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IMPROVING IRRIGATION PERFORMANCE OF RAISED BED WHEAT USING THE WINSRFR MODEL UNDER EGYPTIAN CONDITIONS

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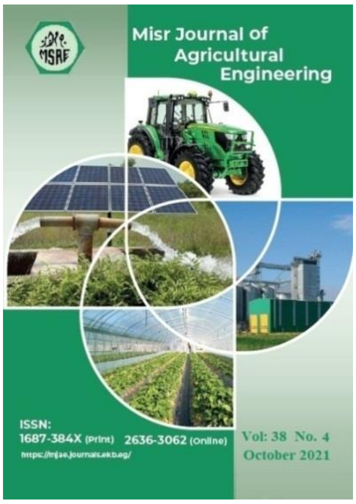


ABSTRACT

Field experiments were carried out at the Sakha Agricultural Research Station in the governorate of Kafr el Sheikh, Egypt to evaluate and optimize the irrigation performance of raised beds wheat using the WinSRFR model during 2019/2020. Raised beds (RB130 cm, and RB100 cm) were prepared using Raised bed planter. The model calibration was based on a close match between the observed and simulated curves of advance and recession time. Simulation Analysis World was used to evaluate the current irrigation performance of the raised bed furrows (RB) and the flat basin (FB) methods. The simulation analysis shows that for RB130 cm, RB100 cm, and FB irrigation systems, the application efficiencies were 80, 64, 43%, and distribution uniformities were 86, 88, 90%, and deep percolation losses were 20, 36, 56%, and adequacy were 1.07, 1.37, 2.08%, respectively. Physical Design World was used to optimize and develop different design strategies. The results showed that irrigation performance decreased with the increasing length of furrow and basin, so extremely long lengths should be avoided because they result in decreased efficiency and uniformity, as well as big deep percolation loss. Managing the inflow rate and irrigation cut-off through Operation Analysis World can increase application efficiency and reduce deep percolation losses by more than 15%, 60%, and 17%, 33%, and 23%, 17.5% respectively, for RB130 cm, RB100 cm, and FB.

Keywords:
Raised bed; Irrigation performance; Optimizing, WinSRFR

1. INTRODUCTION

Water supplies in Egypt are limited due to current intensive agricultural production and are limiting crop production in the newly reclaimed lands. Agriculture in Egypt depends heavily on irrigation (El-Halim, 2013). As a result, Egypt has suffered from severe water scarcity in recent years, while the Nile River is the main source of freshwater, and Egypt's agricultural sector is also considered to be one of the highest water consuming sectors (Khalifa et al., 2019).

The agricultural sector absorbs more than 84% of the water resources available (El-Beltagy et al., 2008). Surface irrigation is the main irrigation method in ancient, cultivated lands with a total area of 6.5 million feddan (2.73 million ha). In this method of irrigation, water use constitutes 61% of the total water supply despite its very low water efficiency in the field. Improving this system will save large quantities of irrigation water, which will be used to extend horizontally (ICARDA, 2020).

The raised bed system is an enhanced surface irrigation technique that increases water productivity and allows water usage to more effective in irrigated systems. It could be carried out efficiently by farmers themselves. Irrigation water is added to the base of the furrows in this system. Less water is required for irrigation, because furrows collect water effectively, instead of spreading it over the entire surface (like border irrigation). Beds can differ in width from 0.25 to 2.00 meters as well as the number of rows of crops per bed. Often the width of the bed is defined by the width of the machine used, either the width of the tractor axle corresponding to the furrow width or multiples of the furrow width (Roth et al., 2005). This technology was spread in 22 governorates, as part of a national initiative by the Egyptian Government on self-sufficiency in wheat production, for sustainable agricultural intensification on a large scale (Ismail S., 1993) and (Swelam, 2017).

Irrigation management requires the distribution of water to all areas of the irrigated field. That is an engineering challenge and it can be efficiently achieved by minimizing losses and maximizing uniformity by optimizing inflow rate, application depth, time to cut-off and field design (Akbar, 2017). The prediction of the behaviour of surface irrigation is complicated due to several analytical problems (N. Pascual-Seva et al., 2013). However, nowadays, it is technically possible to draw up and make operational suggestions based on simulations (Strelkoff, T. S., & Clemmens, A. J., 2007).

The development of IT facilities has led to the creation of several simulation models and optimization of surface irrigation plans. These models are both valuable tools at the design and management phases of surface systems. Simulation models used for irrigation design purposes help to optimize surface irrigation variables, such as field length, field slope and define flow rate. In other words, the models can help the designer to make decisions about the appropriate values of the variables that give the best performance.

One of the most widely used models WinSRFR, one of the modern surface irrigation hydraulic simulation models. It was developed by the USDA Agricultural Research Service. It involves the integration of the SRFR surface irrigation (border, basin, and furrow) program, level basin design program BASIN (Clemmens et al . 1995) and sloping border-strip program BORDER (Strelkoff et al. 1996). This latest software also contains extra functionality and is based on the Windows environment. WinSRFR uses simplified forms of momentum equations (i.e. zero-inertia or kinematic-wave models). This modelling technique was established by the USDA-ALARC (2009) to be sufficiently effective when used under the proper conditions, and also computationally faster.

Thus, the objective of this study was to evaluate the current raised bed irrigation system and using WinSRFR model to identify scenarios for improving irrigation performance.

2. MATERIALS AND METHODS

Site Description

Field experiments were carried out at the Sakha Agricultural Research Station in Egypt's Kafr el-sheik Governorate to evaluate and optimize the irrigation performance of raised bed (RB) and traditional flat basin (FB) using the WinSRFR model during 2019/2020.

The site is located at 30° 57' E longitude and 31° 07' N latitude, with an elevation of approximately 6 meters above mean sea level. According to Klute (1987), the particle size distribution and some soil water constants are presented in Table (1).

Table (1): Some physical characteristics and some soil water constants of the studied site before cultivation

Soil Depth, cm.	**Particle Size Distribution**			**Texture classes**	**F.C %**	**P.W.P %**	**AW %**	**Bd g cm^{-3}**
	Sand%	Silt %	Clay %					
0 – 15	16.6	19.4	64.0	Clay	47.3	25.0	22.3	1.16
15 – 30	19.2	17.9	62.9	Clay	39.9	21.5	18.4	1.19
30 – 45	17.6	19.8	62.6	Clay	38.1	21.1	17.0	1.23
45 – 60	18.8	19.6	61.6	Clay	37.4	20.3	17.1	1.31
Mean	18.1	18.8	62.8	Clay	40.7	22.0	18.7	1.22

Where: F.C % = Soil field capacity, P.W.P % = Permanent wilting point, AW % = Available water and Bd (g cm^{-3}) = Soil bulk density

Preparation of Land and Sowing of Crop

The land at the experimental site was prepared by deep plowing followed by laser land levelling. Raised beds (RB) were prepared using a raised bed shaper with planter which was a research support from ICARDA project, figures (1 and 2). Two RB furrow spacing 130 cm (RB130) and 100 cm (RB100) as well as the traditional flat basin (FB) methods were tested and evaluated.

Figure 1: The Raised bed planter machine that had been used in this experiment to prepare soil for raised beds planting (from ICARDA project)

Figure 2: Prepared soil for raised-bed planting

Experimental Design

The experimental site consisted of three borders divided into three different treatment groups, with three replicates for each treatment. The irrigation performance was evaluated for two-bed treatments: (i) RB130 cm and (ii) RB100 cm, in addition to FB. Each RB130 cm replicate comprised of six furrows and five beds and each RB100 cm replicate had six furrows and seven beds. The field lengths were 72 m per treatment and all raised bed furrows had a slope of ~0.0001 m/m but for the flat basin, the slope was ~0.0002 m/m. The detailed layout of the experimental field is shown in Fig (3).

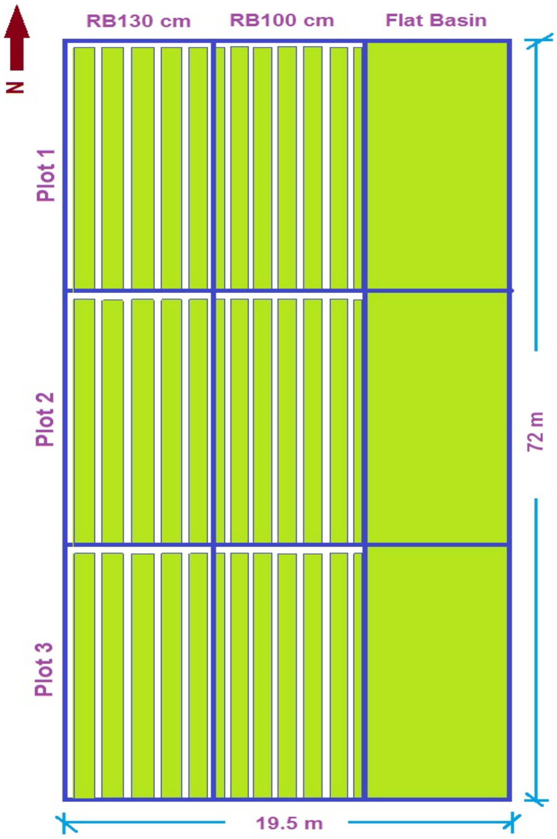


Figure 3: Layout of experimental site

Control Unit

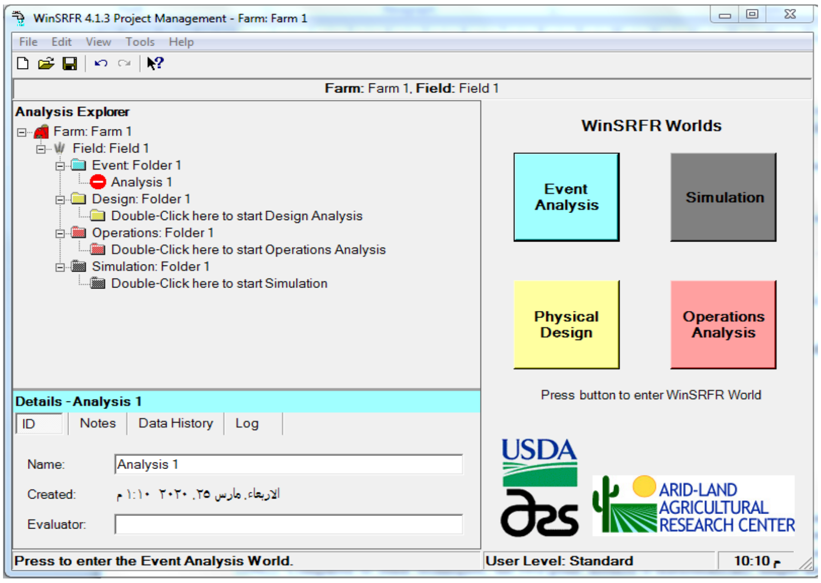
- The pump 6.5 hp with a gasoline engine and 900 L/min inflow rate at 3600 rpm under 26 m water head and 75 mm inside diameter of water outlet.
- Based on the data of physical soil analysis that is given in Table (1), the required depth value was calculated according to the following equation:

$$Dreq = (\theta_{fc} - \theta_{pwp}) \times D \times \rho_b \times dep$$

$$\text{Dreq} = (40.7\% - 22\%) \times 0.60 \times 1.22 \times 0.50 = 0.06844 \text{ m} = 68.44 \text{ mm}$$

Simulation Modeling of Surface Irrigation Systems

Surface irrigation systems were analyzed using the WinSRFR 4.1.3 (Bautista et al., 2012). The WinSRFR integrates tools for irrigation system estimation, operational analysis, and irrigation system design as shown in Fig (4). Field irrigation data and system descriptions were put into the model through the *Event Analysis World* tool to estimate the soil infiltration functions i.e. *a*, and *k* parameters. The calibrated infiltration parameters have been used to optimize and develop various design strategies using the *Design World* of the model. In the optimization stage using *Operation Analysis World*, the model was configured to develop performance contours as a function of inflow rate and cutoff time for the known (furrow set/border) width. Required depth (Dreq) is another important input parameter for surface irrigation simulation. Dreq can be defined as the average depth (mm) required filling the root zone. The maximum required depth can be calculated from the total soil moisture holding capacity, i.e. the total moisture available between field capacity and wilting point (TAM) as well as the allowable depletion fraction thereof, termed the readily available moisture content (RAM) as discussed by Jurriëns et al., (2001). Figure (5) shows the methodological flow chart of the study.



Name: Analysis 1

Created: الاربعاء, مارس ٢٥, ٢٠٢٠ ١:١٠ م

Evaluator:

Press to enter the Event Analysis World.

Figure 4: WinSRFR management windows

Measurements

System Geometry data

Furrow dimensions including furrow spacing (FS); top width (TW); middle width (MW); bottom width (BW), and furrow depth (D), were measured for all furrows at the field head, middle, and tail segments. The average dimensions of all furrows was determined to obtain the overall averages of furrow structure parameters before irrigation for RB130 cm and RB100 cm as shown in Fig (6).

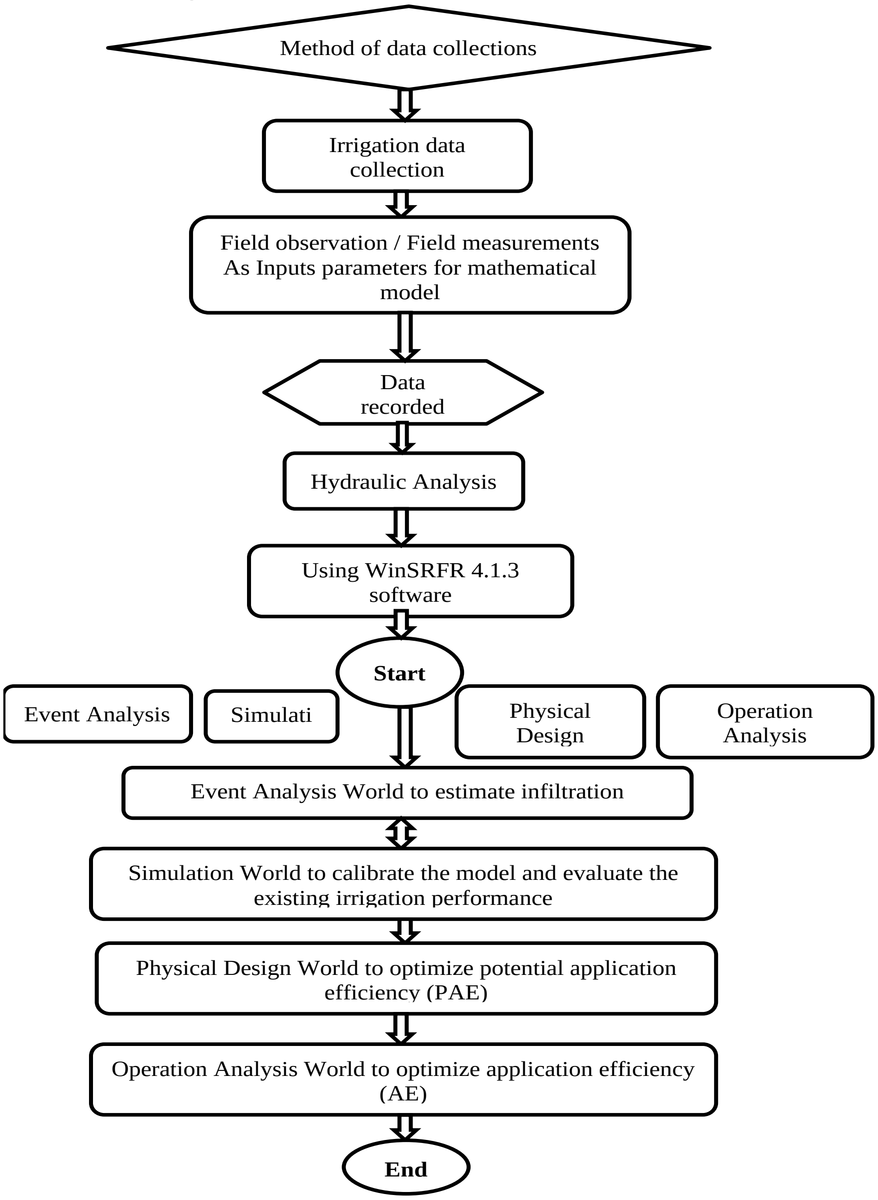


Figure 5: Methodological flow chart of the study

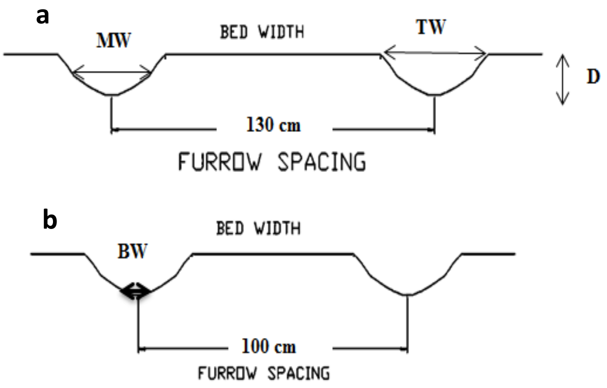


Figure 6: Raised bed furrow dimensions (TW: top width, MW: middle width, BW: bottom width, FS: furrow spacing and D: furrow depth); (a) RB130 cm and (b) RB100 cm

✚ Water flow (Q)and cutoff time (T_{CO})

The flow of water (Q) was continuously determined by a flow meter (ISCO 2150 area velocity flow module; Teledyne ISCO Inc., Lincoln, NE, USA) installed on a small pump located at the water entrance to the experimental plots, irrigation water discharge was calculated based on pre-and post-irrigation flow meter readings, dividing by time to cut-off as the following equation:

$$\boldsymbol{Q} = \frac{\mathbf{v2 - v1}}{\mathbf{Tco}}$$

Where:

Q= discharge with m^3/ h

V1= reading the flow meter before irrigation, m^3

V2= reading the flow meter after irrigation ended, m^3

Tco= irrigation water cut off time, hours.

The inflow rate was assumed to be uniformly distributed over the different simultaneously irrigated furrows, so for the raised bed irrigation system, q was measured as the average Q divided by the total number of irrigated furrows.

✚ Water Advance Rate

The advance of water observed during the irrigation event by recording the arrival time of the water at the fixed stations constructed along with the experimental plot of the raised beds and the flat basin. According to field observations, irrigation inflow to the field was cut-off after the water advance reached the tail end of furrow irrigation fields to ensure wetting of the bed middle.

✚ Advance & Recession

The objective of measuring advance and recession times was to find the manning roughness coefficient (*n*) values and infiltration parameters that minimized the difference between observed and simulated advance and recession times that were used to test irrigation efficiency (Bautista et al., 2009). For all experimental irrigation treatments of raised bed (RB100 and RB130) and flat basin (FB) systems, the advance and recession times were measured at fixed stations (6 m, 12 m, 18 m, and 24 m) constructed along the monitored plots. The infiltration opportunity time along the furrow length at each station was calculated for each furrow as the time difference between the water disappears and the first beginning to advance along the furrow at the same position.

✚ Infiltration

This study focused on only the two methods. The first method is to observe the advance rate and use WinSRFR *Event Analysis World* to calculate infiltration *a* & *k* with the two-point method. This method will provide accurate estimates of infiltration function when the rate of soil infiltration is high and the storage phase is very short in comparison to the advance time (Peter Waller, 2015) (this means that the volume of surface storage is very small compared to the volume of infiltration (Bautista et al., 2012)). And the other method is a double-ring infiltrometer to estimate the basic infiltration rate of the soil.

1. Two-point method

Elliot and Walker (1982) developed a method for determining the constants of the infiltration equation of Kostiakov, based on the relationship between the advances and the advance time of the waterfront in the furrow. The general equations used to calculate the constants are as follows:

$$a = \frac{\ln\left(\frac{V_L}{V_{0.5L}}\right)}{\ln\left(\frac{t_L}{t_{0.5L}}\right)} \qquad K = \frac{V_L}{T_L^a \sigma_z}$$

$$\sigma_z = \frac{a + r(1-a) + 1}{(1+a)(1+r)} \qquad f_o = \frac{Q_{in} - Q_{out}}{L}$$

Where:

σ_z = the subsurface shape factor
L= furrow length (m)
t_L, $t_{0.5L}$= advance time at distance of L and L/2 (min)
Q_{in} and Q_{out} = in and out flow discharge (m^3/min)
r = power of advance trajectory in relationship to time
X = pt^r where X is the distance from the inlet, p and *r*, are constants

For the two-point advance method, fixed signs were positioned as a station to determine the advance time of the water during the irrigation event. Two points, the first at the mid-distance point and another at the downstream end of the furrow, are registered during irrigation water advance and were used to calculate infiltration parameters in the WinSRFR 4.1.3 software. The same previous steps were taken to measure advance time in the flat basin system.

2. Double-ring infiltrometer

The soil basic infiltration rate was measured in the field by using a double-ring infiltrometer. The depth of the water at the start time was quickly recorded along with the elapsed time using a stopwatch and ruler. The depth of water infiltrated into the soil was determined using an elapsed time interval until the infiltration rate reached a constant value. It's important to note that the experiment lasted about 7 hours. In this experiment, the elapsed time interval at the initial and final depth of infiltration was measured with 2-30 min intervals until the steady infiltration depth was obtained. As a result, the infiltration rate and cumulative infiltration were estimated as the two basic parameters.

✚ Manning’s roughness coefficient, n (s m$^{-1/3}$)

Manning's roughness coefficient is the most essential factor for the design and assessment of surface irrigation (Harun-ur-Rashid, 1990). Abbasi (2013), noted that Manning's roughness coefficient is generally considered to be between 0.02 and 0.04 for furrows and changes with time and position (Mazarei et al., 2021). In this study, Manning’s roughness coefficient was based on the recommended values of the NRCS (USDA-SCS, 1991) and this coefficient was great-tuned in the light of the roughness of the furrow bed and the presence of planting (Pascual-Seva et al., 2013). Simulations with WinSRFR 4.1.3 were performed to define n values that reduced the difference between simulated and observed advance and recession times used to evaluate irrigation performance of the raised bed and flat basin system (Bautista, et al., 2009).

Irrigation efficiencies

The following irrigation efficiencies were estimated using simulation modeling as described by Bautista et al., (2012):

1. Application Efficiency (AE):

   It is the ratio of the infiltrated depth that corresponds to the irrigation target (D_z) to the actual irrigation depth added (D_{app}) or the water obtained at the field inlet. When D_z equals the low quarter infiltration depth (D_{lq}), the application efficiency is referred to as the low quarter application efficiency (AE_{lq}), and when Dz equals the minimum infiltration depth (D_{min}), the application efficiency is referred to as the minimum application efficiency (AE_{min}).
2. Potential Application Efficiency (PAE):
   Attainable AE when the inflow rate and time to cut-off are such that Dlq = Dreq (required irrigation depth) is referred to as the low-quarter potential application efficiency (PAElq), and when Dmin = Dreq is referred to as the minimum potential application efficiency (PAEmin).
3. Adequacy (AD):
   Is the D_{min} to D_{req} to Adequacy ratio based on minimum infiltration depth (Ad_{min}) and the D_{lq} to D_{req} ratio based on the low quarter (AD_{lq}).
4. Distribution Uniformity (DU):
   It is the ratio of D_{min} to D_{inf} (the average depth of the water infiltrated) for DU_{min}, and the ratio of D_{lq} to D_{inf} for DUlq. Uniformity refers to the homogeneity of the infiltrated water throughout the field and depends on the design and maintenance of the system.

Calibration and Validation of WinSRFR

Model calibration for irrigation event was obtained by modifying infiltration parameters and current design characteristics using the *Event Analysis World* and Elliott-Walker (1982) method in the WinSRFR model (Bautista et al., 2019). Modifying infiltration parameters and existing design characteristics can be accomplished by a trial-and-error approach used to estimate infiltration parameters (Bautista et al., 2019). These parameters and the Manning coefficient were used in the *simulation analysis world* of the WinSRFR model to obtain simulated advance and recession curves, which were compared to the measured curves and if the fit was weak, new combinations of *n*, *a*, and *k* were validated over an approximate range, and this method was repeated until the best-fit match was achieved between the simulated and measured curves (Mazarei et al., 2021). Once the model is successful, WinSRFR has been used for simulating the hydraulic performance of furrows (Biru Dechasa Sima, 2018). Via this study, the results of the software package were compared to the data observed and validated by the WinSRFR model for use in the conditions of field soil.

3. RESULTS AND DISCUSSION

Cumulative infiltration depth and infiltration rate:

Based on the Double-ring infiltrometer results, the basic infiltration rate was 4.02 mm/hr, indicating that the structural assessment of soil structure quality is extremely poor according to Geeves et al. (1990). Figure (7) illustrates the cumulative infiltration and infiltration rate curves, as well as the basic infiltration rate, for the experiment site.

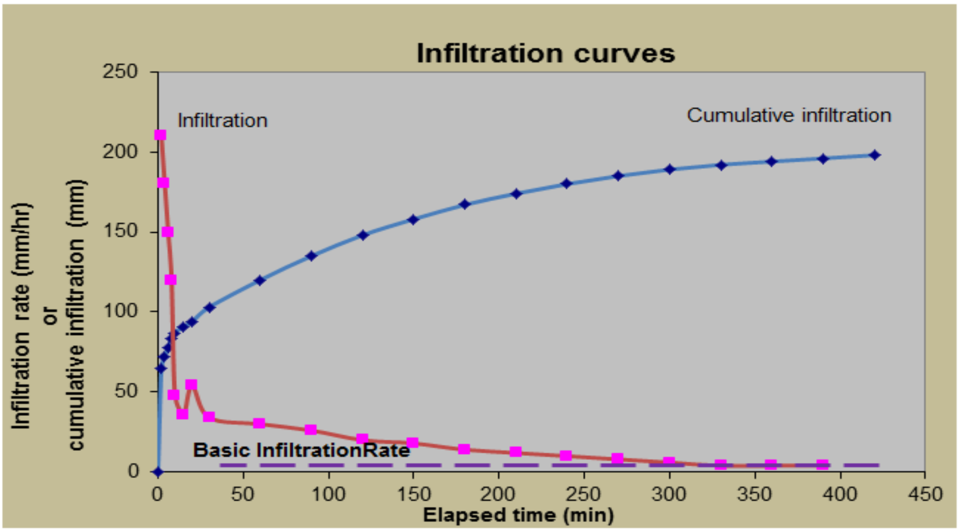


Figure 7: Curves of cumulative infiltration depth and infiltration rate

Observed Advanced and Recession Curve

Figures (8 and 9) illustrate the observed advance and recession curves for RB130 cm and RB100 cm during 1st irrigation respectively. The inflow rate and cutoff time for RB130 cm furrow treatment were 2 l/sec and 22.2 min, and for RB100 cm were 2 l/sec and 21.6 min, respectively. Figure (10) shows the advance and recession curves of the waterfront during the first irrigation for the FB. The inflow rate and cutoff time were 9.67 l/sec and 42.6 min, respectively.

It is noticeable from Figures (8, 9, and 10) the recession wave began to appear from the end of the furrow or basin due to cutting off the irrigation as soon as the water wave reached the end of the furrow or basin (storage period was very small), thus the time of the water wave remaining above the surface of the earth was short compared to at the head of the furrow or basin, and also due to the weak slope of the ground.

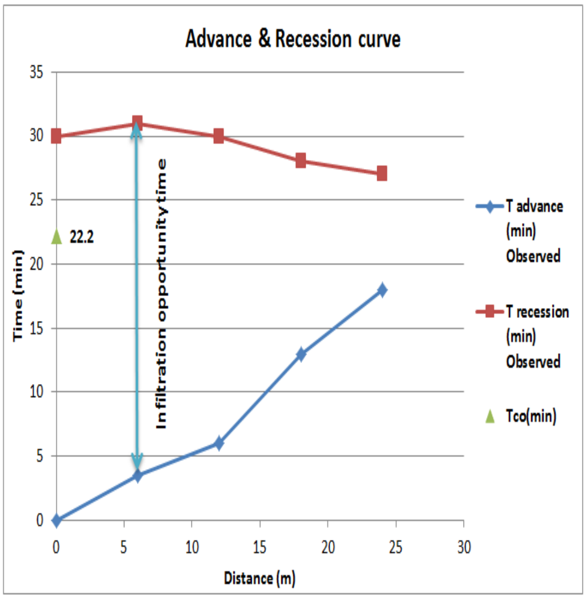


Figure 8: Observed advance and recession curves for RB 130 cm during 1st irrigation

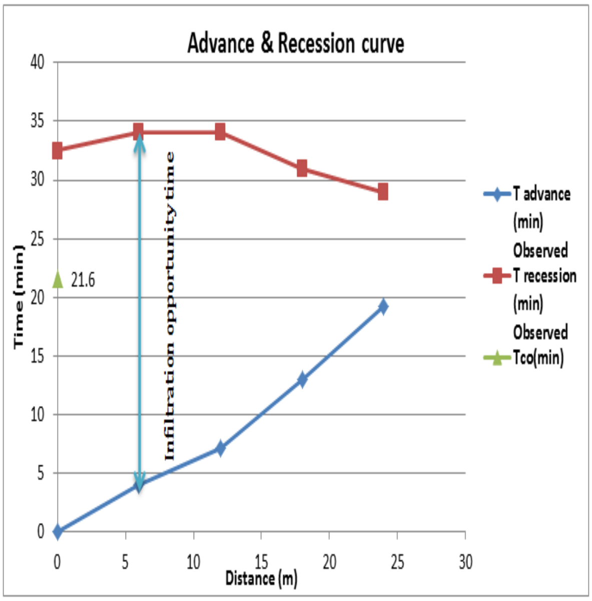


Figure 9: Observed advance and recession curves for RB 100 cm during 1st irrigation

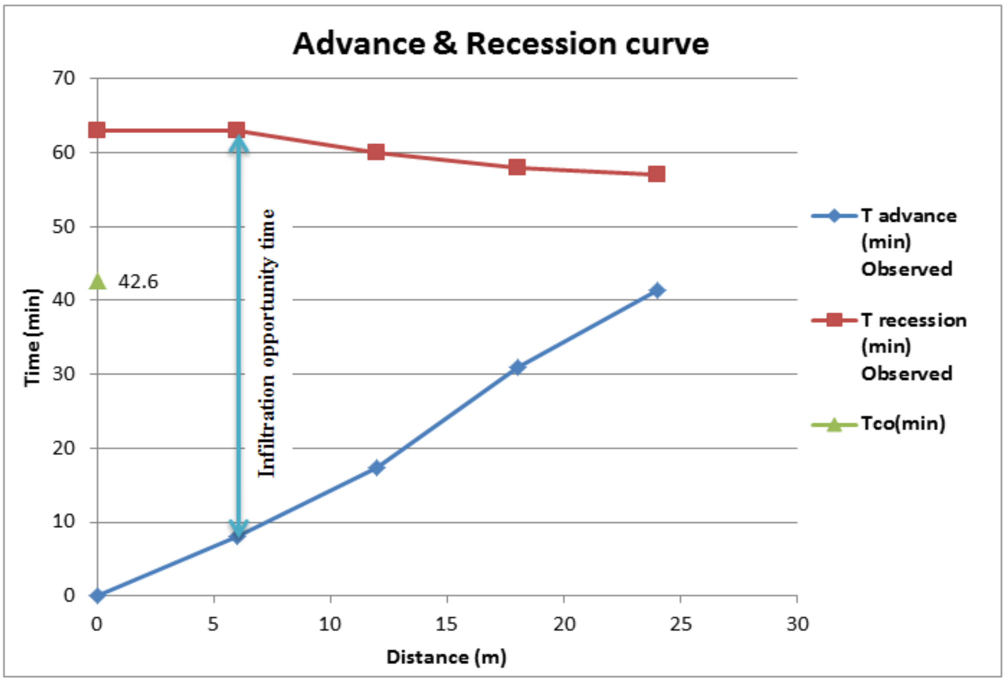


Figure 10: Observed advance and recession curves for flat basin (FB) during 1st irrigation

Estimate Infiltration Parameters Using WinSRFR

Based on field data, *Event Analysis World* (using Elliott and Walker's two-point method analysis) was used to determine the infiltration parameters for irrigation systems. The soil infiltration functions i.e. *a*, and *k* parameters of the Kostiakov equation were computed for raised beds and flat basin irrigation systems.

Event Analysis procedure for RB130 cm, RB100 and FB

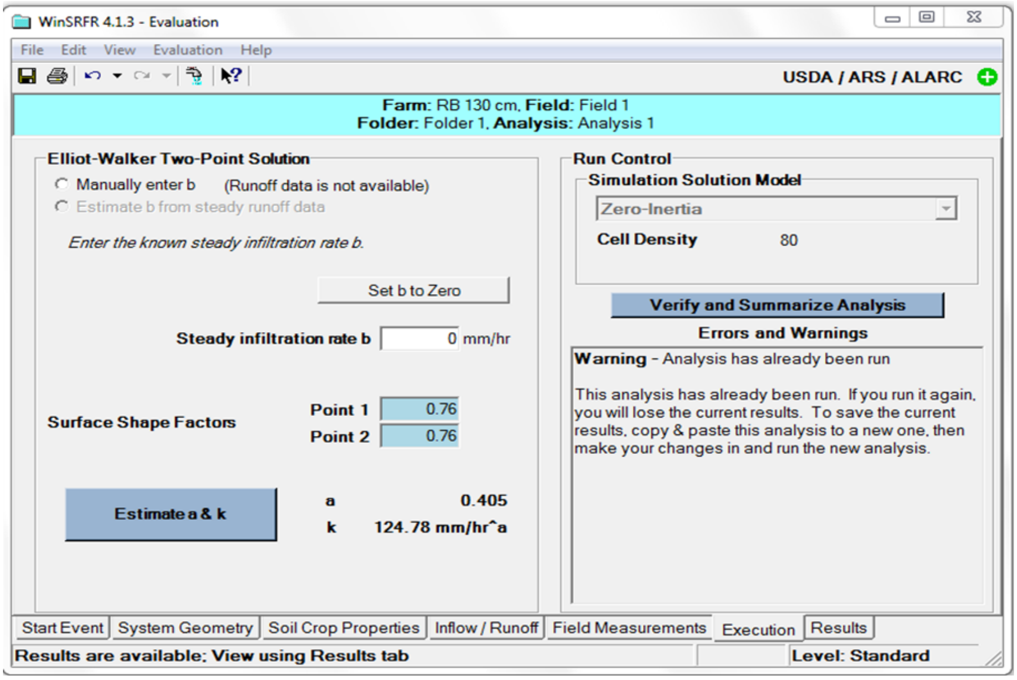
Data in Table (2) is entered into *Event Analysis World* to obtain infiltration parameters. For example, the following paragraph shows how to obtain the infiltration parameters for RB130 cm:

RB Furrow Irrigation Event Analysis: In the event analysis world furrow was selected, required depth (69 mm) was entered while Elliott and Walker's two-point method analysis was selected. In the system geometry field length L (24 m), furrow spacing F.S (1.3m), number of furrows per set (1). In the cross-section, part trapezoid from field data was selected and the edit data button was clicked to enter the top width (487mm), middle width (280 mm), bottom width (140 mm), maximum depth (133 mm), then save data & close was clicked and field slope S_0 (0,0001m/m) was entered. The roughness method based on Manning's *n* (0.04) was selected. In the inflow/runoff tab inflow rate Q (2 l/s), cut-off time (0.37 hr) with no cut-back and blocked end was selected. In the field measurement tab, the two-point advance method that involves distance and time at point one was 12 m, 0.1 hr, respectively, distance and time at point two was 24 m, 0.3 hr. In the execution tab after clicking on estimate *a* & *k* tab, WinSRFR will calculate Kostiakov parameters (*a*= 0.405 and *k*= 124.78 mm/hra) as shown in Figure (11).

For RB100 cm and FB, the Kostiakov parameters as the event analysis procedures output were *a*= 0.309 and *k*= 147.401 mm/hr^a, and *a*= 0.208 and *k*= 171.759 mm/hr^a, respectively.

Table 2: Field data for RB130 cm, RB100 and FB as inputs to the event analysis procedure

Variable	Value for RB130 cm	Value for RB100 cm	Value for FB
System type	Furrow	Furrow	Basin
Length , m	24	24	24
width , m	-	-	6.5
Maximum Depth, mm	-	-	300
Spacing , F.S , m	1.30	1.00	-
Number per set	1	1	-
Top width , mm	487	487	-
Middle Width , mm	280	280	-
Bottom width , mm	140	140	-
Max depth , mm	133	133	-
Manning's n	0.04	0.04	0.04
Slope , m/m	0.0001	0.0001	0.0002
Q , L/s	2	2	9.7
T_{co}, hr	0.37	0.36	0.71
Point 1 , m	12	12	12
Point 2 , m	24	24	24
Time at point 1 , hr	0.10	0.12	0.29
Time at point 2 , hr	0.30	0.32	0.69
Downstream condition	blocked	blocked	Blocked



Farm: RB 130 cm, **Field:** Field 1
Folder: Folder 1, **Analysis:** Analysis 1

○ Manually enter b (Runoff data is not available)
○ Estimate b from steady runoff data

Enter the known steady infiltration rate b.

Steady infiltration rate b 0 mm/hr

Surface Shape Factors **Point 1** 0.76 **Point 2** 0.76

a 0.405
k 124.78 mm/hr^a

Zero-Inertia
Cell Density 80

Warning - Analysis has already been run

This analysis has already been run. If you run it again, you will lose the current results. To save the current results, copy & paste this analysis to a new one, then make your changes in and run the new analysis.

Results are available: View using Results tab
Level: Standard

Figure 11: Screenshot of the execution window for the RB 130 cm

Variation of Infiltration Characteristics

The Event Analysis world (Kostiakov parameters) results for RB130 cm, RB100 cm, and FB irrigation systems were different, where the values of a parameter were 0.405, 0.309, and

0.208, respectively. And the k values for RB130 cm, RB100 cm, and FB were 124.78, 147.401, and 171.759 mm/hr^a, respectively.

Variation in infiltration parameters due to spatial variation in soil characteristics has been reported by Strelkoff et al., (1999), who stated that changes in soil moisture, compression, and irrigation system, even in the same type of soil, all affect infiltration characteristics. Infiltration is also affected by soil texture, which can vary even within a single field due to spatial variation in soil properties. Xu et al., (2019) reported that soil bulk density and soil moisture content can explain temporal variability in infiltration. Furthermore, the soil structure is continuously disturbed and damaged as a result of cultivation, irrigation, and rainfall, possibly resulting in different values of infiltration parameters.

Simulation Analysis

Based on infiltration parameters obtained from the *Event Analysis World*, the simulation analysis world was used to conduct the model calibration based on the appropriate compatibility of the observed advance and recession curves with the simulated ones (The *n* and *α* were calibrated to re-run the model until a reasonable match between the two curves were obtained (Li, 2019)).

Figure (12), (13), and (14) show the observed and simulated advance & recession curve in a single graph showing the degree of convergence between them for RB 130, RB 100 cm, and FB respectively.

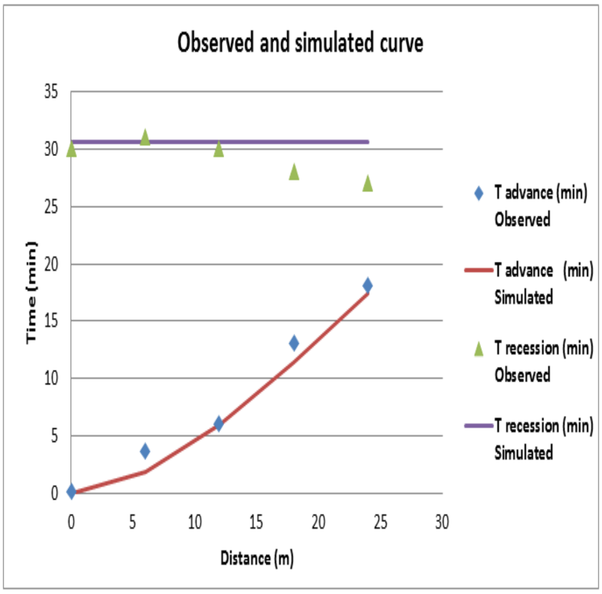


Figure 12: Comparison of observed and simulated advance and recession curve for the RB130 cm

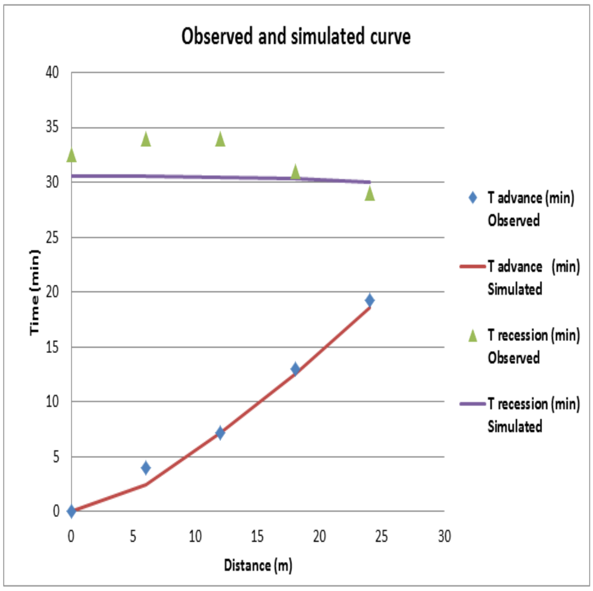


Figure 13: Comparison of observed and simulated advance and recession of RB100 cm

Evaluating Irrigation Performance

Based on event analysis results (infiltration parameters) in the previous section, in this section, we will use the Simulation Analysis World to evaluate the existing RB furrows and basin irrigation performance. The same a, n and k model parameters as the calibrated values in the model testing section will be used here. Following running the WinSRFR model, predicted irrigation efficiency values were obtained by feeding inputs obtained from field measurements in the WinSRFR software.

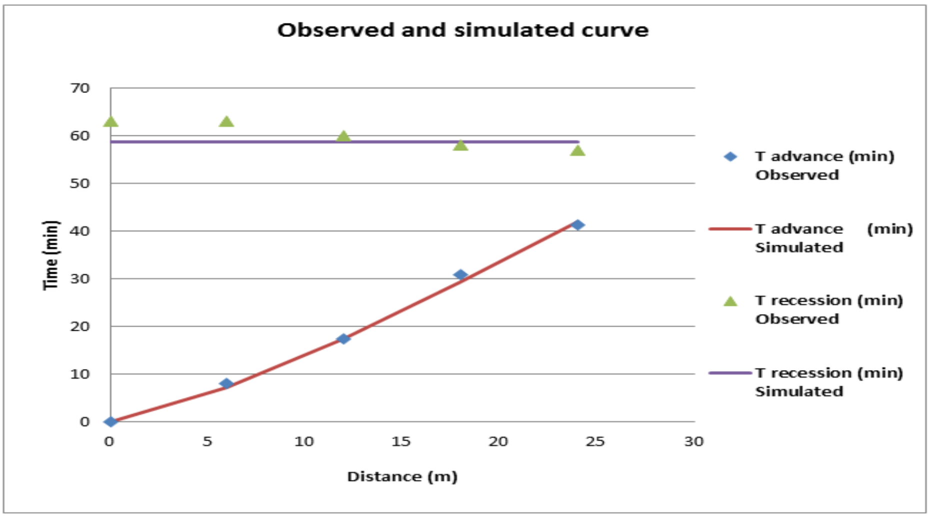


Figure 14: Observed and simulated curve of the advance and recession time for FB

Figure (15) shows Efficiency and uniformity indicators for raised beds and flat basins, the RB130 cm was the highest achieved application efficiency, followed by RB100 cm, while the FB irrigation system was the lowest achieved application efficiency. It is also evident from Fig (15) that the raised beds system achieved the least percentage of deep percolation during irrigation events from a flat basin.

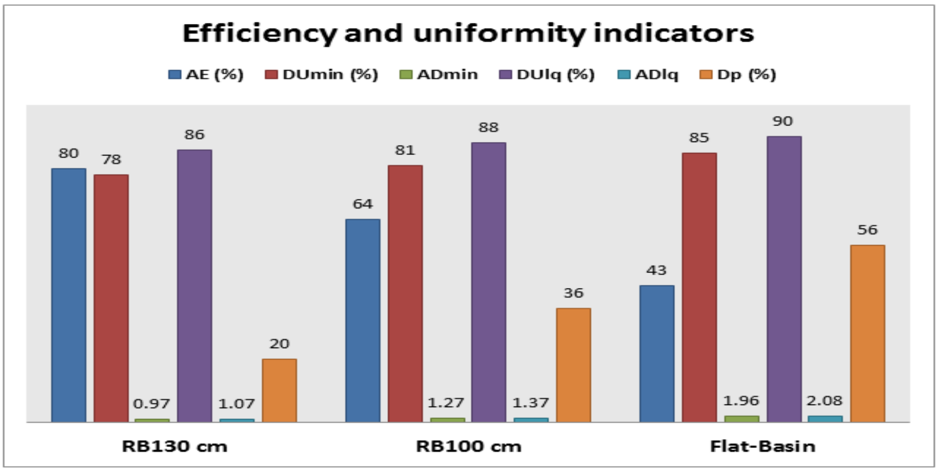


Figure 15: Efficiency and uniformity indicators for raised beds and flat basin during 1st irrigation event

Under the existing field conditions, the current irrigation efficiencies were poor on-farm for raised beds and flat basins, where the application efficiency was 80, 64, and 43% for RB130 cm, RB100 cm, and FB, respectively. The present irrigation event was over-irrigated, where the AD_{lq} value was above 1 for RB130 cm, RB100 cm, and FB. Excessive irrigation applications have been lost as deep drainage because the downstream condition was blocked for all fields, as the value of the deep drainage was 20, 36, and 56% for RB130 cm, RB100 cm, and FB, respectively. The higher DU_{lq} or DU_{min} for RB130 cm, RB100 cm, and FB indicates that the depth required (Dreq) to fill the root zone was fulfilled with large deep drainage losses. The reason for the low application efficiency was that the large inflow rate with a short field length and a long cutoff time resulted in an amount of applied water that was greater than the required application. So, deep percolation loss could be created.

These results closely agree with those obtained by (Biru Dechasa Sima, 2018) who said that the results of the current furrow irrigation performance parameters were evaluated by WinSRFR based on design variables including infiltration parameters. This finding revealed low application efficiency (AE) that could have been expected based on variations in opportunity time along the furrows. This is created for all losses where the deep percolation loss (DP) amounted to almost 60%.

Significant variations in irrigation efficiency (AE) were observed between all RB130, RB100 cm, and FB irrigation systems evaluated on farms. As a result, the irrigation system was never optimally designed and operated for variable field conditions and to satisfy the SMDs. This showed us the need to change the current irrigation system design and operate to improve irrigation performance.

Optimizing Irrigation Performance with Physical Design World

The calibrated infiltration parameters have been used to optimize and develop various design strategies using the *Physical Design World* of the model. Throughout the optimization process, the model was configured to develop performance contours as a function of width (furrow set/border) and length for a given inflow rate. Performance contours were used to determine the impact of optimizing field width and length on potential application efficiency (PAE_{min}), distribution uniformity (DU_{min}), and deep percolation losses (Dp). After field width and length were optimized using the WinSRFR model, more improvement in irrigation efficiency was explored.

The strategy of optimizing field length and width together using WinSRFR demonstrated that irrigation performance can be improved by optimizing the existing field sizes for the available inflow rate and cutoff time.

Optimizing irrigation performance for RB130 cm

The results shown in Table (3) confirmed that the irrigation efficiency of the RB130 system is very sensitive to field length and width. When the furrow width was 1.3 m, the highest irrigation performance was achieved at a furrow length of 12 m where PAE_{min}= 80%, DU_{min}= 94%, and DP=5%. Also, when the furrow width was 2.6, 3.9, 5.2 m, the highest irrigation performance was achieved at a furrow length of 12 m. The results showed that irrigation performance decreased with increasing furrow length, so extremely long furrow lengths should be avoided because they result in decreased efficiency and uniformity, as well as big deep percolation loss.

The results shown in Fig (16) confirmed that the irrigation efficiency of the RB130 system is very sensitive to field length and width. When the furrow width was 1.3 m, the highest irrigation performance was achieved at a furrow length of 12 m where PAE_{min}= 80%, DU_{min}= 94%, and DP=5%. Also, when the furrow width was 2.6, 3.9, 5.2 m, the highest irrigation performance was achieved at a furrow length of 12 m.

Figure (16) shows the irrigation efficiency of the current design of the RB130 system and the best strategies for optimizing furrow length and width that have achieved the highest irrigation performance. These management strategies have allowed PAE_{min} to increase from 76% to 80, 81, 82, and 82% for furrow widths of 1.3, 2.6, 3.9, and 5.2 m, respectively, at furrow lengths of 12 m, and DU_{min} to increase from 76% to 94, 93, 92 and 90% for furrow widths of 1.3, 2.6, 3.9, and 5.2 m, respectively, at furrow lengths of 12 m, and to reduce DP from 24% to 5, 6, 8 and 9% for furrow widths of 1.3, 2.6, 3.9, and 5.2 m, respectively, at furrow lengths of 12 m.

Table 3: Optimizing irrigation performance for RB130 cm of a given inflow rate (Q=15 l/s)

	Performance indicators	**W = 1.3 m (Number per set = 1)**					**W = 2.6 m (Number per set = 2)**				
		L=12 m	**L=24 m**	**L=50 m**	**L=75 m**	**L=100 m**	**L=12 m**	**L=24 m**	**L=50 m**	**L=75 m**	**L=100 m**
RB130 cm	**PAEmin (%)**	**80**	**78**	**75**	**72**	**68**	**81**	**79**	**74**	**69**	**64**
	DUmin (%)	**94**	**89**	**82**	**77**	**73**	**93**	**87**	**78**	**72**	**66**
	Dp (%)	**5**	**9**	**16**	**21**	**26**	**6**	**11**	**20**	**27**	**33**
	Performance indicators	**W = 3.9 m (Number per set = 3)**					**W = 5.2 m (Number per set = 4)**				
		L=12 m	**L=24 m**	**L=50 m**	**L=75 m**	**L=100 m**	**L=12 m**	**L=24 m**	**L=50 m**	**L=75 m**	**L=100 m**
	PAEmin (%)	**82**	**79**	**71**	**64**	**59**	**82**	**78**	**68**	**60**	**54**
	DUmin (%)	**92**	**85**	**74**	**66**	**60**	**90**	**83**	**70**	**61**	**55**
	Dp (%)	**8**	**14**	**25**	**33**	**39**	**9**	**16**	**29**	**38**	**45**

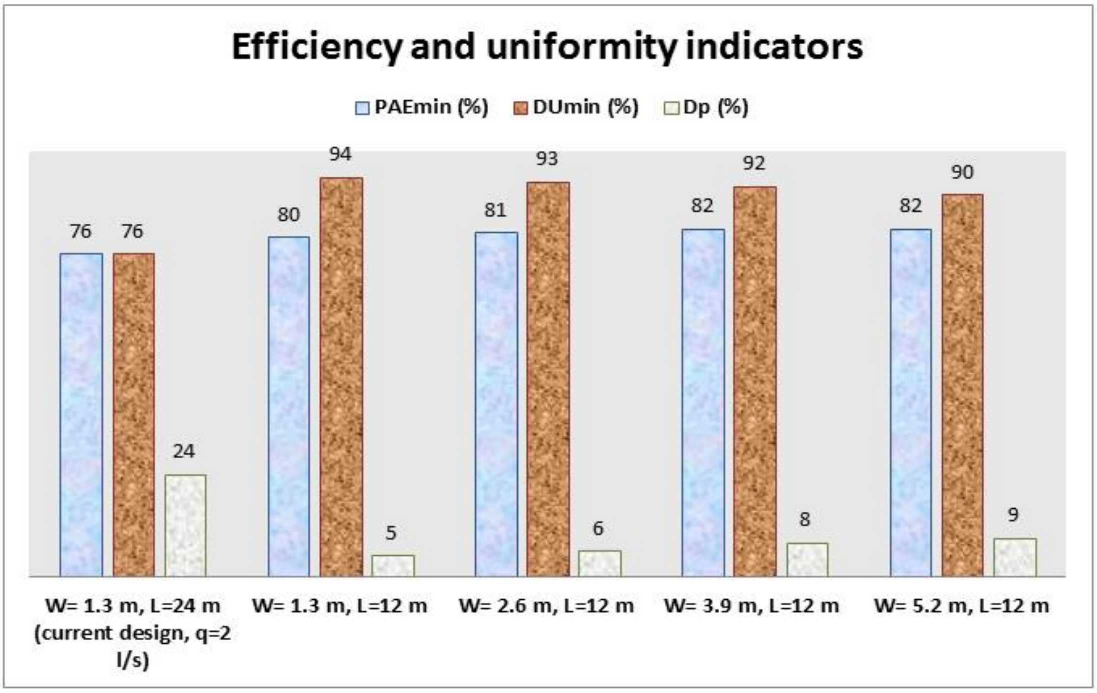


Figure 16: Develop performance contours as a function of length and width for RB130 cm

These results agree with those obtained by (Akbar et al., 2016) who reported that findings obtained clearly demonstrated that there is more potential to increase PAE by reducing field length and width.

Optimizing irrigation performance for RB100 cm

The results are shown in Table (4) indicate that the best strategies to obtain high irrigation efficiency at furrow width 1, 2, 3, and 4 m were achieved when furrow length was 12 m. The results showed that PAE decreased with increased furrow length due to increased deep drainage losses.

Figure (17) shows the irrigation efficiency of the current design of the RB100 system and the best techniques for maximizing furrow length and width that have achieved the highest irrigation performance. These management techniques have enabled PAE_{min} to increase from 68% to 69, 71, 72, and 73% for furrow widths of 1, 2, 3, and 4 m, respectively, at furrow lengths of 12 m, and DU_{min} to increase from 68% to 86, 85, 83 and 82% for furrow widths of 1, 2, 3, and 4 m, respectively, at furrow lengths of 12 m, and to reduce DP from 32% to 12, 13, 15 and 16% for furrow widths of 1, 2, 3, and 4 m, respectively, at furrow lengths of 12 m.

The increase in PAE and DU by reducing field length under furrow irrigation closely corresponds to the results found by (Mazarei et al., 2020) who stated that decreased furrow length leads to an increase in the value of the objective function (including application efficiency, distribution uniformity and deep percolation).

Table 4: Optimizing irrigation performance for RB100 cm of a given inflow rate (Q=15 l/s)

RB100 cm	**Performance indicators**	**W = 1 m (Number per set = 1)**				**W = 2 m (Number per set = 2)**			
		L=12 m	**L=24 m**	**L=50 m**	**L=75 m**	**L=12 m**	**L=24 m**	**L=50 m**	**L=75 m**
	PAEmin (%)	**69**	**66**	**61**	**57**	**71**	**68**	**61**	**56**
	DUmin (%)	**86**	**79**	**69**	**63**	**85**	**77**	**66**	**60**
	Dp (%)	**12**	**18**	**27**	**33**	**13**	**21**	**32**	**38**
	Performance indicators	**W = 3 m (Number per set = 3)**				**W = 4 m (Number per set = 4)**			
		L=12 m	**L=24 m**	**L=50 m**	**L=75 m**	**L=12 m**	**L=24 m**	**L=50 m**	**L=75 m**
	PAEmin (%)	**72**	**68**	**60**	**54**	**73**	**68**	**58**	**52**
	DUmin (%)	**83**	**74**	**63**	**56**	**82**	**72**	**60**	**53**
	Dp (%)	**15**	**23**	**35**	**42**	**16**	**26**	**39**	**46**

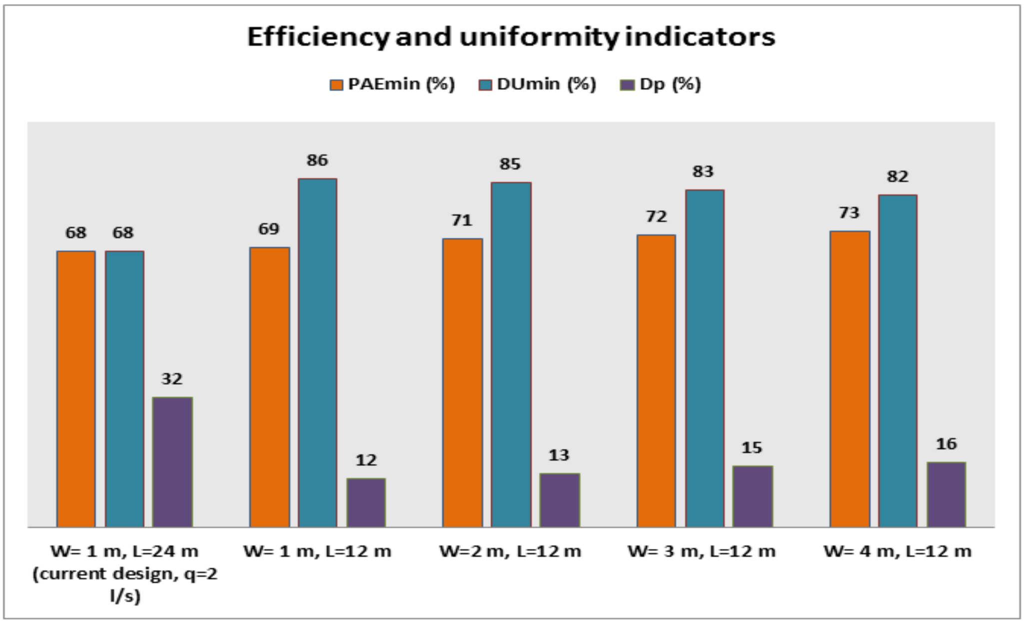


Figure 17: Develop performance contours as a function of length and width for RB100 cm

Optimizing irrigation performance for Flat-Basin

By optimizing the existing basin sizes for the available inflow rate and cut-off time, the irrigation performance can be improved as shown in Table (٥). Figure (18) depicts the irrigation efficiency of the current FB system design as well as the best strategies for optimizing basin length and width that have resulted in the best irrigation performance. When the basin width was 1.3 m, the best irrigation performance was obtained at a basin length of 12 m, with PAE_{min}= 54%, DU_{min}= 57%, and DP= 50%. Furthermore, when the basin width was 2.6, 3.9, or 5.2 m, the furrow length of 12 m also provided the best irrigation performance compared to the other lengths. PAE and DU were found to decrease as basin length and width increased. Large length and width for flat basins should be avoided because they result in poor irrigation performance.

These management strategies have increased PAE_{min} from 47% to 54 and 49% for basin widths of 1.3 and 2.6 m, respectively, at a basin length of 12 m, and DU_{min} to rise from 50% to 57, 61, 61, and 58% for basin widths of 1.3, 2.6, 3.9, and 6.5 m, respectively, at a basin length of 12 m, and to reduce DP from 58% to 50, and 56% for basin widths of 1.3, and 2.6 m, respectively, at basin lengths of 12 m.

Table 5: Optimizing irrigation performance for FB of a given inflow rate

Flat-Basin	Performance indicators	W= 1.3 m					W= 2.6 m				
		L=12 m	L=24 m	L=50 m	L=75 m	L=100 m	L=12 m	L=24 m	L=50 m	L=75 m	L=100 m
	PAEmin (%)	54	48	46	42	39	49	51	44	40	37
	DUmin (%)	57	52	46	42	40	61	55	44	40	37
	Dp (%)	50	52	54	58	61	56	54	56	60	63
	Performance indicators	W= 3.9 m					W= 6.5 m				
		L=12 m	L=24 m	L=50 m	L=75 m	L=100 m	L=12 m	L=24 m	L=50 m	L=75 m	L=100 m
	PAEmin (%)	47	4	42	38	35	46	47	39	35	33
	DUmin (%)	61	53	42	38	35	58	50	39	35	33
	Dp (%)	58	56	58	62	65	59	58	61	65	68

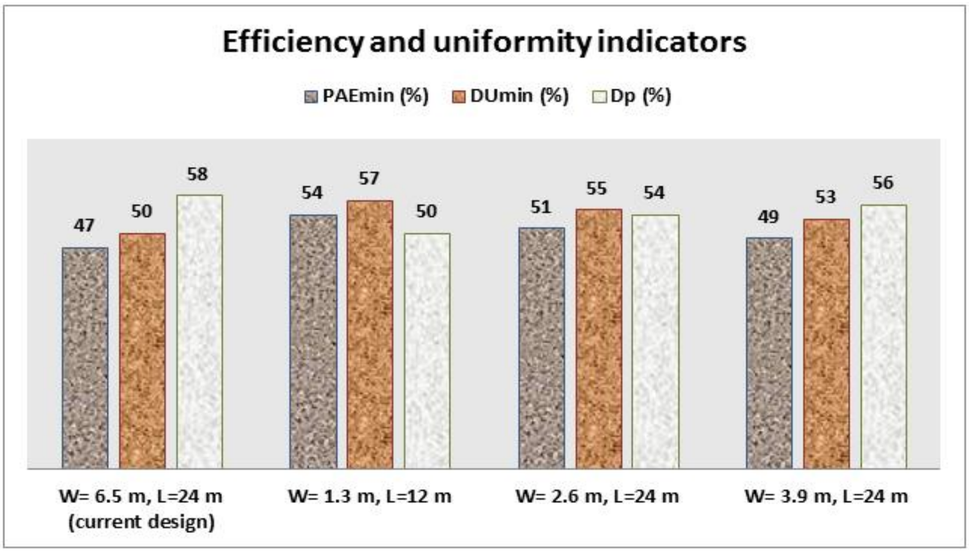


Figure 18: Develop performance contours as a function of length and width for FB

The results showed that irrigation performance decreased with increasing furrow length, so a very long furrow length should be avoided because it leads to reduced efficiency and uniformity, and also huge deep percolation loss.

Understanding the previous optimization of field sizes leads to a better understanding of the interactions between field sizes and irrigation efficiencies, which may aid irrigators in making decisions to improve irrigation performance without any significant cost to infrastructure, labor, or machinery (Akbar et al., 2016).

Optimizing Irrigation Performance with Operation Analysis World

The main objective of the WinSRFR software is to help find a strategy for managing surface irrigation leading to a satisfactory level of efficiency. These strategies may be a decrease in the flow rate and its time of application. According to (Mazarei et al., 2020), it is easy for growers to adjust flow discharge and cutoff time compared to soil properties modification and field design.

The calibrated infiltration parameters have been used to optimize and develop various operation strategies using the *Operation analysis World* of the model. In the optimization phase, the model was configured to develop performance contours as a function of inflow rate and cutoff time for the known width (number of furrows per set /border). Performance contours were used to determine the impact of optimizing inflow rate and cutoff time on application irrigation efficiency (AE)**,** distribution uniformity (DU_{min}), and deep percolation losses (DP).

✚ Optimizing irrigation efficiency for RB130 cm, RB100 and FB

Figures (19, 20, and 21) illustrate the irrigation efficiency of the existing RB130, RB100 cm, and FB respectively, and the best strategies for maximizing inflow rate and time to the cutoff that has resulted in the best irrigation performance. The analysis indicates that optimizing inflow rate could increase application efficiency by more than 15%, 17%, 23%, and decrease deep percolation up to 60%, 33%, and 17.5% for RB130, RB100 cm, and FB respectively. For RB130, and RB100 cm the maximum irrigation application efficiency and minimum deep percolation loss were obtained for an inflow rate of 2 l/s and a cutoff time of 0.30 hr, while inflow rate of 18 l/s and a cutoff time of 0.31 hr for FB. However, knowing the specific values is less essential than understanding the Q-Tco relationship that optimizes both AE and DUmin (N. Pascual-Seva et al., 2013). These findings are consistent with those obtained by Bautista et al. (2013). Mazarei et al., (2021) the results indicated that under higher inflow rates, the AE values decreased while the DP increased. The results reveal that a very low inflow rate associated with a shorter cutoff time must be avoided because it will result in incomplete irrigation water advance.

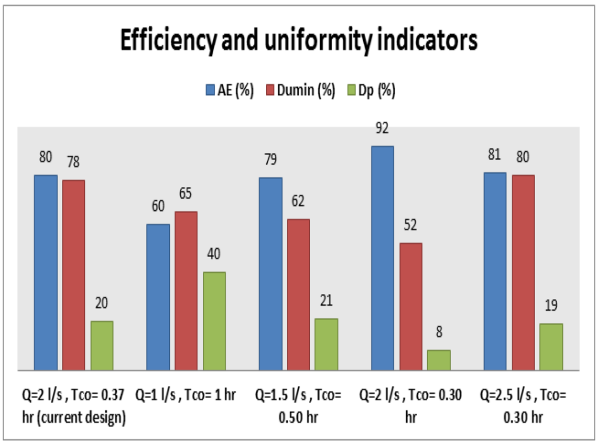


Figure 19: Develop performance contours as a function of inflow rate and cutoff time for RB 130 cm

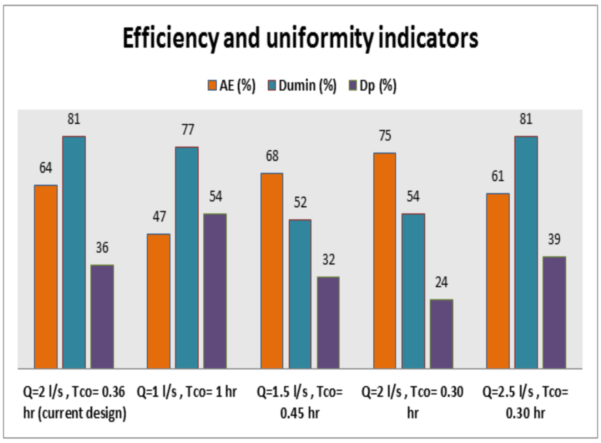


Figure 20: Develop performance contours as a function of inflow rate and cutoff time for RB 100 cm

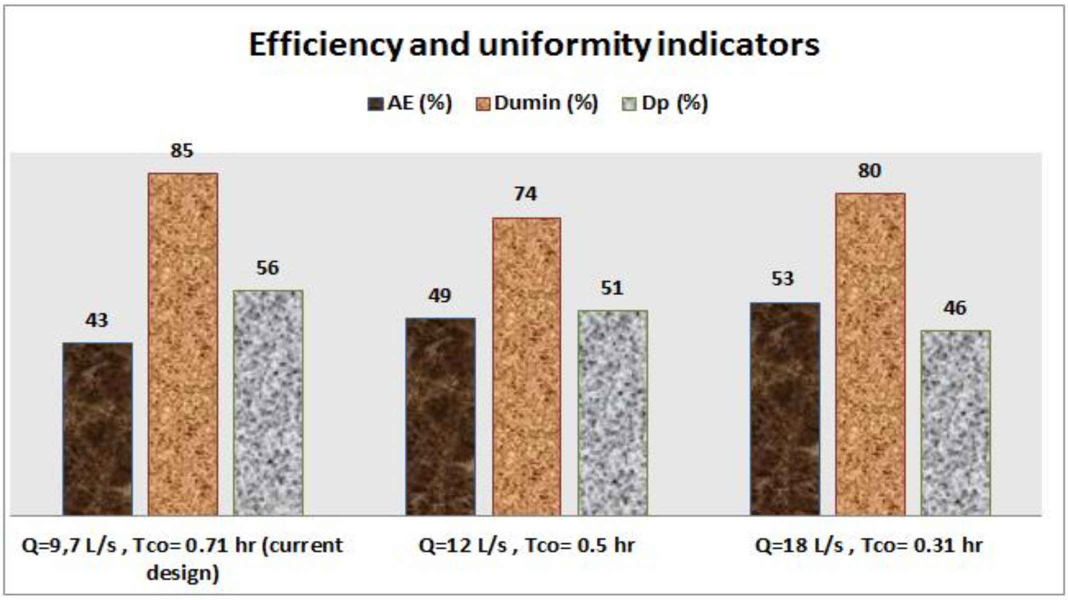


Figure 21: Develop performance contours as a function of inflow rate and cutoff time for FB irrigation system

RECOMMENDATION

The following recommendations were drawn for the study of evaluating, optimizing the design, and managing the operation of raised bed furrow and flat basin irrigation systems:

1. When compared to field tests, WinSRFR can assist the designer in determining the appropriate values of the variables that will provide the best irrigation performance at the lowest cost and in the shortest time.
2. Based on the results of evaluating irrigation performance for raised beds and flat basin using *Simulation Analysis World*, farmers should use the RB130 cm method because it achieved higher irrigation performance than the RB100 cm and FB methods.
3. According to Physical Design Analysis, increasing the length of the furrow and flat basin reduces irrigation performance, so a very long length should be avoided because it leads to reduced efficiency and uniformity, as well as huge deep percolation loss.
4. According to the analysis, managing the inflow rate and irrigation cutoff can increase application efficiency and reduce deep percolation losses by more than 15%, 60% for RB 130 cm, and 17%, 33% for RB100 cm, and 23%, 17.5% for FB irrigation system, respectively.
5. Using Operation Analysis World, the optimal inflow rate and cutoff time is recommended as 2 L/s and 0.30 hr for RB130 cm and RB100 cm, and 18 L/s and 0.31 hr for FB method.
6. We recommend that concerned government agencies spread raised bed cultivation in the old lands by making more improvements to this method in order to achieve the highest productivity and irrigation water savings under Egyptian conditions, as well as work to provide farmers with affordable raised bed cultivated machinery.

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تحسين آداء ري القمح على مصاطب باستخدام نموذج WinSRFR

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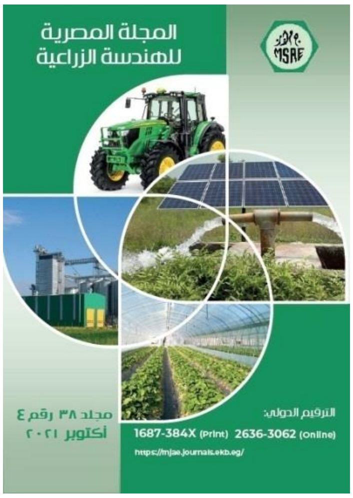
الملخص العربي

أجريت تجارب حقلية بمحطة البحوث الزراعية في سخا بمحافظة كفر الشيخ خلال ٢٠٢٠/٢٠١٩ لتقييم وتحسين أداء الري السطحى للقمح المنزرع على مصاطب ومقارنته بالطريقة الزراعة التقليدية بنظام الاحواض المستوية، وذلك باستخدام أنموذج WinSRFR. تم تنفيذ الزراعة على مصاطب (مصاطب بعرض ١٣٠ سم، مصاطب بعرض ١٠٠ سم) باستخدام آلة الزراعة على مصاطب التي تم الحصول عليها من مشروع الايكاردا بمصر. استندت معايرة النموذج الرياضي الى التطابق الوثيق بين منحنيات التقدم والركود المرصودة والمنحنيات المحاكاة، تم استخدام بارامترات التسرب المعايرة في تقييم وتحسين آداء الري عند استراتيجيات مختلفة. تم استخدام تحليل المحاكاة لتقييم أداء الري للتجربة المنفذة لطريقة المصاطب والحوض المسطح، حيث كانت كفاءة اضافة المياه ٨٠ , ٦٤ و٤٣٪ وتجانس التوزيع ٨٦ , ٨٨ و٩٠٪ وفواقد التسرب ٢٠ , ٣٦ و٥٦٪ العميق وكفاية الري ١,٠٧، ١,٣٧ و٢,٠٨٪ لطريقة المصاطب ١٣٠ سم والمصاطب ١٠٠ سم وطريقة الاحواض المستوية على التوالي. تم استخدام اجراء التحليل الفيزيائي في أنموذج WinSRFR لتحسين وتطوير استراتيجيات التصميم المختلفة، أظهرت النتائج أن أداء الري انخفض مع زيادة الطول للمصاطب والاحواض المستوية، لذلك يجب تجنب الأطوال الكبيرة للغاية لأنها تؤدي إلى انخفاض كفاءة الري وتجانس توزيع المياه، فضلاً عن فقد كبير للمياه في التسرب العميق. يمكن ايضا أن تؤدي إدارة معدل التدفق وزمن الري من خلال النموذج الرياضي إلى زيادة كفاءة اضافة المياه وتقليل فواقد التسرب العميق لطريقة المصاطب ١٣٠ سم لأكثر من ١٥٪ و ٦٠٪, وبنسبة ١٧٪ و ٣٣٪ لطريقة المصاطب ١٠٠ سم, وبنسبة ٢٣٪ و ١٧,٥٪ لطريقة الاحواض المستوية على التوالي.



الكلمات المفتاحية:
الزراعة على مصاطب، أداء الري، التحسين، WinSRFR