# A Comparative Analysis of WinSRFR and SIRMOD Software for Simulating Surge and Alternate Furrow Irrigation Performance in Maize Fields

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## Abstract

In order to compare of WinSRFR and SIRMOD software in simulating furrow irrigation performance, a field experiment was carried out in the Jayedar plain of Lorestan province, Iran. Different furrow irrigation methods including conventional furrow irrigation (CFI), surge irrigation with on/off cycle ratios of 1 and 0.5 (SFI1-1 and SFI1-2, respectively), fixed alternate irrigation (FFI) and variable alternate irrigation (AFI) were investigated. A total of 15 irrigation evaluations were performed at the growing season by measuring inflow rate, cutoff time, outflow rate, infiltration and advance time. The length and spacing of experimental furrows were 120 and 0.75 m, respectively and the inflow rate of furrows and the flow cutoff times at the initial (3rd irrigation), middle (6th irrigation), and end (9th irrigation) of the season were 0.28 L/s and 240 min, 0.42 L/s and 360 min, 0.35 L/s and 300 min, respectively. The WinSRFR 3.1 and SIRMOD software were calibrated, validated and compared using field measurements based on the zero-inertia model. Both softwares demonstrated a strong correlation between the measured and simulated values of runoff, infiltration and advance time with coefficient of determination of (0.9984, 0.9976), (0.9908, 0.9932 ) and (0.9449, 0.9331), respectively. The relative error values of WinSRFR and SIRMOD Software in estimating runoff, infiltration and advance time were (2.96, 3.15), (3.03, 3.30) and (2.09, 2.46) respectively. Both software overestimates the runoff ($\lambda$=1.0296 in WinSRFR and $\lambda$= 1.0315 in SIRMOD) and the advance time ($\lambda$=1.0209 in WinSRFR and $\lambda$= 1.0246 in SIRMOD). The WinSRFR software underestimates infiltration ($\lambda$=0.9697) but SIRMOD software overestimates infiltration ($\lambda$=1.0333). Based on research result, AFI is a more suitable method for maize irrigation in the study area. The WinSRFR software has an advantage over the SIRMOD software in simulating furrow irrigation performance due to its higher ability and the use of a wide range of input parameters.

**Keywords**: Furrow irrigation, Performance assessment, Runoff, Infiltration, WinSRFR, SIRMOD .

## Introduction

Surface irrigation is the oldest and common irrigation method due to the low cost and energy requirements compared to sprinkler and drip irrigation. Thus, many studies have been carried out to increase the efficiency of surface irrigation systems (Ebrahimian and Playán, 2014; Lalehzari et al., 2015). In surface irrigation, it is observed that water losses can reach up to 40% of the total water input. This implies that furrow irrigation systems incur higher operational costs due to increased irrigation losses. However, achieving high irrigation efficiency can lead to reduced operating costs, enhanced production per unit of water utilized and improved environmental management and benefits (Ahmadabadi et al., 2020). The effective management of irrigation involves the equitable distribution of water across all sections of the irrigated field. This task presents an engineering obstacle that can be efficiently addressed by minimizing water losses and maximizing uniformity through the optimization of factors such as inflow rate, application depth, time to cut-off, and field design (Akbar et al., 2016). Surge irrigation is one of the advanced methods of surface irrigation which has been defined as the intermittent application of water to the field surface under gravity flow which results in a series of on and off modes of constant or variable time spans. Water is applied for a set period of time after which inflow is stopped (Mazarei et al., 2020). Surge irrigation has been proven to be advantageous in various aspects, including the reduction of irrigation duration, enhancement of infiltration uniformity, and mitigation of nutrient runoff from agricultural fields (Radmanesh et al., 2023). The implementation of the alternate furrow irrigation (AFI) method offers it has several benefits, including water conservation and enhanced irrigation efficiency, and often causes a decrease in yield. Surface irrigation models serve as valuable tools for the planning and evaluation of surface irrigation strategies. Through the utilization of these models, it becomes possible to simulate and design a comprehensive irrigation system. By manipulating the variables within these models, which represent planned factors, it is feasible to achieve high levels of efficiency and uniformity in irrigation practices (Smith et al., 2018; Pereira and Goncalves, 2018). The WinSRFR and SIRMOD are among the most powerful softwares used to design and evaluate surface irrigation systems in continuous and surge irrigation. Xu et al. (2019), Nie et al. (2019) and Mehri et al. (2023) used the WinSRFR software to evaluate and optimize the physical parameters of furrows. Likewise, various researchers as (Ebrahimian and Liaghat, 2011; Wu et al., 2017) used the SIRMOD software to evaluate continuous surface irrigation systems. Radmanesh et al. (2023) used WinSRFR and SIRMOD software to evaluates continuous and surge irrigation. However, because of the difficulty in implementing and managing surge irrigation, few studies have been done on surge irrigation. Valipour and Montazar (2012) employed the full hydrodynamic, zero-inertia, and kinematic wave models within the SIRMOD package to simulate border and basin irrigation. The findings indicated that the full hydrodynamic and zero-inertia models were capable of accurately simulating these irrigation techniques. In research Mehanna et al. (2015) the SIRMOD software exhibited the greatest levels of application efficiency and irrigation uniformity. Wu et al. (2017) effectively calibrated the SIRMOD software to evaluate and enhance the uniformity of irrigation distribution in both alternate and conventional furrow irrigation systems in China. Akbar et al. (2016) and Nie et al. (2019) also demonstrated that a proper combination of inflow and cutoff time increased application efficiency to the 75-90% range. Ahmadabadi et al. (2020) investigated various scenarios using the SIRMOD software to improve furrow irrigation application efficiency in sugar beet fields located in the Moghan plain of Ardebil province, Iran. The results demonstrated that using different scenarios could significantly reduce water losses in the field. Mazarei et al. (2020) applied the WinSRFR software to optimize furrow irrigation performance in sugarcane farms (Southwestern of Iran) under different inflow rates and geometric parameters. They suggested a flow rate of 3 L/s and a cut-off time of 379.5 min to achieve the highest irrigation performance in their conditions. Ebrahimian et al. (2020) used various methods to estimate infiltration parameters of furrow irrigation. The results demonstrated that the Elliott and Walker method was the most accurate among the various two-point methods. Ismail et al. (2021) evaluated and optimized the performance of furrow irrigation systems in Egypt using the WinSRFR software. They concluded that increasing the furrow length reduced irrigation performance, and the optimal combination of inflow rate and cut-off time resulted in increased application efficiency and reduced deep percolation losses. Yadeta et al. (2022) assessed the furrow irrigation performance using the WinSRFR software in Ethiopia. The results indicated that changing decision variables (inflow rate and cut-off time) significantly improved performance indices, such as application efficiency and deep percolation, but the uniformity of distribution remained unchanged. The performance calculated by the software was better than the performance determined in the irrigation evaluation. Adamu et al. (2022) employed WinSRFR and SIRMOD software to optimize furrow irrigation in Wonji Shoa Sugar Estate, located in Ethiopia. Their investigation revealed that the application efficiencies for furrow lengths of 48 m and 32 m ranged from 25% to 43%, respectively. In order to improve furrow irrigation performance in the Jayder plain of southwest Iran, this research was conducted during the grain maize growing season. The study examined five different furrow irrigation methods, including one conventional method, two alternate methods, and two surge methods. The objectives of the study were as follows:

1- To parameterize the WinSRFR and SIRMOD software in order to improve the performance of various furrow irrigation methods (conventional, surge, and alternate) and alleviate stress on water resources.

2- To compare and evaluate the performance of the WinSRFR and SIRMOD software in simulating surge and alternate furrow irrigation.

3- Compare the performance of different furrow irrigation methods.

## Materials and methods

### The study area

Field experiments were carried out in the Jayder plain of Lorestan province in Iran. The study area is located at a longitude of 47◦ 41’ E, a latitude of 33◦ and 6′ N, and an altitude of 686 m above sea level. The average annual precipitation was 375 mm, and the mean annual temperature was 24°C. Figure (1) shows the geographical location of the study area on the Iran map.

### Field data

Hydrometric method and soil texture triangle were utilized to determine the soil texture of the experimental field. The soil moisture at field capacity (FC) and permanent wilting point (PWP) were determined using a pressure plate apparatus and a pressure membrane, respectively. The results of the soil physicochemical analyses are presented in Table (1).

Furrows at 0.75 m spacing and a length of 120 m were made after plowing, disc, fertilizing, and re-disc operations. The experimental field was then prepared under grain maize cultivation (*Single Cross 704*) with a furrow irrigation system. The crop was sown in the third week of March 2021 and harvested in mid-July 2021. Maize seed was planted at the rate of 20 kg per hectare and at a density of about 80 thousand plants per hectare with a planting depth of 4-6 cm and a distance between plants in the row of 20 cm with a pneumatic seeder. The longitudinal and cross slopes of the field were determined at 0.0085 and 0.0022 m/m, respectively, by a using survey equipment. Five furrow irrigation methods including conventional furrow irrigation (*CFI*), surge furrow irrigation with on/off cycle ratios of 1 and 0.5 (*SFI1*-1 and *SFI1-2*, respectively), and fixed and variable alternate furrow irrigation (*FFI* and *AFI*, respectively) were investigated. In total, 20 furrows were established. The lateral furrows of each treatment acted as buffer furrows, and the required parameters were measured in the middle furrow. As a result of variations in soil infiltration characteristics throughout the growing season, a total of three assessments were conducted at the onset (third irrigation), midpoint (sixth irrigation), and end of the season (ninth irrigation). During each evaluation, measurements were taken of inflow rate, cutoff time, runoff, infiltration, and advance time. The maximum non-erosive inflow rate (0.7 L/s) of the experimental furrows was determined using the Bohr (1976) equation. In all irrigation methods, inflow rates and cutoff times were 0.28 L/s and 240 min, 0.42 L/s and 360 min, and 0.35 L/s and 300 min in the third, sixth, and ninth irrigations, respectively. The inflow and outflow rates of the furrows were quantified using WSC flumes. Advance time was determined and documented at designated intervals of 10 m along the experimental furrows. Figure (2) shows some of the work steps before cultivation.

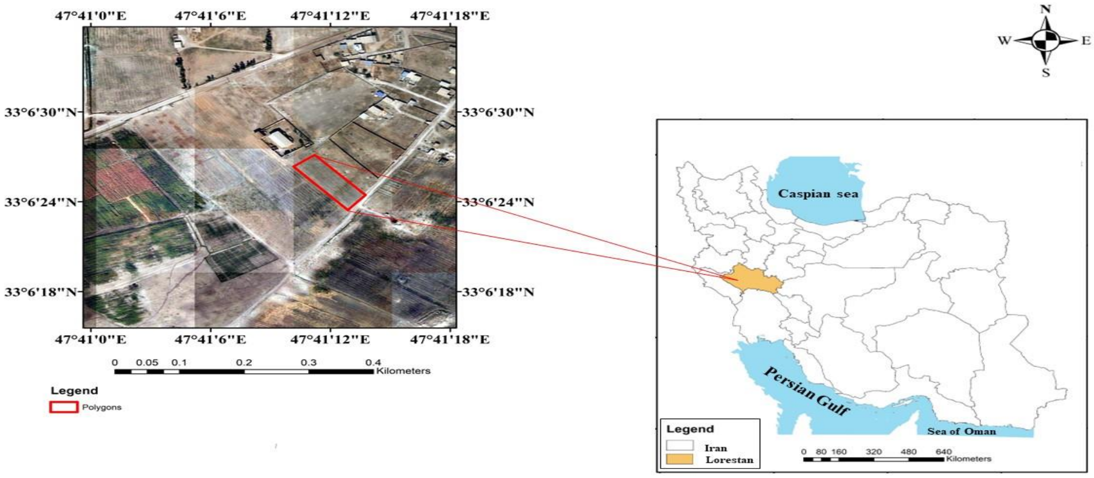

Fig. 1- Location of the study area

Table 1- Average soil physical and chemical characteristics of the experimental field

| Percentage of soil particles | | | Texture soil | $\rho_b$ (Mg m$^{-3}$) | *FC* (m$^3$ m$^{-3}$) | *PWP* (m$^3$ m$^{-3}$) | *ECe* (dS m$^{-1}$) | *pH* |
|---|---|---|---|---|---|---|---|---|
| clay | silt | sand | | | | | | |
| 39 | 41 | 20 | Clay loam | 1.26 | 0.36 | 0.18 | 1.01 | 7.86 |

$\rho_b$= dry bulk density; *FC*= Field Capacity; *PWP* = Permanent Wilting Point; *ECe* = Electrical Conductivity of saturated soil extract

Fig. 2- WSC flume and determining the slope of the field with Nivo camera

**Crop water requirement**

The crop water requirement during the growth period were calculated by Equation (1) (Allen et al., 1998):

$$ETc=K_C \times K_P \times E_{Pan} \quad (1)$$

where *ETc* is crop evapotranspiration (mm/day), $K_C$ is the crop coefficient and $K_P$ denotes the pan coefficient, and $E_{Pan}$ indicates the evaporation rate from Class A pan in mm/day. The pan evaporation data were obtained from the Poldakhtar synoptic meteorological station near the study area. It should be noted that no effective precipitation occurred during the plant growth period. The $K_P$ was considered 0.7 on average. The growth period of the crop was 141 days, and the initial, developmental, mid and final stages lasted 27, 27, 51, and 36 days, respectively. The $K_C$ values in four stages were on average 0.55, 0.94, 1.15 and 0.6, respectively. It should be noted that it is quite easy for the local farmers to use the pan evaporation for the estimation of reference evapotranspiration (ET$_o$) due to the metrological data scarcity.

**Infiltration equation**

The modified Kostiakov-Lewis equation is one of the most useful infiltration equations in surface irrigation (Mazarei et al., 2020; Mehri et al., 2023). In the present study, cumulative infiltration was estimated using the Kostiakov–Lewis equation as follows (2):

$$Z=kt^{a}+f_{o}t \qquad (2)$$

where $Z$ is the cumulative infiltration volume in along furrow length $(m^{3}.m^{-1})$, $f_o$ the final infiltration rate $(m^{3}.min^{-1}.m^{-1})$, $t$ the infiltration opportunity time (min), $k$ $(m^{3}.min^{-a}.m^{-1})$ and $a$ (-) are the empirical parameters of the equation. In different irrigation methods, the inflow-outflow method was used to determine the basic infiltration rate (Ahmadabadi et al., 2020; Mehri et al., 2023). The advance time data and the two-point method were also used to determine the coefficients $a$ and k (Ahmadabadi et al., 2020). The Kostiakov-Lewis infiltration equation coefficients for surge irrigation were determined using the Walker-Humpherys method (Walker and Humpherys, 1983) for furrows in a saturated state (3, 6 and 9 irrigations events).

### Manning's roughness coefficient

Due to the significance of the Manning’s roughness coefficient within the design and assessment of furrow irrigation systems, appropriate estimation of this coefficient is critical. It is difficult to estimate Manning's roughness coefficient in furrow irrigation. Manning's equation was used to estimate the roughness coefficient assuming uniform flow and reaching the depth of flow to the normal depth (Mazarei et al., 2020; Kamali et al., 2018):

$$n=\frac{A^{2/3}\sqrt{S}}{Q\,P^{2/3}} \qquad (3)$$

where $n$ is Manning's roughness coefficient, $A$ is the area of cross section (m$^2$), $P$ is the wetted perimeter (m), $S$ is the longitudinal slope of the water surface (m/m) and Q is the inflow rate (m$^3$/S).

At three points (the beginning, middle and end) of the experimental furrows, the flow cross-sectional area and wetted perimeter were measured using a cross-sectional measuring device (Ahmadabadi et al., 2020).

### WinSRFR Software

The WinSRFR software package, created by the Agricultural Research Service of the United States Department of Agriculture, is designed to facilitate the hydraulic analysis of surface irrigation systems (Bautista and Schlegel, 2019). *WinSRFR* software it performs calculations with zero-inertia and kinematic wave models with the numerical solution strategy (Mehri et al., 2023). The implementation of WinSRFR software has four parts: event analysis, performance analysis, physical design and simulation. In event analysis, the model evaluates field data and then uses the Miriam-Keller, field infiltration data, and Elliott and Walker two-point methods to estimate the infiltration parameters. The performance analysis part consists of testing various applied scenarios of the system. These tests suggest different combinations of inflow rate and cutoff time for a system with specific dimensions, slopes, and soil characteristics to evaluate the performance of the irrigation system. The various performance parameters analyzed by the model such as the uniformity of distribution, water application efficiency, deep percolation and runoff, minimum infiltrated depth and total applied water depth. In the design part, the physical dimensions of the field (length and width) are determined using field data to achieve acceptable performance. In the simulation part, the model simulates the data given in the event analysis, physical design, and performance to run the simulation scenarios alternatively (Bautista and Schlegel, 2019). In the present study, the zero-inertia model was used in the WinSRFR3.1 software. The main inputs of the software include the length and slope of the field, the geometric characteristics of the furrow cross-section, the inflow rate, and infiltration and Manning's roughness coefficients.

### SIRMOD Software

*SIRMOD* is a software package utilized for designing, assessing, and simulating surface irrigation systems, proposed by Walker (2005) in Utah State University, Logan, *UT*, *USA*. The *SIRMOD* software permits the user to indicate furrow, border, or basin configurations with free-draining or blocked downstream boundary conditions under continuous or surged flow regimes and cutback options. This Software utilized the zero inertia (*ZI*), kinematic wave (*KW*) and hydrodynamic (*HD*) approaches to solve Saint-Venant equations (Mahdizadeh Khasraghi et al., 2015). The most objective of the *SIRMOD* Software is assessment of the shape of field (slope and length of field) and management strategy (application flow rate and cut-off time). The input data requirements for the simulation component include the field length, slope, infiltration characteristics, and advance data, target application depth, water application rate, Manning's resistance, and furrow geometry. The ability and high accuracy of the Software have been reported in different publications such as Walker and Humpherys (1983) and Ebrahimian and Liaghat (2011). This model simulates infiltration utilizing the Kostiakov– Lewis equation. In the present study, the zero-inertia model was used in simulating with *SIRMOD*.

### Calibration of the WinSRFR and SIRMOD software

To calibrate the software, the required data such as furrow geometry, Manning's roughness coefficient, inflow and outflow hydrograph and advance time were input data to the software. To evaluate the WinSRFR software, the simulated values of runoff, infiltration, and advance time were compared with the measured values. The volume of infiltrated water was calculated using the volumes of inflow and outflow from the field (runoff). The calibration of the software under the field conditions was done using different evaluation criteria including Relative Error (RE), Root Mean Square Error (RMSE) and the coefficient of determination ($R^2$) (Ebrahimian et al., 2020):

$$X_P = \lambda X_m \tag{4}$$

$$RE = \frac{|X_P - X_m|}{X_m} \times 100 \tag{5}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(X_m - X_p)^2}{\sum_{i=1}^{n}(X_m - \bar{X}_m)^2} \tag{6}$$

where $X_P$ is the simulated value, $X_m$ is the measured value, $\bar{X}_m$ is the average measured value and $\lambda$ is the slope of the fitting line equation. If $\lambda < 1$, the software underestimated, and if $\lambda > 1$, the software overestimated. The $\lambda$ value near to 1 and an *RE* value near to zero show a great estimate by the software (Ebrahimian et al., 2020).

## Irrigation performance indicators

In this study, four parameters were utilized to estimate performance of irrigation including Application Efficiency (*AE*), Runoff (RO), Distribution Uniformity (*DU*) and Deep percolation (*DP*) (Radmanesh et al., 2023):

$$AE = \frac{D_{req}}{D_{app}} \times 100 \tag{7}$$

$$RO = \frac{D_{ro}}{D_{app}} \times 100 \tag{8}$$

$$DP = \frac{D_{dp}}{D_{app}} \times 100 = (100\text{-AE-RO}) \tag{9}$$

$$DU = \frac{D_{min}}{D_{avg}} \times 100 \tag{10}$$

where $D_{req}$, $D_{app}$, $D_{ro}$, $D_{dp}$, $D_{min}$ and $D_{avg}$ are the depth of water included to the root zone (mm); depth of water applied to the furrow (mm); the depth of runoff (mm); depth of deep percolated water (mm); minimum depth of infiltrated water (mm) and average depth of infiltrated water over the furrow length (mm), respectively.

Irrigation method performance is generally surveyed utilizing the distribution uniformity index, whereas the irrigation management performance is evaluated with the application efficiency (Radmanesh et al., 2023).

## Results and Discussion

### Parameters of the infiltration equation

Table (2) presents the values of the Kostiakov-Lewis infiltration equation coefficients and the Manning's roughness coefficient for all irrigation methods at different times of the growing season. In irrigation events, the basic infiltration value in surge and alternate methods is higher than the conventional method. Also, by increasing the value of the parameter *k*, the value of the parameter *a* decreased. The greatest and least values of the parameter *a* did not differ significantly. The range of the parameters *a*, *k* and $f_0$ are 0.2309–0.4869, 0.001986–0.008943 $m^3.min^{-a}.m^{-1}$ and 0.002497–0.005767 $m^3.min^{-1}.m^{-1}$, respectively, showing that $k$ had greater changes than the other parameters. As reported by Fu et al. (2019), the Kostiakov-Lewis infiltration equation can precisely determine the cumulative infiltration under different conditions, however, it is difficult to calculate its coefficients due to changes within boundary conditions (Dialameh et al., 2017). In the current research, changes in the inflow discharge influenced the coefficients of the Kostiakov-Lewis infiltration equation and the infiltration rate increased by increasing inflow. The impact of inflow rate on infiltration was also reported by several researchers (Ebrahimian and Playán, 2014; Ebrahimian et al., 2020).

### Manning’s roughness coefficient

During the third, sixth, and ninth irrigation events, the mean values of n were observed to be 0.038, 0.024 and 0.029, respectively. Also the lowest and highest values of n were associated with the alternate and conventional irrigation methods, respectively. The inflow rate increased from 0.28 (the third irrigation) to 0.35 (the ninth irrigation) and 0.42 L/s (the sixth irrigation), the value of n decreased by 20% and 33.4%, respectively. Similar results were reported by Xu et al. (2019). According to the studies of Mailapali et al. (2008) and Kamali et al. (2018), the Manning's roughness coefficient in bare and vegetated furrows has an inverse relationship with inflow discharge. On the other side, the Manning equation (Eq. 3) demonstrates that there is an inverse relationship between the inflow rate and the Manning's roughness coefficient, which is consistent with the results of the present study. However, the effect of successive irrigation on the smoothness of the furrow soil surface is another reason of decreasing the value of the Manning $n$ during the growing season. The number of successive irrigations typically reduces the value of the Manning $n$.

### Parameterization of the model for irrigation events

The observed and estimated values of runoff, infiltration, and advance time are displayed in Table (3). Both software showed a high correlation between the measured and simulated values of runoff, infiltration and advance time, so that the coefficient of determination ($R^2$) in WinSRFR and SIRMOD software was obtained for runoff (0.9984 , 0.9976), infiltration (0.9908 , 0.9932) and advance time (0.9449, 0.9331), respectively, (Fig. 3,4 and 5). In WinSRFR and SIRMOD software, the RE values in estimating runoff, infiltration and advance time were (2.96, 3.15), (3.03, 3.30) and (2.09, 2.46), respectively, (Table 4). Previous studies (Gillies and Smith, 2015; Anwar et al., 2016; WU et al., 2017; Alejo et al., 2020) demonstrated that the WinSRFR and SIRMOD softwares could predict the advance time and runoff of furrow irrigation systems with acceptable precision, which is consistent with the results of this research. In our particular experiments, the software WinSRFR and SIRMOD overestimates the runoff (λ=1.0296 and 1.0315) and the advance time (λ=1.0209 and 1.0246), respectively. The WinSRFR software underestimates infiltration (λ=0.9697) but SIRMOD software overestimates infiltration (λ=1.0333). The value of λ close to 1 and RE close to zero indicate a good performance of the software. In both WinSRFR and SIRMOD software, The highest accuracy in estimating runoff belong to the AFI, SFI1-1, SFI1-2, FFI, and CFI irrigation methods, respectively, (Table 4), and the highest accuracies in infiltration estimation are related to the AFI, FFI, SFI1-1, SFI1-2 and CFI irrigation strategies, respectively (Table 4). Therefore, the best and poorest estimates of runoff and infiltration are related to the AFI and CFI irrigation methods, respectively. In both software, the highest accuracy in estimating advance time was obtained for SFI1-1, SFI1-2, CFI, FFI, and AFI irrigation methods, respectively (Table 4). Hence, SFI1-1 and AFI irrigation methods represent the best and weakest both model estimates for the advance time. Sayari et al. (2017), Alejo et al.(2020), Mehri et al.(2023) and Radmanesh et al. (2023) reported that winSRFR and SIRMOD software had good accuracy to Parameterization furrow irrigation systems.

Table 2- Coefficients of the Kostiakov-Lewis infiltration equation and Manning's roughness coefficient (n)

| Irrigation event | Irrigation method | K ($m^3.min^{-a}.m^{-1}$) | a (-) | $f_o$ ($m^3.min^{-1}.m^{-1}$) | n |
|---|---|---|---|---|---|
| 3 | CFI | 0.001986 | 0.3849 | 0.004875 | 0.040 |
| | SFI1-1 | 0.002136 | 0.3319 | 0.005152 | 0.039 |
| | SFI1-2 | 0.002160 | 0.3109 | 0.005010 | 0.038 |
| | FFI | 0.002264 | 0.2539 | 0.005272 | 0.037 |
| | AFI | 0.003128 | 0.2479 | 0.005460 | 0.036 |
| 6 | CFI | 0.007815 | 0.3329 | 0.002745 | 0.026 |
| | SFI1-1 | 0.008011 | 0.2969 | 0.003060 | 0.025 |
| | SFI1-2 | 0.008079 | 0.2928 | 0.002932 | 0.024 |
| | FFI | 0.007313 | 0.2559 | 0.005452 | 0.023 |
| | AFI | 0.008943 | 0.2309 | 0.005542 | 0.021 |
| 9 | CFI | 0.006593 | 0.4019 | 0.002497 | 0.032 |
| | SFI1-1 | 0.007842 | 0.3639 | 0.002797 | 0.031 |
| | SFI1-2 | 0.007815 | 0.3739 | 0.002610 | 0.030 |
| | FFI | 0.004344 | 0.4869 | 0.005542 | 0.028 |
| | AFI | 0.005131 | 0.4539 | 0.005767 | 0.026 |

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**Table 3- Measured and simulated values of runoff, infiltration and advance time for different furrow irrigation methods in WinSRFR and SIRMOD software**

| Irrigation method | Irrigation event | Measured runoff ($m^3$) | Measured infiltration ($m^3$) | Measured advance time (min) | WinSRFR Software |  |  | SIRMOD Software |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  | Simulated runoff ($m^3$) | Simulated infiltration ($m^3$) | Simulated advance time (min) | Simulated runoff ($m^3$) | Simulated infiltration ($m^3$) | Simulated advance time (min) |
| CFI | 3 | 1.30 | 2.74 | 53 | 1.37 | 2.58 | 55.2 | 1.42 | 2.91 | 55.4 |
|  | 6 | 5.37 | 3.68 | 43 | 5.67 | 3.62 | 43.9 | 5.67 | 3.86 | 44.0 |
|  | 9 | 3.36 | 3.01 | 49 | 3.55 | 2.72 | 49 | 3.58 | 3.21 | 49.1 |
| SFI1-1 | 3 | 1.17 | 2.88 | 52 | 1.18 | 2.75 | 52 | 1.21 | 2.94 | 52.1 |
|  | 6 | 5.20 | 3.84 | 41.5 | 5.26 | 3.62 | 41.9 | 5.22 | 4.12 | 41.9 |
|  | 9 | 3.00 | 3.37 | 47 | 3.03 | 3.28 | 46.5 | 3.11 | 3.48 | 46.8 |
| SFI1-2 | 3 | 1.24 | 2.81 | 53 | 1.27 | 2.67 | 52.5 | 1.26 | 2.92 | 52.8 |
|  | 6 | 5.29 | 3.75 | 42 | 5.42 | 3.58 | 42.4 | 5.35 | 3.95 | 42.6 |
|  | 9 | 3.09 | 3.28 | 48 | 3.17 | 3.13 | 48 | 3.17 | 3.45 | 48.1 |
| FFI | 3 | 1.14 | 2.92 | 55 | 1.19 | 2.84 | 56.1 | 1.18 | 2.93 | 56.1 |
|  | 6 | 3.62 | 5.42 | 45 | 3.78 | 5.35 | 47.7 | 3.85 | 5.56 | 47.9 |
|  | 9 | 1.90 | 4.47 | 51 | 1.98 | 4.35 | 52 | 1.99 | 4.59 | 52.3 |
| AFI | 3 | 0.93 | 3.15 | 57 | 0.93 | 3.24 | 59.8 | 0.95 | 3.18 | 58.4 |
|  | 6 | 3.39 | 5.63 | 47 | 3.38 | 5.52 | 47.9 | 3.41 | 5.75 | 49.6 |
|  | 9 | 1.63 | 4.74 | 52 | 1.63 | 4.62 | 55.6 | 1.66 | 4.79 | 56.4 |

**Table 4- Parameterization of WinSRFR and SIRMOD software for irrigation events in different irrigation methods**

| Irrigation method | WinSRFR Software |  |  |  |  |  | SIRMOD Software |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | Runoff |  | Infiltration |  | Advance time |  | Runoff |  | Infiltration |  | Advance time |  |
|  | λ | RE | λ | RE | λ | RE | λ | RE | λ | RE | λ | RE |
| CFI | 1.056 | 5.60 | 0.949 | 5.10 | 1.022 | 2.20 | 0.935 | 6.50 | 0.945 | 5.50 | 0.975 | 2.50 |
| SFI1-1 | 1.011 | 1.10 | 0.956 | 4.40 | 0.999 | 0.10 | 0.987 | 1.30 | 0.954 | 4.60 | 0.998 | 0.20 |
| SFI1-2 | 1.025 | 2.50 | 0.954 | 4.60 | 0.9986 | 0.14 | 0.985 | 1.50 | 0.952 | 4.80 | 0.997 | 0.30 |
| FFI | 1.044 | 4.40 | 0.980 | 2.00 | 1.0305 | 3.05 | 0.945 | 5.50 | 0.977 | 2.30 | 0.967 | 3.30 |
| AFI | 0.998 | 0.20 | 0.986 | 1.40 | 1.0477 | 4.77 | 0.991 | 0.90 | 0.984 | 1.60 | 0.949 | 5.10 |

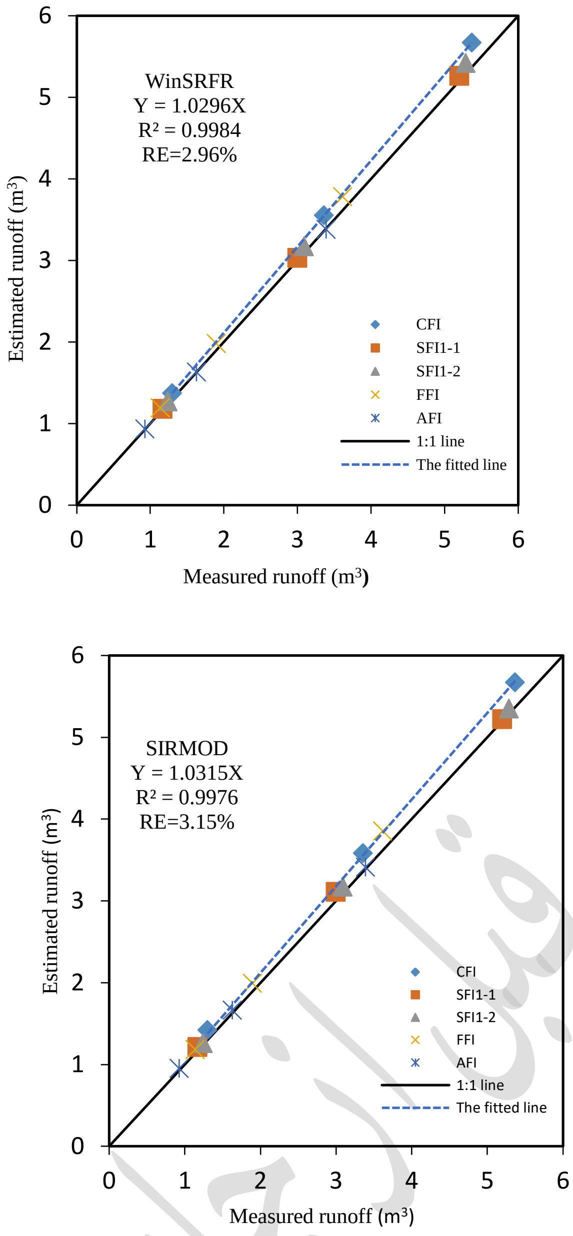

**Fig. 3- Comparison of actual and simulated runoff by WinSRFR and SIRMOD software in the study area**

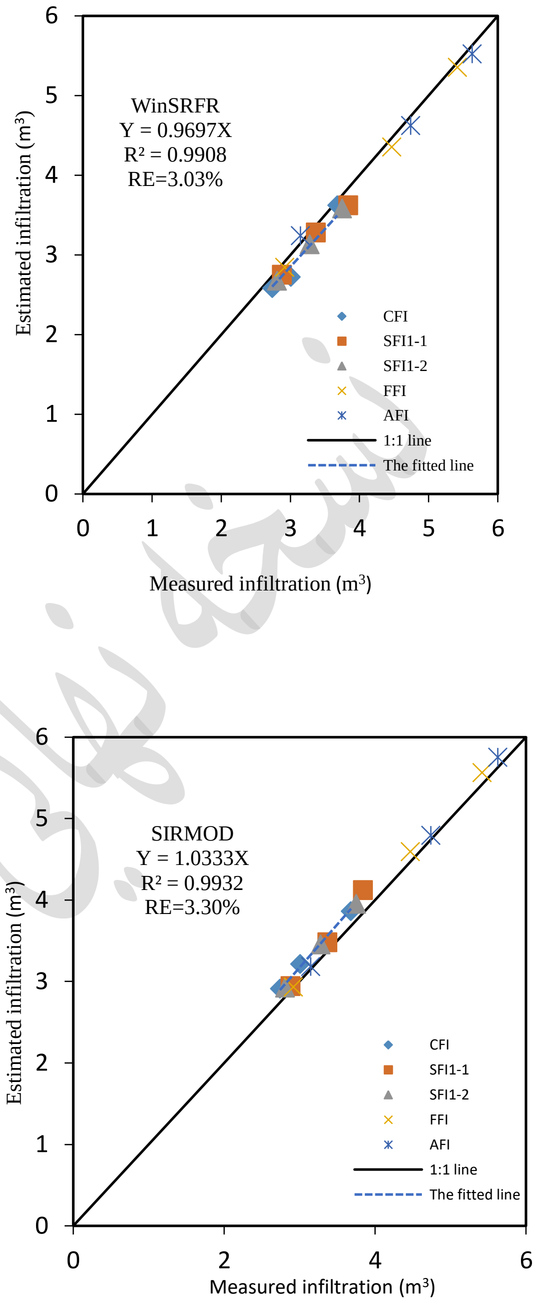

**Fig. 4- Comparison of actual and simulated infiltration by WinSRFR and SIRMOD software in the study area**

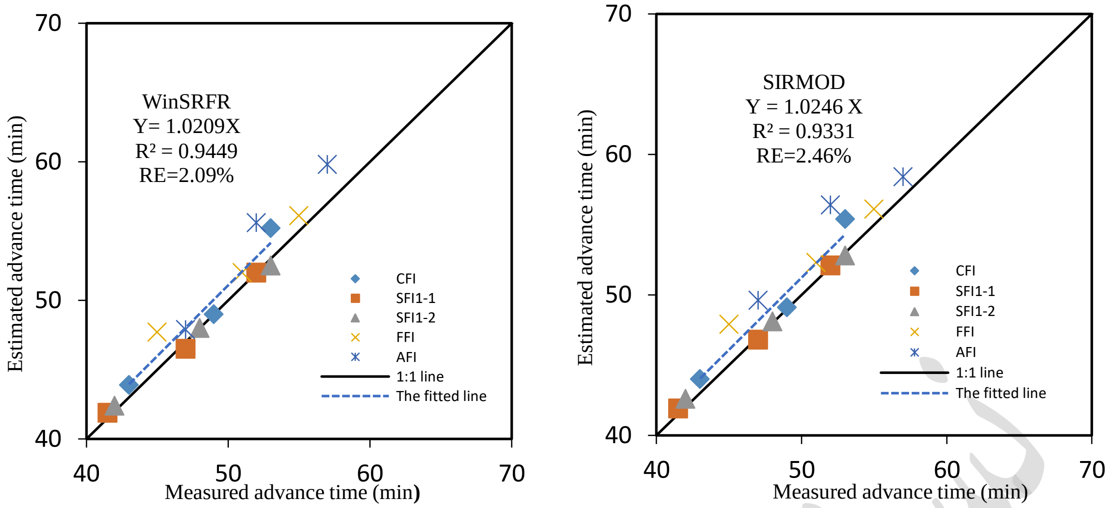

**Fig. 5- Comparison of actual and simulated advance time by WinSRFR and SIRMOD software in the study area**

**Furrow irrigation performance indicators**

The performance indicators of furrow irrigation in the conditions of field experiment and simulated with *WinSRFR* and *SIRMOD* softwares are displayed in table (5). The study examined the average performance indices of five furrow irrigation methods across three irrigation events (Table 6). The findings indicated that the AFI methods demonstrated the highest application efficiency (69.5%), the greatest reduction in runoff (28.7%), and uniform distribution (86.2%). Conversely, the CFI method exhibited the highest level of uniform distribution (94.5%) among the irrigation methods. Some studies (Kifle et al., 2017; Salahou et al., 2018) reported that increasing the flow cutoff time increased irrigation losses, particularly runoff. In this study for the third, ninth, and sixth assessment times different irrigation strategies, with increasing the inflow rate and cutoff times, descending trend in *AE and* Rising trends in *DU* was observed. The findings of this study indicate that the AFI (Alternate Furrow Irrigation) and CFI (Conventional Furrow Irrigation) methods had the best and worst performance, respectively. Based on the results, it is recommended to implement the AFI irrigation method in the study area. After the AFI irrigation method, the FFI, SFI1-1 and SFI1-2 irrigation methods, respectively, demonstrated better performance compared to the CFI irrigation method. The low application efficiency and high losses of irrigation (runoff and deep percolation) in the *CFI* strategy (49.5, 48.2 and 2.3%, respectively), indicate the weakness of surface irrigation management. Hence, implementing appropriate strategies such as determine the optimal amount and duration of irrigation, as well as providing training to farmers and irrigators, are essential measures for enhancing the level of agricultural efficiency. Radmanesh et al. (2023) shows that surge irrigation increased *AE* and decreased DP and RO compared to continuous irrigation which is consistent with the results of this research. Both software were very accurate in simulating furrow irrigation performance indicators (*AE*, *RO*, *DP* and *DU*) and the accuracy of *WinSRFR* software was better than *SIRMOD*, with the difference that *WinSRFR* software has more error in simulation deep percolation. Both software overestimated application efficiency and runoff but underestimated deep percolation and distribution uniformity. *SIRMOD* software overestimates deep percolation of *CFI* and *AFI* irrigation methods. Previous studies (Gillies and Smith, 2015; Anwar et al., 2016; Ahmadabad et al., 2020; Mehri et al., 2023; Radmanesh et al., 2023; Adamu et al., 2022) confirmed that both *SIRMOD* and *WinSRFR* are dependable analytical tools to evaluate furrow irrigation strategies for improving irrigation management.

**Table 5- Irrigation performance indices (%) measured in the field and simulated by SIRMOD and WinSRFR software for different furrow irrigation methods**

| | | Third irrigation | | | | | Sixth irrigation | | | | | Ninth irrigation | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | CFI | SFI1-1 | SFI1-2 | FFI | AFI | CFI | SFI1-1 | SFI1-2 | FFI | AFI | CFI | SFI1-1 | SFI1-2 | FFI | AFI |
| Field data | AE | 65.1 | 68.2 | 66.7 | 70 | 74.6 | 39.1 | 41.6 | 40.2 | 59.4 | 61.1 | 44.3 | 52.1 | 50.3 | 68.6 | 72.9 |
| | RO | 32.2 | 29 | 30.7 | 28.3 | 23 | 59.2 | 57.3 | 58.3 | 39.9 | 37.3 | 53.3 | 47.3 | 49 | 30.1 | 25.8 |
| | DP | 2.7 | 2.8 | 2.6 | 1.7 | 2.4 | 1.7 | 1.1 | 1.5 | 0.7 | 1.6 | 2.5 | 0.3 | 0.7 | 1.3 | 1.3 |
| | DU | 93.5 | 91.9 | 92.3 | 91.0 | 83.2 | 94.6 | 94.3 | 94.4 | 93.3 | 88.3 | 95.4 | 94.4 | 94.6 | 91.6 | 87.0 |
| WinSRFR | AE | 65.1 | 68.3 | 66.6 | 70.2 | 74.6 | 45.8 | 48.8 | 47 | 61.9 | 65.5 | 51.4 | 59.3 | 57.4 | 71.9 | 78.1 |
| | RO | 32.3 | 29 | 30.8 | 28.4 | 23.1 | 52.6 | 50.2 | 51.6 | 36.6 | 34 | 46.2 | 40.3 | 42.5 | 26.8 | 20.4 |
| | DP | 2.6 | 2.7 | 2.6 | 1.4 | 2.3 | 1.6 | 1 | 1.4 | 1.5 | 0.5 | 2.4 | 0.4 | 0.1 | 1.3 | 1.5 |
| | DU | 93.2 | 91.6 | 92 | 90.9 | 82.9 | 94.5 | 94 | 94.2 | 92.9 | 88.1 | 95.1 | 94.1 | 94.5 | 90.8 | 87 |
| SIRMOD | AE | 65 | 68.4 | 66.8 | 70.3 | 74.7 | 46.0 | 50 | 47.5 | 55.8 | 57.3 | 52.8 | 60.4 | 58.5 | 72.8 | 78.6 |
| | RO | 32.4 | 29.2 | 30.6 | 28.5 | 23.2 | 51.5 | 49.1 | 50.9 | 44.1 | 40.7 | 44.7 | 39.5 | 41.3 | 25.6 | 19.7 |
| | DP | 2.6 | 2.4 | 2.6 | 1.2 | 2.1 | 2.5 | 0.9 | 1.6 | 0.1 | 2 | 2.5 | 0.1 | 0.2 | 1.6 | 1.7 |
| | DU | 93 | 91.1 | 91.7 | 90.7 | 82 | 94.3 | 93.2 | 93.8 | 92.2 | 87.7 | 94.2 | 93.3 | 93.8 | 89 | 86 |

AE = Application Efficiency; RO = Runoff; DP = Deep Percolation; DU = Distribution Uniformity

**Table 6- Average irrigation performance indices (%) measured in the field and simulated by SIRMOD and WinSRFR Software for different furrow irrigation methods**

| | Field data | | | | | WinSRFR | | | | | SIRMOD | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CFI | SFI1-1 | SFI1-2 | FFI | AFI | CFI | SFI1-1 | SFI1-2 | FFI | AFI | CFI | SFI1-1 | SFI1-2 | FFI | AFI |
| AE | 49.5 | 53.9 | 52.4 | 66 | 69.5 | 54.1 | 58.8 | 57 | 68 | 72.7 | 54.6 | 59.6 | 57.6 | 66.3 | 70.2 |
| RO | 48.2 | 44.5 | 46 | 32.7 | 28.7 | 43.7 | 39.8 | 41.6 | 30.6 | 25.8 | 42.9 | 39.3 | 40.9 | 32.7 | 27.8 |
| DP | 2.3 | 1.5 | 1.6 | 1.3 | 1.7 | 2.2 | 1.4 | 1.3 | 1.3 | 1.4 | 2.5 | 1.1 | 1.4 | 0.9 | 1.9 |
| DU | 94.5 | 93.6 | 93.7 | 92 | 86.2 | 94.3 | 93.2 | 93.5 | 91.5 | 86 | 93.8 | 92.5 | 93.1 | 90.6 | 85.2 |

AE = Application Efficiency; RO = Runoff; DP = Deep Percolation; DU = Distribution Uniformity

### Comparison of SIRMOD and WinSRFR software

WinSRFR and SIRMOD software both had excellent accuracies in parameterization the field observations such as runoff volume, infiltrated water volume, advance time (Tables 3, 4; Fig 3, 4 and 5). SIRMOD and WinSRFR softwares had high accuracies in simulating continuous and surge irrigation performance indicators, and the accuracy of *WinSRFR* software was better than *SIRMOD*, with the difference that *WinSRFR* software had more error in simulation deep percolation (Tables 5 and 6). In our particular experiments, both software overestimates application efficiency and runoff but it underestimates deep percolation and distribution uniformity (Table 6). SIRMOD software has been used extensively in different part of the world due to its longer history in surface irrigation simulation, while the WinSRFR has been more popular in the USA because of being user-friendly as well as extensive and flexible modeling. Furthermore, WinSRFR software can analyze, simulate, design, and optimize the irrigation systems, which highlights the higher ability and flexibility of WinSRFR compared to SIRMOD in irrigation assessments (Akbar et al., 2016; Radmanesh et al., 2023). However, comparing the SIRMOD and WinSRFR in simulating the irrigation performance indices (Tables 5 and 6) revealed that WinSRFR resulted in more consistent simulations under combinations of stream size and furrow length for either of the continuous or surge irrigation. The SIRMOD software, last updated in 2005 (Walker, 2005), has not received any subsequent updates, rendering it unlikely to enhance the performance of surge irrigation simulation. Conversely, the WinSRFR software is regularly updated (Bautista and Schlegel, 2019). Consequently, WinSRFR is a more dependable and assured tool for the planning, design, and evaluation of various furrow irrigation methods.

## Conclusion

In various furrow irrigation methods, the *WinSRFR* and *SIRMOD* software were used to accurately predict runoff, infiltration, and advance time. The *RE* values for estimating runoff, infiltration, and advance time were within acceptable ranges for both software. Specifically, the *RE* values for *WinSRFR* were 2.96%, 3.03%, and 2.09% for runoff, infiltration, and advance time, respectively, while the *RE* values for *SIRMOD* were 3.15%, 3.30%, and 2.46% for the same parameters. The performance of *WinSRFR* and *SIRMOD* varied depending on the irrigation method. In both WinSRFR and SIRMOD software, the best and poorest estimates of runoff and infiltration are related to the AFI and CFI irrigation methods, respectively. Also the highest and poorest accuracy in estimating advance time was obtained for SFI1-1 and AFI irrigation methods, respectively. In the simulation of furrow irrigation performance indicators (*AE*, *RO*, *DP*, and *DU*), *WinSRFR* demonstrated superior accuracy compared to *SIRMOD*. However, *WinSRFR* had more error in simulating deep percolation. Both software overestimated application efficiency and runoff, but underestimated deep percolation and distribution uniformity. *SIRMOD* specifically overestimated deep percolation for the *CFI* and *AFI* irrigation methods. Overall, *WinSRFR* outperformed *SIRMOD* in simulating application efficiency and distribution uniformity. This can be attributed to the advanced infiltration equations and consistent updates made by the model developer. Additionally, *WinSRFR* allows for a wider range of input information and provides better facilities for entering the geometric characteristics of the furrow. A comprehensive comparison of different methods of furrow irrigation in one place and the combination and extent of field experiments led to the use of only two software WinSRFR and SIRMOD (due to the high accuracy in simulating performance indicators of furrow irrigation). Future studies should focus on the development and comparison of different surface irrigation simulation software. Furthermore, it is recommended to test surface irrigation models in various soil types to improve application efficiency and reduce water losses in agricultural fields.

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