Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA)
Available online at www.inia.es/sjar

Spanish Journal of Agricultural Research 2011 9(2), 641-649
ISSN: 1695-971-X
eISSN: 2171-9292

Evaluating models for the estimation of furrow irrigation infiltration and roughness

H. Ramezani Etedali[1], H. Ebrahimian[1]*, F. Abbasi[2] and A. Liaghat[1]

[1] *Department of Irrigation and Reclamation Engineering, University College of Agricultural and Natural Resources. University of Tehran. P.O. Box 4111. 31587-77871 Karaj. Iran*
[2] *Agricultural Engineering Research Institute (AERI). Karaj. Iran*

Abstract

Several methods have been proposed for estimating infiltration and roughness parameters in surface irrigation using mathematical models. The EVALUE, SIPAR_ID, and INFILT models were used in this work. The EVALUE model uses a direct solution procedure, whereas the other two models are based on the inverse solution approach. The objective of this study is to evaluate the capacity of these models to estimate the Kostiakov infiltration parameters and the Manning roughness coefficient in furrow irrigation. Twelve data sets corresponding to blocked-end and free draining furrows were used in this work. Using the estimated parameters and the SIRMOD irrigation simulation software, the total infiltrated volume and recession time were predicted to evaluate the accuracy of the mathematical models. The EVALUE and SIPAR_ID models provided the best performance, with EVALUE performing better than SIPAR_ID for estimating the Manning roughness coefficient. The INFILT model provided lower accuracy in cut-back irrigation than in standard irrigation. The performance of SIPAR_ID and INFILT in blocked-end and free draining furrows was similar.

Additional key words: EVALUE; furrow irrigation; INFILT; infiltration parameters; Manning roughness coefficient; SIPAR_ID.

Resumen

Evaluación de modelos para estimar la infiltración y rugosidad del riego por surcos

En el riego por superficie se han propuesto varios métodos basados en modelos matemáticos para estimar los parámetros de infiltración y rugosidad. En este trabajo se han utilizado los modelos EVALUE, SIPAR_ID e INFILT. El modelo EVALUE utiliza un procedimiento de solución directa, mientras que los otros dos se basan en un enfoque de solución inversa. El objetivo de este estudio fue evaluar la capacidad de estos modelos para estimar los parámetros de infiltración de Kostiakov y el coeficiente de rugosidad de Manning en el riego por surcos. Se utilizaron en doce evaluaciones de riego por surcos, bien bloqueados en el extremo o bien con desagüe libre. Utilizando los parámetros estimados y el software de simulación de riego por gravedad SIRMOD, se predijeron el volumen total infiltrado y el tiempo de receso para evaluar la precisión de los modelos matemáticos. Los modelos EVALUE y SIPAR_ID proporcionaron el mejor rendimiento, dando mejores resultados EVALUE que SIPAR_ID para estimar el coeficiente de rugosidad de Manning. El modelo INFILT fue menos preciso en el riego con recorte de caudal que en el riego estándar. El rendimiento de SIPAR_ID e INFILT fue similar en los surcos bloqueados en el extremo y con desagüe libre.

Palabras clave adicionales: coeficiente de rugosidad de Manning; EVALUE; INFILT; parámetros de infiltración; riego por surcos; SIPAR_ID.

Introduction

The infiltration parameters and the Manning roughness coefficient are critical variables in the design and evaluation of surface irrigation systems (Harun-ur-Rashid, 1990; Valiantzas, 1994; Mailapalli *et al.*, 2008; Rodríguez and Martos, 2010). Their values vary during an irrigation event, and the estimation of advance and

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* Corresponding author: ebrahimian@ut.ac.ir
Received: 09-09-10; Accepted: 30-03-11.

Abbreviations used: EF (modeling efficiency), MAC (Maricopa Agricultural Center), ME (maximum error), RE (relative error), RMSE (root mean square error), RST (Research Station for Tobacco), SPIRI (Seed and Plant Improvement Research Institute).

recession times using constant values may lead to considerable errors. Several methods have been reported for the estimation of infiltration parameters. Khatri and Smith (2005) used six different methods to estimate infiltration parameters for furrow irrigation systems. These methods included: the two-point method of Elliott and Walker (1982), the computer model INFILT (McClymont and Smith, 1996), the method proposed by Upadhyaya and Raghuwanshi (1999), Valiantzas' one-point method (Valiantzas *et al.*, 2001), Shepard's one-point method (Shepard *et al.*, 1993), and a simple linear infiltration function (Austin and Prendergast, 1997; Mailhol *et al.*, 1997). Their results showed that INFILT was the most accurate method. The two-point and linear estimation methods also performed well. None of the methods proved entirely suitable for use in real-time control systems. Ebrahimian *et al.* (2010) evaluated various methods for estimating furrow and border infiltration parameters. The results showed that the modified Mailapalli method (Vatankhah *et al.*, 2010) and the method proposed by Elliott and Walker (1982) provided the lowest prediction errors for both furrow and border irrigations. Elliott and Walker's method resulted in the highest accuracy in predicting advance times.

Trout (1992) carried out several experiments on 6 m long furrows with the assumption of flow rate uniformity, and presented empirical equations in power and exponential forms for the estimation of roughness. Sepaskhah and Bondar (2002) estimated the Manning roughness coefficient (n) in furrow irrigation using different inflow rates and furrow slopes at various growth stages of wheat in a clay loam soil. The results indicated that the n values for the first irrigation were high (0.07-0.121), but for the second and third irrigations decreased by about 60-70%.

Mailapalli *et al.* (2008) studied the spatial and temporal variation of Manning's n for three 40 m long free-draining furrows. For both bare and cropped field conditions, Manning roughness coefficient was higher at the furrow sections where erosion was observed. Manning's n decreased in time for both bare and cropped furrow conditions, particularly for the lower inflow rates.

Walker (2005) introduced a multilevel optimization method for estimating the Manning's n and the parameters of a Kostiakov-Lewis infiltration equation:

$$z = k\tau^{a} + f_0\tau \qquad [1]$$

where z is infiltrated water volume per unit length of the field ($m^3\,m^{-1}$), τ is infiltration opportunity time (min), and k ($m^2\,min^{-a}$), a and f_0 ($m^2\,min^{-1}$) are infiltration parameters.

The proposed method was based on trial and error using the SIRMOD model. The principal advantage of this method is the reduction on the required field data (advance and recession trajectories were not needed). The multilevel approach was found to be better in developing intake parameters that led to more accurate simulation of surface runoff and recession as compared to the two-point method (Elliott and Walker, 1982).

Strelkoff *et al.* (1999) presented three methods to assess roughness. In the first method, the roughness coefficient was estimated using normal flow depth. The assumption of uniform flow is valid for relatively high slopes. This method would not be appropriate for slopes lower than 0.001. The second method was based on surface irrigation mathematical models and selects the best Manning's n value using trial and error. The different roughness values are introduced to the model and simulated advance and recession phases are compared to the measured ones. In the third method, roughness was determined using the Manning equation, using the slope of the water surface (S_f) instead of the bottom slope (S_0). This method requires measurement of flow depth at different points along the field and provides acceptable results in fields with low slope, although measurements of flow depth are difficult and time consuming. Strelkoff *et al.* (1999) proposed the EVALUE model, based on the third approach. Abbasi *et al.* (2003) and Ramezani Etedali *et al.* (2009) applied EVALUE to estimate Manning's n in blocked-end furrows.

Strelkoff *et al.* (2009) and Bautista *et al.* (2009) divided the existing methods for the estimation of infiltration and roughness in two general groups. The first group provides direct solution through the use of simplified volume balance theory. In the second group the inverse solution was obtained fitting measured and simulated data. Such results should be assessed for reliability, convergence, and uniqueness. The EVALUE model (Strelkoff *et al.*, 1999) makes part of the first group, while SIPAR_ID (Rodríguez and Martos, 2010) and INFILT (McClymont and Smith, 1996) make part of the second group.

The purpose of this study is to evaluate three models, EVALUE, SIPAR_ID, and INFILT for the estimation of the Kostiakov infiltration parameters and Manning's n coefficient in both blocked-end and free draining furrows under different flow regimes.

Methods

Models description

EVALUE model

As previously mentioned, this model was proposed for low-slope fields, and uses a direct solution procedure. The continuity, momentum, and Manning equations are simultaneously solved (Strelkoff *et al*., 1999). The flow model is based on neglecting the acceleration terms in the momentum equation (the so-called zero-inertia model). EVALUE estimates Manning's n and the parameters of a Kostiakov branch function (Strelkoff *et al*., 1999):

$$\begin{cases} z = c + k\,\tau^{a} & \tau \le \tau_B \\ z = c_B + b\,\tau^{a} & \tau > \tau_B \end{cases} \qquad [2]$$

where z is infiltrated water volume per unit length of the field ($m^3\,m^{-1}$), τ is infiltration opportunity time (min), τ_B is a threshold time (min), and k ($m^2\,min^{-a}$), a, c ($m^3\,m^{-1}$), b ($m^2\,min^{-1}$) and c_B ($m^3\,m^{-1}$) are empirical constants. This equation has proven useful for characterizing infiltration in cracking clay soils or fresh tilled soils (Strelkoff *et al*., 1999).

The model permits to simplify the Kostiakov branch equation to the Kostiakov equation. It is applicable to furrow, border and basin irrigation under blocked-end conditions. Model input data include: furrow length, furrow cross-section, inflow hydrograph and flow depth in several stations at different times.

SIPAR_ID model

This model estimates Kostiakov infiltration parameters and Manning's n in surface irrigation (Rodríguez and Martos, 2010). SIPAR_ID can be applied to open- and blocked-end fields. The model uses the volume-balance equation and an inverse modeling procedure for parameter estimation. Artificial neural networks are used to improve accuracy, while an efficient evolutionary optimization algorithm is used to minimize the difference between the observed and simulated advance phases in a robust multiobjective inverse modeling process.

Input data include: inflow hydrograph, advance curve, bed slope, hydraulic section parameters (ρ_1 and ρ_2), furrow geometry parameters (σ_1 and σ_2) and flow depth in one station at different times. The relationship between flow cross-sectional area, A (m^2), and flow depth, y (m), can be expressed as (Walker, 2003):

$$A = \sigma_1 y^{\sigma_2} \qquad [3]$$

It has been found that for most furrows the hydraulic section can be defined as (Walker, 2003):

$$A^2 R^{4/3} = \rho_1 A^{\rho_2} \qquad [4]$$

where R is the hydraulic radius (m).

SIPAR_ID also provides analyses of the uncertainty and sensitivity of the identified parameters.

INFILT model

INFILT estimates the parameters of a Kostiakov-Lewis infiltration equation [Eq. 1] in furrow irrigation, but cannot estimate Manning's n (McClymont and Smith, 1996).

The model is able to simplify the Kostiakov-Lewis equation to the Kostiakov equation (assuming $f_0 = 0$). This model is applicable for open and blocked-end fields. It uses the volume-balance equation and inverse modeling to minimize the differences between the observed and simulated advance phases. Model input data are restricted to advance observations and the average inflow rate. The geometric and hydraulic characteristics of the furrow cross-section are not needed in the model.

Data and model evaluation

Three sets of field data presented by Abbasi *et al*. (2003, 2009a,b) were used in this comparative analysis. Field experiments represented different conditions, including field length, slope, and flow regime. Data included inflow and outflow hydrographs, advance and recession phases and field geometry. The first set of experiments was collected in three furrows (MAC1 to MAC3) located at the Maricopa Agricultural Center (MAC), Maricopa, Phoenix, AZ, USA (Abbasi *et al*., 2003). The second set was collected in three furrows (SPIRI1 to SPIRI3) at the research station of the Seed and Plant Improvement Research Institute (SPIRI), Karaj, Iran (Abbasi *et al*., 2009a). Finally, the third set was collected in six furrows (RST1 to RST6) located at the Research Station for Tobacco, Urmia, Iran (Abbasi *et al*., 2009b).

In sets MAC1 to MAC3 soil texture was sandy loam, with 115 m furrow length and 0.0001 m m^{-1} bed slope.

In sets SPIRI1 to SPIRI3 soil texture was loam, with 175 m furrow length and 0.0059 to 0.0067 m m^{-1} bed slope. In sets RST1 to RST6 soil texture was clay silty loam, with 175 m furrow length and 0.0059 to 0.0067 m m^{-1} bed slope. For all experimental furrows, two buffer furrows were considered around the monitored ones. Furrows MAC1 to MAC3 and SPIRI1 to SPIRI3 were blocked-end. As a consequence, the data could be analyzed using the three models. Furrows RST1 to RST6 were open-end, and their data could only be analyzed using SIPAR_ID and INFILT. SPIRI1 to SPIRI3 and RST1 to RST6 were irrigated under cut-back flow regime, while the other furrows were irrigated under standard irrigation (constant irrigation discharge). A summary of the data sets corresponding to the experimental furrows is presented in Table 1.

In furrows MAC1 to MAC3 and SPIRI1 to SPIRI3 stations were marked at 20 m intervals. Advance and recession times as well as flow depth measurements were recorded at those stations at different times. Flow depths were measured using staff gauges placed at the bottom of the experimental furrows. Water depths were initially measured every minute for the first 10 min after the completion of advance, and then every 5-10 min till cut off. Flow depths were recorded at 2-5 min intervals between cutoff and the completion of recession. Furrow cross-sections were measured before and after the irrigation at three different locations along the monitored furrows.

The accuracy in infiltration parameter estimation was assessed by comparing predicted and measured infiltrated volume for each furrow. Total measured infiltrated volume was estimated as the difference between the total inflow, outflow and overland furrow volumes. Total predicted infiltrated volume was estimated from infiltration parameters using the trapezoidal rule.

Walker (2005) reported that the recession times were very sensitive to the basic intake rate, f_0, and to the Manning's *n* value. Since Kostiakov infiltration parameters (*i.e.* without f_0) were predicted by the models, to assess the accuracy in Manning's *n* estimation, the recession times were simulated using the hydrodynamic model included in SIRMOD (Walker, 2003) and compared to the measured recession times.

The statistical indexes used for evaluation of the parameter estimation models were:

— Coefficient of determination (R^2):

$$R^2 = \frac{\left[\sum_{i=1}^{m}(Q_i - \bar{Q})(P_i - \bar{P})\right]^2}{\sum_{i=1}^{m}(Q_i - \bar{Q})^2 \times \sum_{i=1}^{m}(P_i - \bar{P})^2} \qquad [5]$$

— Relative error (RE):

$$RE = \frac{(P_i - Q_i)}{Q_i} * 100 \qquad [6]$$

— Maximum error (ME):

$$ME = Max\left|P_i - Q_i\right|_{i=1}^{m} \qquad [7]$$

Table 1. Data summary for the experimental furrows

Furrows	MAC1	MAC2	MAC3	SPIRI1	SPIRI2	SPIRI3	RST1	RST2	RST3	RST4	RST5	RST6
Furrow length (m)	115	115	115	175	175	175	200	200	200	200	200	200
Furrow spacing (m)	1	1	1	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Slope (%)	0.01	0.01	0.01	0.67	0.59	0.64	1.77	1.75	1.73	1.71	1.74	1.75
Time of cut (min) back	—	—	—	41	55	29	34	59	32	57	87	—
Time of cut off (min)	140	140	140	120	120	120	99	120	120	122	122	121
Average inflow rate (L s^{-1})	1.29	1.32	1.28	0.67	0.98	0.72	0.72	0.81	0.72	0.96	0.98	1.31
Irrigation event	1	1	1	3	3	3	2	2	2	2	2	2
Hydraulic section parameters												
ρ_1	0.33	0.33	0.33	0.46	0.46	0.17	0.37	0.41	0.36	0.38	0.39	0.42
ρ_2	2.76	2.76	2.76	2.82	2.83	2.61	2.77	2.79	2.77	2.78	2.79	2.79
Furrow geometry parameters												
σ_1	1.31	1.31	1.31	0.73	1.09	1.32	0.47	0.40	0.43	0.40	0.39	0.39
σ_2	1.65	1.65	1.65	1.50	1.53	1.71	0.57	0.60	0.58	0.59	0.59	0.60

MAC: Maricopa Agricultural Center. SPIRI: Seed and Plant Improvement Research Institute. RST: Research Station for Tobacco.

— Root mean square error (RMSE):

$$RMSE = \left[\frac{\sum_{i=1}^{m} \left(P_i - Q_i \right)^2}{m} \right]^{1/2} \qquad [8]$$

— Modeling efficiency (EF):

$$EF = \frac{\sum_{i=1}^{m} \left(Q_i - \bar{Q} \right)^2 - \sum_{i=1}^{m} \left(P_i - Q_i \right)^2}{\sum_{i=1}^{m} \left(Q_i - \bar{Q} \right)^2} \qquad [9]$$

where P_i are the predicted (simulated) values, Q_i the observed (measured) values, m is the number of samples, and $\bar{Q}$ and $\bar{P}$ represent the mean of observed and predicted values, respectively. The value of R^2 ranges from 0.0 to 1.0, indicating better agreement for values close to 1.0. If simulated and measured data were the same, the values of ME, RE and RMSE would be zero, and value of EF would be one (Homaee *et al*., 2002).

Results and discussion

Infiltration

Parameter estimation results for the different experimental sets are presented in Table 2. The observed and predicted total infiltrated volumes are also presented in Figure 1 for all the experimental furrows. All models predicted the infiltration parameters reasonably well. The values of RMSE for the various models indicated that the EVALUE and SIPAR_ID provided similar accuracy. The low determination coefficient (R^2) resulting from the use of the EVALUE model may be explained by the fact that the number of experimental furrows used in this model was lower than for the other two models. The results of this section are presented for different conditions (blocked-end and free draining furrows and cut-back and constant flow regime).

Table 2. Results obtained for the experimental furrows with the different models

Furrow	**EVALUE**			**SIPAR_ID**			**INFILT**	
	a	***k* (m^2 min^{-a})**	***n***	***a***	***k* (m^2 min^{-a})**	***n***	***a***	***k* (m^2 min^{-a})**
MAC1	0.850	0.00123	0.092	0.687	0.00287	0.070	0.874	0.00135
MAC2	0.750	0.00209	0.073	0.706	0.00265	0.083	0.763	0.00238
MAC3	0.800	0.00208	0.102	0.747	0.00334	0.118	0.822	0.00219
SPIRI1	0.560	0.00273	0.044	0.439	0.00228	0.081	0.585	0.00108
SPIRI2	0.500	0.00349	0.038	0.647	0.00179	0.103	0.590	0.00218
SPIRI3	0.550	0.00263	0.020	0.195	0.00050	0.123	0.482	0.00041
RST1	—	—	—	0.642	0.00052	0.137	0.114	0.00519
RST2	—	—	—	0.441	0.00251	0.082	0.628	0.00081
RST3	—	—	—	0.658	0.00050	0.152	0.127	0.00544
RST4	—	—	—	0.658	0.00089	0.172	0.824	0.00056
RST5	—	—	—	0.328	0.00817	0.042	0.621	0.00178
RST6	—	—	—	0.702	0.00157	0.178	0.855	0.00078

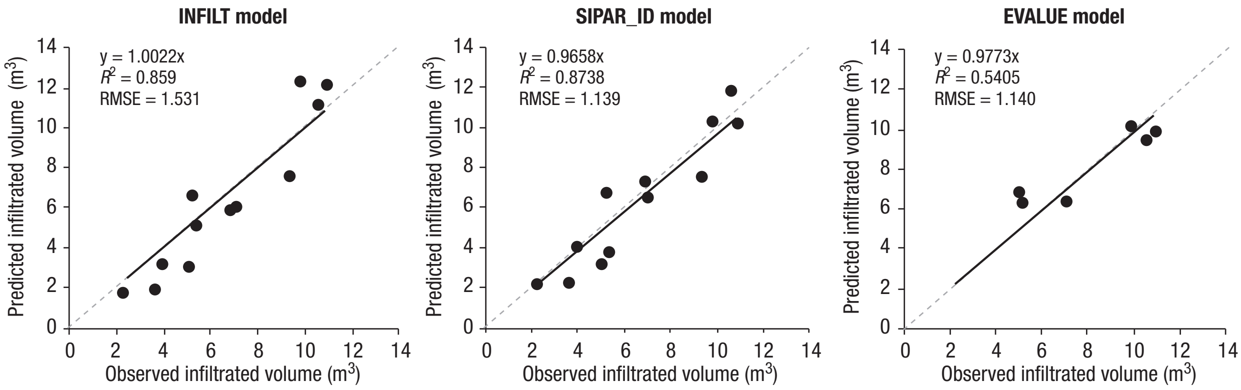

Figure 1. Predicted and observed total infiltrated volumes for different experimental furrows.

Table 3. Statistical indexes for the evaluation of the EVALUE, SIPAR_ID and INFILT models in estimating total infiltrated volume for the experimental blocked-end furrows

Furrows	RE (%)		
	EVALUE	SIPAR_ID	INFILT
MACl	–9.5	–6.5	11.6
MAC2	2.5	4.5	24.9
MAC3	–10.4	11.5	4.9
SPIRIl	37.2	–35.5	–38.7
SPIRI2	–9.9	–7.6	–14
SPIRI3	23.7	31.3	28.3
Ave. RE (%)	15.5	16.1	20.4
ME (m^3)	1.86	1.78	2.45
RMSE (m^3)	1.14	1.17	1.54
EF	0.85	0.84	0.80

RE: relative error. ME: maximum error. RMSE: root mean square error. EF: modeling efficiency.

Table 4. Statistical indexes for the evaluation of the SIPAR_ID and INFILT models in estimating total infiltrated volume for the experimental free-draining furrows

Furrows	RE (%)	
	SIPAR_ID	INFILT
RSTl	–3.2	–21.6
RST2	4.2	–18.2
RST3	–37.7	–45.3
RST4	–28.8	–3.2
RST5	4.5	–13.5
RST6	–18.3	–18.1
Ave. RE (%)	16.1	20
ME (m^3)	1.68	1.71
RMSE (m^3)	1.11	1.09
EF	0.74	0.74

RE: relative error. ME: maximum error. RMSE: root mean square error. EF: modeling efficiency.

Blocked-end furrows

Statistical indexes for model comparison in the estimation of total infiltrated volumes are presented for the blocked-end furrow experiments in Table 3. The values of average RE, ME, RMSE, and EF indicated that the EVALUE and SIPAR_ID models had similar performance for blocked-end furrows. Additionally, EVALUE and SIPAR_ID had higher performance indexes than INFILT model. Use of SIPAR_ID is easier than EVALUE, since data requirements are lower. Even if flow depth measurements were not available, SIPAR_ID could satisfactorily predict infiltration parameters.

Free-draining furrows

SIPAR_ID performed better than INFILT for both blocked-end and free draining furrows (Table 4). Having fewer and simpler input data, INFILT showed lower accuracy relative to the other two models. For example, INFILT needs as input data the average inflow instead of the inflow hydrograph (typical inputs in EVALUE and SIPAR_ID). Rodríguez (2003) reported that constant *vs.* variable inflow can affect the estimation of infiltration parameters in furrow irrigation. Additionally, the geometric and hydraulic characteristics of furrow cross-section can not be defined in INFILT.

Standard and cut-back flow regimes

Simulation results showed that the three models were more accurate in the standard (constant flow) regime than in the cut-back regime (Table 5). INFILT provided the lowest performance for the cut-back flow regime because of using average inflow instead of the inflow hydrograph. The good performance of SIPAR_ID

Table 5. Statistical indexes for the evaluation of the EVALUE, SIPAR_ID and INFILT models in estimating total infiltrated volume for different flow regimes

Furrows	EVALUE		SIPAR_ID		INFILT	
	Constant flow	Cut-back flow	Constant flow	Cut-back flow	Constant flow	Cut-back flow
RE(%)	7.5	23.6	13.6	17.6	14.9	22.85
ME (m^3)	1.10	1.86	1.71	1.78	2.45	1.94
RMSE (m^3)	0.88	1.35	1.14	1.13	1.18	1.63
EF	0.85	0.32	0.44	0.45	0.58	0.25

RE: relative error. ME: maximum error. RMSE: root mean square error. EF: modeling efficiency.

for both constant and cut-back flow regimes can be attributed to the use of inflow hydrograph as an input parameter. Although EVALUE also used inflow hydrograph, this model did not result as suitable for the estimation of the total infiltrated volume under cut-back flow regime as the SIPAR_ID model. It has to be noted that EVALUE is more suitable for low slope furrows, and furrows SPIRI1 to SPIRI3 (irrigated under cut-back regime) had higher slopes than furrows MAC1 to MAC3 (irrigated under standard regime).

Manning roughness coefficient

In order to assess the relative performance of EVALUE and SIPAR_ID models for the estimation of Manning's *n*, the recession phase was simulated in all furrows using the SIRMOD hydrodynamic model (Fig. 2). Figure 2 shows that EVALUE adequately estimated the recession curve for furrows MAC1 to MAC3. In furrows SPIRI1 to SPIRI3, the agreement between predicted and measured recession data was not satisfactory. EVALUE was recommended for use

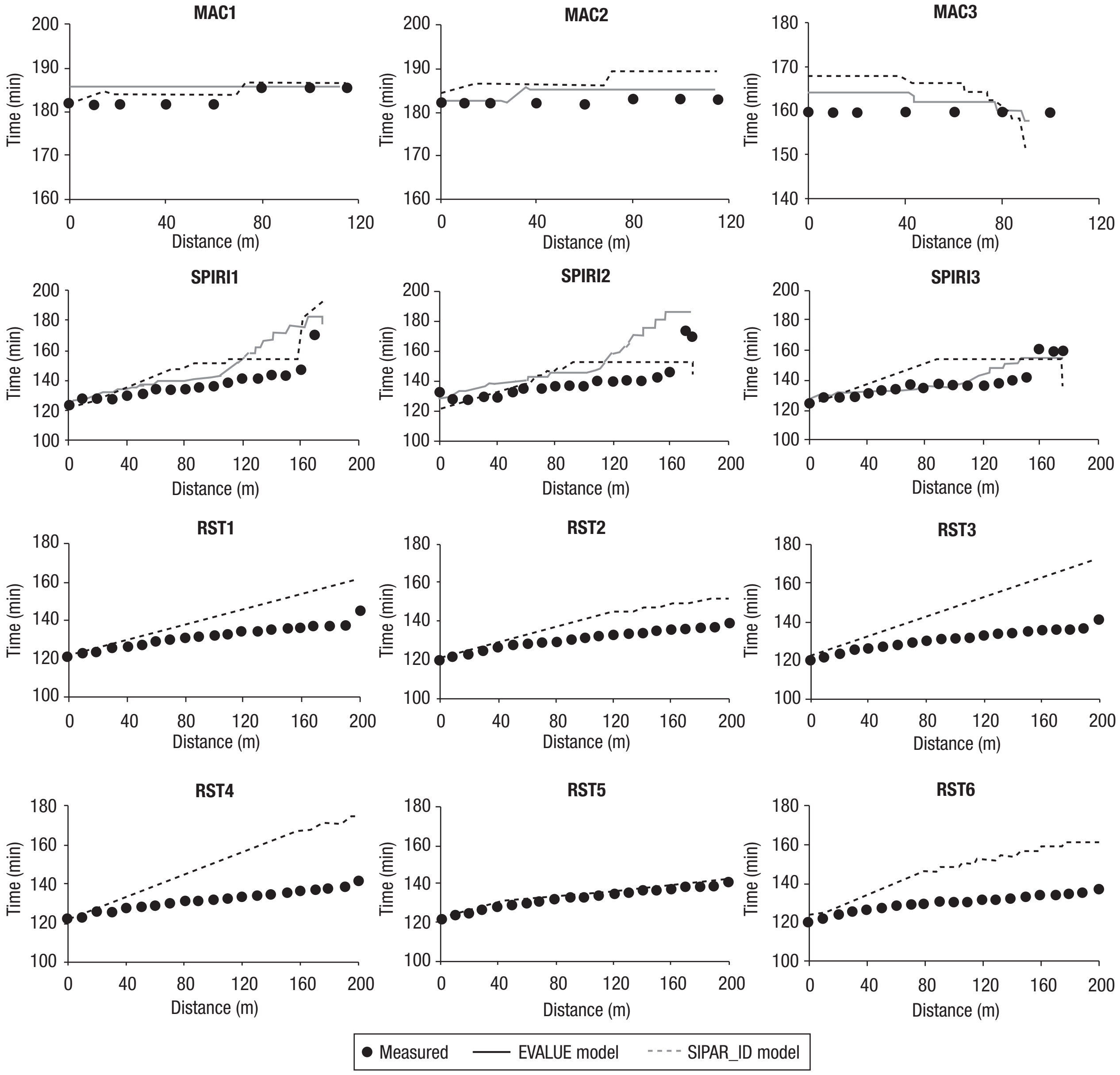

Figure 2. Predicted and observed recession trajectories for different experimental furrows.

in fields with mild slope, while the longitudinal bottom slopes in these furrows were relatively high.

As already mentioned, a reduction in flow rate may decrease the accuracy of EVALUE in estimating infiltration parameters and Manning's roughness coefficient. An adequate agreement could be observed between measured and simulated recession trajectories at the upstream part of the furrows. However, differences rise at the downstream part, where the effect of flow reduction was more evident (Fig. 2).

Statistical indexes to compare EVALUE and SIPAR_ID models in estimating recession are presented in Table 6. EVALUE predicted the recession times better than SIPAR_ID in furrows MAC1 to MAC3 and SPIRI1 to SPIRI3. EVALUE could not be applied to furrows RST1 to RST6 (since these are free-draining furrows). For these furrows, SIPAR_ID could not predict well, except for furrow RST5 (Fig. 2).

With respect to EF values from Tables 3, 4 and 6, for the EVALUE and SIPAR_ID models the predicted infiltration parameters were more accurate than the Manning roughness coefficients.

The EVALUE model (based on the direct solution) showed more accuracy than the inverse models (SIPAR_ID and INFILT) in predicting infiltration parameters and Manning roughness coefficients for blocked-end furrows. Strelkoff *et al*. (2009) and Bautista *et al*. (2009) arrived to similar results using different data sets.

Table 6. Statistical indexes for the evaluation of the EVALUE and SIPAR_ID models in estimating the recession times

Furrows	RE (%)	
	EVALUE	**SIPAR_ID**
MACl	1.2	0.6
MAC2	0.9	2.5
MAC3	2.1	5.1
SPIRIl	6.3	9.7
SPIRI2	9.1	6.5
SPIRI3	2.7	8.1
RSTl	—	6.8
RST2	—	5.6
RST3	—	12.7
RST4	—	13.6
RST5	—	1.2
RST6	—	11.8
Ave. RE (%)	3.7	6.9
ME (min)	39.7	39.6
RMSE (min)	7.2	11.1
EF	0.21	–0.06

RE: relative error. ME: maximum error. RMSE: root mean square error. EF: modeling efficiency.

Conclusions

The performance of SIPAR_ID and INFILT for estimating the infiltration volume in blocked-end and free-draining furrows was similar. Our results indicated that EVALUE and SIPAR_ID provided the lowest errors for estimating the infiltrated volume. Regarding simplicity and under Windows-interface, use of SIPAR_ID can be recommended to estimate infiltration parameters. SIPAR_ID also provides an estimation of the uncertainty and sensitivity of the identified parameters. INFILT provided lower accuracy in cut-back flow regime than in standard regime. The performance of EVALUE was somewhat better than SIPAR_ID for estimating the Manning roughness coefficient. As a result, EVALUE was suitable for estimating the Kostiakov infiltration parameters and Manning roughness coefficient in blocked-end furrows with low slopes, particularly when the inflow rate was constant. Finally, the performance of all three models depends on the type and number of input data, assumptions, and solution methods of parameter estimation.

Acknowledgements

This research was supported by The Center of Excellence for Evaluation and Rehabilitation of Irrigation and Drainage Networks in University of Tehran. We gratefully acknowledge an anonymous reviewer for his constructive advices.

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