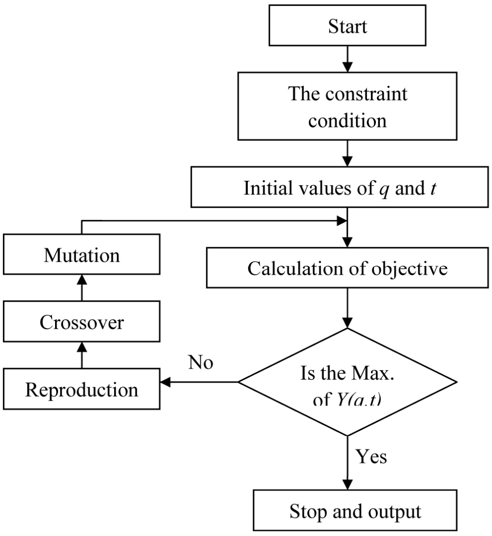

Figure 1. Flow chart of genetic algorithm.

Table 2. Infiltration parameters and Manning roughness as estimated with SIPAR_ID software.

Site No.	Kostiakov formula		Manning's	Average absolute error /%		No.	Kostiakov formula		Manning's	Average absolute error /%	
	k/m^2.min^{-a}	a	n	Advance distances	Flow depth		k/m^2.min^{-a}	a	n	Advance distances	Flow depth
W1	0.00636	0.698	0.085	5.30	11.10	F1	0.00908	0.598	0.089	4.94	10.57
W2	0.00556	0.687	0.100	4.26	8.80	F2	0.00860	0.520	0.104	3.25	8.13
W3	0.00656	0.688	0.110	7.23	6.54	F3	0.00626	0.647	0.096	3.01	7.86
W4	0.00575	0.705	0.111	7.30	9.77	F4	0.00987	0.545	0.108	3.85	10.83
W5	0.01023	0.597	0.099	6.63	14.43	F5	0.00613	0.692	0.114	6.32	3.47
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		0.00799	0.600	0.102	4.27	8.17

Note: Average absolute error of advance distances=$|(x_{isim}-x_{iobs})|/x_{iobs}\times100\%$; Average absolute error of flow depth $=|(h_{isim}-h_{iobs})|/h_{iobs}\times100\%$.

However, collecting accurate data of flow depth on each test furrow was never an easy job.

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 put into the WinSRFR software, and the advance trajectory and flow depths in the upstream were simulated on each test furrow to ensure the reliability of the estimated parameters. Then, the simulated values were compared with the measured values. The results are presented in Figure 2 and Table 2.

As shown in Figure 2 and Table 2, the simulated water advance trajectory by using the WinSRFR software were in excellent agreement with the measured data. The absolute error average values of advance distance between measured and simulated were 5.89% and 4.27% in Wang Shang village and Fa Xi village, respectively. The simulated and measured flow depth in the upstream showed acceptable agreement, with the absolute error average values of 10.24% and 8.17% in Wang Shang village and Fa Xi village, respectively. This was probably due to the flow depth in the upstream that had not yet become steady enough at the beginning of irrigation (Figure 2), or the variation in flow depth during irrigation. However, the error of flow depth between measured and simulated values were within a 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.

Evaluating Irrigation Performance

The parameters of Table 1 and Table 2 were provided as input in WinSRFR software to simulate the irrigation performance. The simulated indices of irrigation performance were compared with the measured values. The results are listed in Table 3.

It can be seen from Table 3 that the simulated irrigation performance with the WinSRFR software were in agreement with measured values, and the absolute error average values of *Ea*, *Du,* and *Es* of all the irrigation furrows were 6.87%, 7.67%, and 6.15%, respectively. However, it is obvious in the Table3 that, for the F1 and F5, there were some differences between the measured and simulated values of irrigation performance. This may be due to incorrect inputted field parameters, either infiltration or Manning roughness, but also, conceivably, incorrect cross-sectional area or bottom slope of furrow. Besides, while the spatial variability of soil infiltration characteristics and Manning

Table 3. Simulated indices of irrigation performance with WinSRFR software compared with the measured values.

Experiment Village	No.	Measured values of irrigation performance /%			Simulated values of irrigation performance /%			Error /%		
		Ea	*Du*	*Es*	*Ea*	*Du*	*Es*	*Ea*	*Du*	*Es*
Wangshang village	W1	93.21	77.82	79.98	99.80	88.05	86.25	7.07	13.15	7.84
	W2	91.45	79.54	73.74	99.80	83.88	80.00	9.13	5.46	8.49
	W3	98.64	85.47	94.14	96.90	81.29	92.50	-1.76	-4.89	-1.74
	W4	86.89	80.21	97.50	89.30	84.31	98.75	2.77	5.11	1.28
	W5	66.89	74.26	96.72	68.90	74.36	100.00	3.00	0.13	3.39
	W6	77.59	84.50	98.75	78.20	78.83	98.75	0.79	-6.71	0.00
	W7	95.64	86.06	78.34	99.90	90.69	82.50	4.45	5.38	5.31
Faxi village	F1	86.23	70.86	72.07	99.90	86.31	83.75	15.85	21.80	16.21
	F2	91.61	86.49	59.83	99.90	90.86	56.25	9.05	5.05	-5.98
	F3	92.71	85.12	54.32	99.90	91.41	52.50	7.76	7.39	-3.35
	F4	92.56	88.21	74.52	99.90	93.19	80.00	7.93	5.65	7.35
	F5	88.54	74.35	70.91	99.90	82.73	80.00	12.83	11.27	12.82
Average absolute error								6.87	7.67	6.15

Note: Error of irrigation performance = (simulated values - measured values)/ measured values ×100%.

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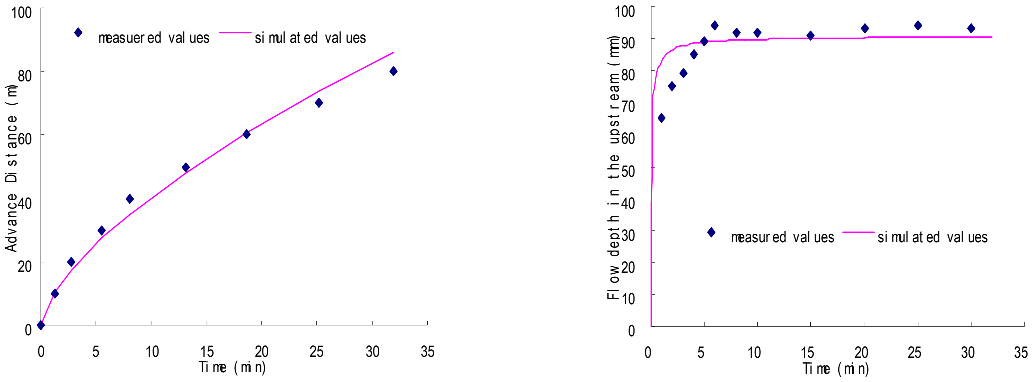
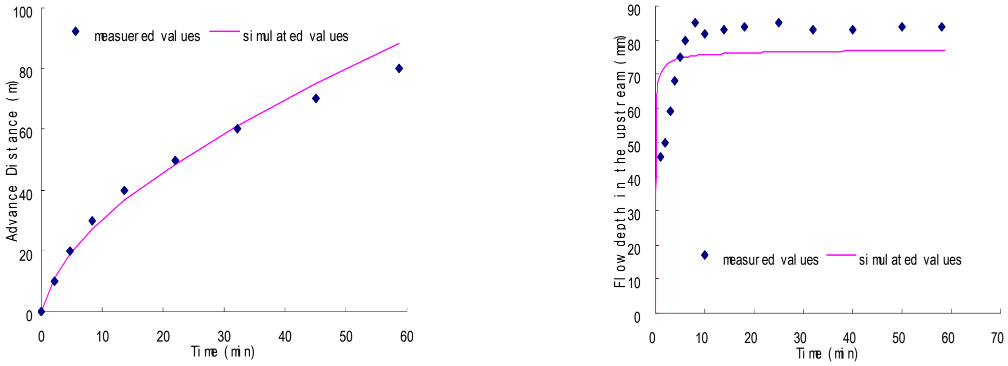
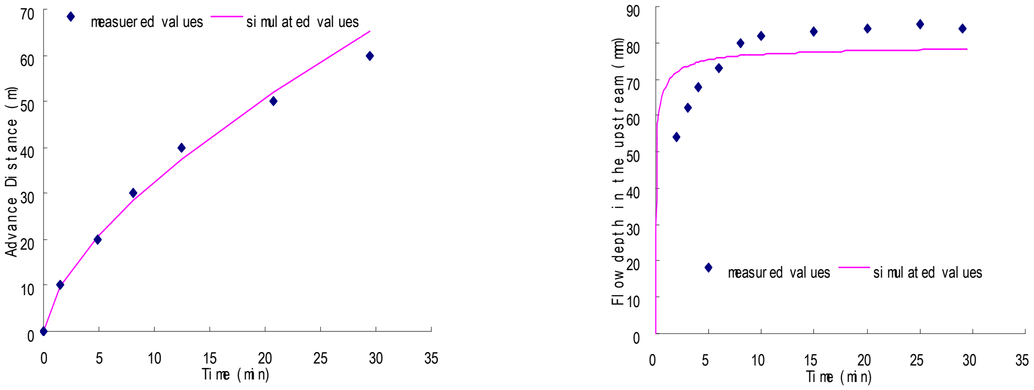


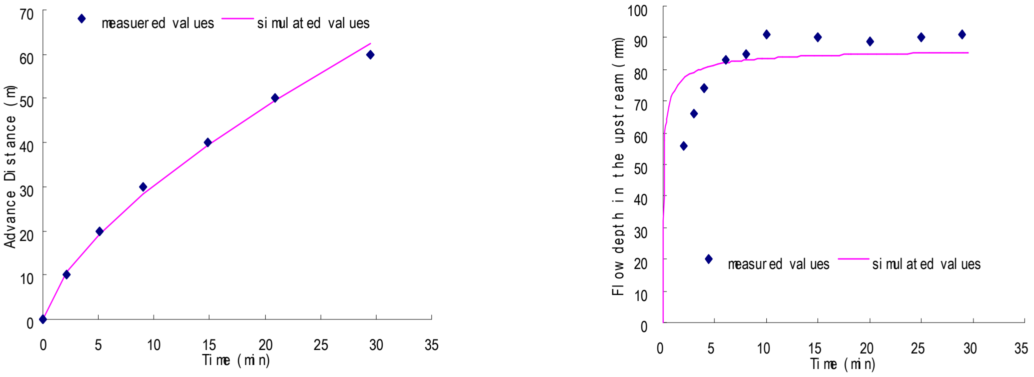
(a) W3 of Wang Shang village



(b) W5 of Wang Shang village



(c) F1 of Fa Xi village



(d) F4 of Fa Xi village

Figure 2. Simulated advance trajectory and flow depth in the upstream by the WinSRFR software compared with the measured values.

roughness are the most important factors affecting the performance of surface irrigation (Khatri and Smith, 2006), constant values of infiltration parameters and Manning roughness were provided as input in WinSRFR software when simulating irrigation performance of furrow irrigation. It is perhaps for these reasons that the WinSRFR software did not work well in F1 and F5. However, as a whole, the irrigation performance of furrow irrigation simulated with the WinSRFR software was reliable.

According to the measured values of irrigation performance in Table 3, the W5 site in Wang Shang village had low application efficiency. The reasons were that the inflow discharge was relatively small and the cutoff time was too long, which led to the volume of applied water being larger than the required application. Therefore, deep percolation loss was serious in W5. The F2 and F3 in Fa Xi village were had low storage efficiency. The reasons were that the inflow discharge was relatively large and the cutoff time was quite short, which led to the volume of applied water being less than the required application. Therefore, it is normal that the F2 and F3 had high values of application efficiency and distribution uniformity, but an insufficient irrigation. The results showed that, generally, adequate and efficient irrigations could not be obtained in closed-end furrows due to the improper selection of inflow discharge and cutoff time.

Regression Analysis

The present study, known as the project of Uniform Design (Fang and Ma, 2001), was conducted based on two variables i.e. inflow discharge and cutoff time, with 16 treatments consisting of random combinations of the two variables. According to the actual situations of Wang Shang village and Fa Xi village, the ranges of those factors were determined. Inflow discharge varied from 2.0 L.s^{-1} to 5.0 L.s^{-1} with increment of 0.2 L.s^{-1}, cutoff time varied from 15 min to 60 min with increment of 3 min. Details of Uniform Design project U16^2 are listed in Table 4.

Irrigation performance was simulated with WinSRFR software under different combinations of inflow discharge and cutoff time (Table 4). However, the infiltration parameters and Manning roughness values were provided as input in WinSRFR software, and these parameters must be the representative ones. For example, in Wang Shang village, the average values of the infiltration parameters and Manning roughness were k=0.00753m^2.min^{-a}, a=0.655, n=0.097, W=0.9m, L=80m and

Table 4. Details of Uniform Design project and irrigation performance as simulated with WinSRFR software.

Treatments	Factors		Irrigation performance /%			Treatments	Factors		Irrigation performance /%		
	Inflow discharge q / l.s^{-1}	Cutoff time t /min	*Ea*	*Du*	*Es*		Inflow discharge q / l.s^{-1}	Cutoff time t /min	*Ea*	*Du*	*Es*
1	2.0	42	85.8	15	75	9	3.6	27	96.5	82	88
2	2.2	21	100	0[a]	48	10	3.8	60	42.1	68	100
3	2.4	57	70.2	88	100	11	4.0	24	94.4	89	95
4	2.6	30	97.9	44	80	12	4.2	39	58.6	73	100
5	2.8	36	91.4	81	96	13	4.4	45	48.5	66	100
6	3.0	51	62.8	89	100	14	4.6	18	97.4	88	84
7	3.2	15	100	22	50	15	4.8	54	37.0	58	100
8	3.4	48	58.8	82	100	16	5.0	33	58.2	66	100

[a] The water advance did not reach downstream in furrow irrigation process. The distribution uniformity *Du* was calculated with Eq. (5b).

S_0=0.006, respectively, and the required application depth was 80mm. Irrigation performance was simulated with WinSRFR software in Wang Shang village and the results are listed in Table 4.

The *Ea*, *Du* and *Es* were regressively analyzed with SPSS software (Table 4). The inflow discharge and cutoff time were independent variables in the regression analysis process in Wang Shang village. (see Eq (8) in the below).

Coefficients of determination from the regression were 0.96, 0.91, and 0.94 for *Ea*, *Du*, and *Es*, functions, respectively. Figure 3 shows the correlation between the calculated values based on Eq. (8) and those simulated with the WinSRFR software. The high correlation showed that the Eq. (8) provided reasonable results. In this figure, the regression lines were very close to 1:1 line, which indicated the accuracy of Eq. (8) for calculating the indices of irrigation performance.

Optimizing the Inflow Discharge and Cutoff Time

The closed-end furrow irrigation system can be optimized when the maximum value of objective equation *Y (q,t)* is reached. Therefore, substituting Eq (8) into Eq (6). (see Eq (9) in the below).

The weight factors must be determined before Eq (9) is solved. The application efficiency, distribution uniformity, storage efficiency, runoff ratio and the deep percolation ratio were generally considered the critical indices of irrigation performance which can be used for design and management of free-drainage furrow irrigation system (EI-Hakim *et al.,* 1988; Zerihun *et al.,* 1997a, b; Gillies, 2008). With closed-end furrows, the runoff =0 and deep percolation ratio = 1- application efficiency. Therefore, the application efficiency, distribution uniformity, and storage efficiency were also the critical indices to the design and management of closed-end furrow irrigation system. Meanwhile, the measured values of irrigation performance (Table 3) were analyzed, and the results showed that the performance of furrow irrigation could be an all round evaluation, only when those indices were comprehensively considered. With the above proposals under comprehensive considerations, three indices of irrigation performance are supposed to be equally important. With this assumption, let $a=b=c=1/3$ in this paper, Eq (9) becomes:

$$\max Y(q,t) = -158.827 + 91.445q + 4.259t - 0.71767qt - 8.717q^2 - 0.02301t^2 \tag{10}$$

According to the actual situation of Wang Shang village and Fa Xi village, the ranges of inflow discharge and cutoff time were determined. Inflow discharge varied from 2.0 $L.s^{-1}$ to 5.0 $L.s^{-1}$ and cutoff time varied from 15 min to 60 min, therefore, Eq. (7) becomes:

$$2l/s \le q \le 5l/s \quad 15\min \le t \le 60\min \tag{11}$$

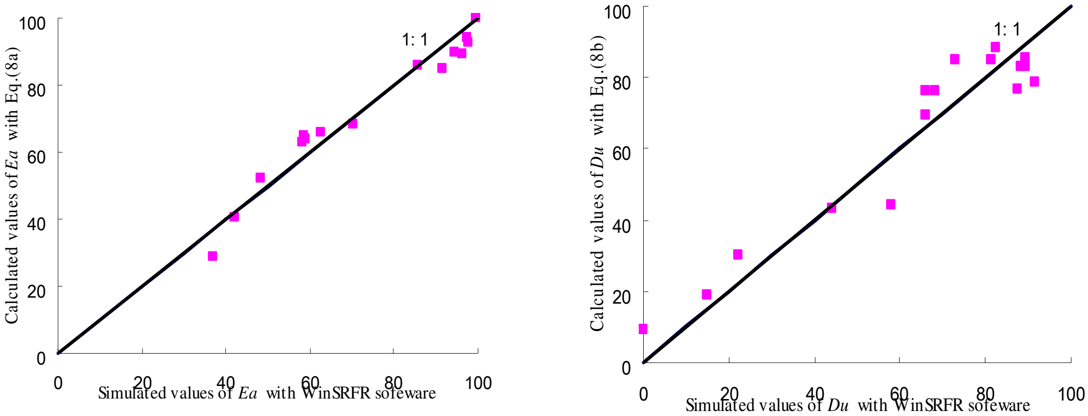
Eq.(10) is a single-objective function, and its solution requires the use of optimized methodology. Therefore, Eq. (10) was solved with GA, and Eq. (11) was in constraint condition. The flow chart of GA is presented in Figure 1 and the optimized

$$Ea = 100.458 + 13.079q - 0.117t - 0.341qt - 1.704q^2 - 0.0001211t^2 \tag{8a}$$

$$Du = -428.776 + 192.834q + 7.6t - 1.337qt - 18.484q^2 - 0.0311t^2 \tag{8b}$$

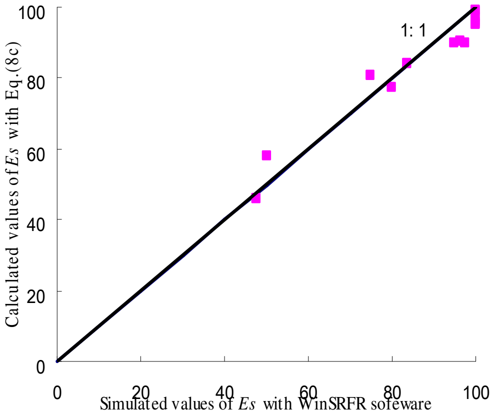
$$Es = -148.162 + 68.422q + 5.294t - 0.475qt - 5.963q^2 - 0.0378t^2 \tag{8c}$$

$$\begin{aligned}\max Y(q,t) = {} & a(100.458 + 13.079q - 0.117t - 0.341qt - 1.704q^2 - 0.0001211t^2) \\ & + b(-428.776 + 192.834q + 7.6t - 1.337qt - 18.484q^2 - 0.0311t^2) \\ & + c(-148.162 + 68.422q + 5.294t - 0.475qt - 5.963q^2 - 0.0378t^2)\end{aligned} \tag{9}$$



(a) Application efficiency *Ea*

(b) Distribution uniformity *Du*



(c) Storage efficiency *Es*

Figure 3. Comparison of simulated values of irrigation performance with WinSRFR software and values calculated with Eq. (8)

results can be written as below:

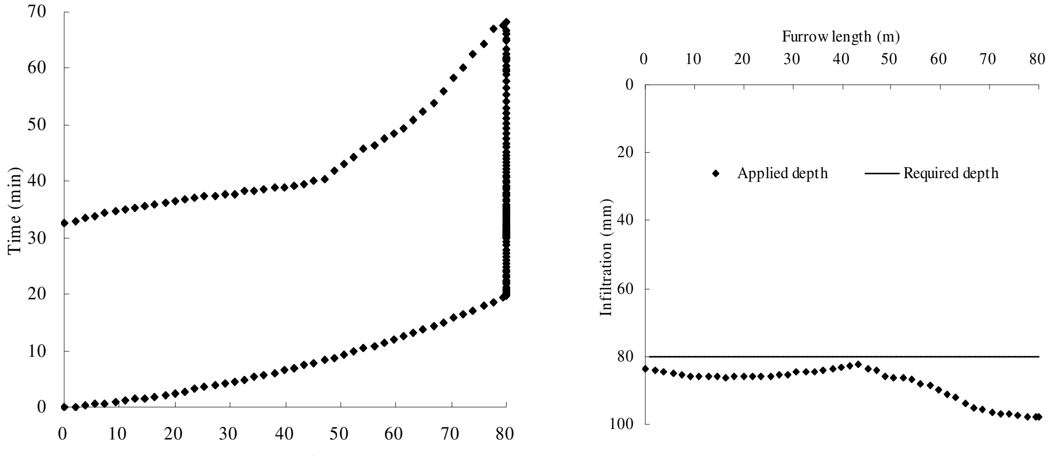
$$q = 4.0\,l/s \quad t = 30\,\min \qquad (12)$$

Substituting Eq (12) into Eq (8), then *Ea*=80.97, *Du*=86.38 and *Es*=97.92. Then, *q* and *t* were provided as input in WinSRFR software to simulate the water advance and recession trajectories and infiltration.

As shown in Figure 4, the water advance trajectory was almost parallel to the recession trajectory, and the infiltration depth was relatively uniform in furrow irrigation process. The results showed that the relatively small volume of deep percolation and the volume of water stored in the root zone both were equal to the required application water volume. The simulated results indicated that the irrigation performance had reached the maximum value for the optimized design of furrow irrigation system in Wang Shang village.

Similarly, the closed-end furrow irrigation design can be optimized with the proposed method of this paper in Wang Shang village and Fa Xi village (Table 5), if different application water depths were required. The inflow discharge and cutoff time were optimized with the proposed method to ensure rationality, and the optimized values were put into the WinSRFR software. The irrigation performance was simulated with WinSRFR software. The results were listed in Table 5.

The irrigation performance calculated with Eq (8) and Eq (10) based on the optimized values of inflow discharge and cutoff time was in agreement with the simulated values



(a) Water advance and recession trajectories

(b) Infiltration depth

Figure 4. The water advance, recession trajectories and infiltration were simulated with WinSRFR software in Wang Shang village.

Table 5. Optimized design of closed-end furrow irrigation systems in Wang Shang village and Fa Xi village

Testing Place	Required application water depth (mm)	Optimized values of independent variables		Irrigation performance with Eq.(8) and Eq.(10)				Irrigation performance with WinSRFR software		
		q/ l.s^{-1}	t/min	*Ea*	*Du*	*Es*	Max $Y(q,t)$	*Ea*	*Du*	*Es*
Wang Shang village	60	4.6	15.0	90.5	81.9	94.1	88.9	98.0	90.3	93.3
	80	4.0	30.0	81.0	86.4	97.9	88.4	80.0	83.9	98.5
	100	3.2	49.0	79.4	87.1	99.9	88.8	76.5	86.1	100
Fa Xi village	60	2.1	30.6	84.6	82.1	90.3	85.7	93.4	95.5	98.5
	80	2.0	41.8	87.4	82.5	95.7	88.5	95.3	94.2	98.9
	100	2.0	51.0	89.1	83.0	94.0	88.7	94.3	87.3	96.0

Note: The optimized values should not allow extrapolating for other combinations furrow length and bottom slope.

obtained by WinSRFR software, and the differences were only the consequences of multiple linear regression of the Eq (8). The results indicated that the inflow discharge and cutoff time optimized with the proposed method were reasonable.

DISCUSSION

The data of recession trajectories were not collected to estimate the infiltration parameters and Manning roughness with SIPAR_ID software. The reason is that soil infiltration has spatial variability, i.e. in some spots water may totally infiltrate, but in some it may not, which makes the recession time non-continuous. Therefore, there is not a common criterion to measure the recession time. Fortunately, the data of flow depth in the upstream and advance trajectories were collected, though collecting accurate data of flow depth in each test furrow was never an easy job, to estimate the infiltration parameters and Manning roughness with SIPAR_ID software, which can compensate the disadvantage. The results were sufficiently satisfactory to fulfill the objectives of this work. This is confirmed by the excellent agreement between the simulated and measured advance curves for each of the field evaluations (Figure 2 and Table 2).

The particular weighting factors used in the Eq (9) implied that the three indices of irrigation performance were of equal value (a=b=c=1/3) in this paper. However, in practice, individual irrigators may give the weighting factors different importance depending on their individual preferences. For example, Eldeiry *et al.* (2005) and Ampas *et al.* (2009) believe that application efficiency is the most important index of irrigation performance. Sanchez *et al.* (2009) and Ma *et al.* (2010) considered application efficiency and distribution uniformity as the most important indices. Valipour and Montazar (2012) analyzed the important degree of each index of irrigation performance with the hierarchical analysis, and the results showed that application efficiency played an important role in index of irrigation performance, followed by the distribution, uniformity, and the storage efficiency. Therefore, the optimized procedure with GA remains unchangeable, though the weighting factors may be given different values, except the optimized values of inflow discharge and cutoff time which are based on Eq. (9).

CONCLUSIONS

This study was conducted to develop an optimized method and guidelines for the efficient irrigation by using closed-end furrows. The results of this research can be summarized as follows:

(1) Infiltration parameters and Manning roughness values were estimated with the SIPAR_ID software for closed-end furrows, and reliability of the estimated values were verified. The absolute error average values of advance distances and flow depth in the upstream between measured and simulated values were 5.89% and 10.24%, in Wang Shang village, and 4.27% and 8.17% in Fa Xi village, respectively. The results showed that the infiltration parameters and Manning roughness estimated with SIPAR_ID software were reliable.

(2) The irrigation performance was evaluated for the existing closed-end furrow system based on measured values. The results showed that irrigation in the W5, F2, and F3 sites were inefficient due to improper selection of inflow discharge and cutoff time. Meanwhile, the irrigation performance was simulated by using WinSRFR software and the results were satisfactory compared with the measured values.

(3) An optimized method was described for design of closed-end furrow irrigation system, and its solution required the use of optimized methodology with genetic algorithm (GA). The results showed that, generally, adequate and efficient irrigations can be attained through a proper selection of inflow discharge and cutoff time.

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طراحی بهینه جویچه های آبیاری انتها بسته بر پایه داده های مزرعه ای و شبیه سازی شده

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چکیده

در مناطق شمالی چین، استفاده ازجویچه های انتها بسته برای آبیاری گیاهان رایج است.اما کارآیی این روش آبیاری در منطقه مزبور پایین است. هدف مقاله حاضر راست آزمایی و اطمینان ازمقادیر برآورد شده نرم افزارSIPAR ID از پارامترهای نفوذپذیری و ورود آب به خاک و ضریب زبری مانینگ و نیز ارایه روشی بهینه برای طراحی روش آبیاری جویچه ای با انتهای بسته است.پژوهش انجام شده شامل آزمون مزرعه ای و شبیه سازی عددی بود. آزمایش های مزرعه ای در دو روستای بخش یانگ لینگ در اکتبر سال ۲۰۰۷ انجام شد. پارامترهای نفوذپذیری و ورود آب به خاک و ضریب زبری مانینگ با استفاده از نرم افزارSIPAR ID برآورد شد و سپس این برآوردها به نرم افزار WinSRFR داده شد . بعد از آن، منحنی پیشرفت آب در جویچه و عمق جریان آب و کار آیی آبیاری برای هر جویچه شبیه سازی شد. نتایج نشان داد که برآورد هایWinSRFR همآهنگی بسیارخوبی با داده های اندازه گیری شده دارد.بنا براین برآوردهای نرم افزارSIPAR ID از پارامترهای نفوذپذیری و ورود آب به خاک و ضریب زبری مانینگ قابل اطمینان بودند. سپس، بر پایه دادها ی مزرعه ای پروژه" طراحی یکنواخت" و نرم افزارWinSRFR مدلی بهینه برای طراحی جویچه های انتها بسته ارایه و پیشنهاد شد. حل این مدل نیازبه کاربرد روش بهینه سازی با الگوریتم ژنتیک (GA) داشت و متغیرهای مستقل آن دبی ورودی جریان و زمان قطع یا کاهش جریان بود. نتایج نشان داد که با انتخاب مناسب مقدار جریان ورودی و زمان قطع جریان آب د رجویچه می توان آبیاری جویچه های انتها بسته را با کارآیی و به اندازه کافی انجام داد.

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