Agrociencia Uruguay 2023 | Volume 27 |Number NE1 |Article e1187
DOI: 10.31285/AGRO.27.1187
ISSN 2730-5066

Advances in Water in Agroscience

Performance assessment of furrow irrigation in two different soil textures under high rainfall and field slope conditions

Análisis del rendimiento del riego por surcos en dos texturas de suelo diferentes bajo condiciones de alta precipitación y topografía del suelo

Analise de desempenho da irrigação por sulcos em duas texturas de solo diferentes sob condições de alta precipitação e inclinação de campo

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Received *29 Apr 2023*
Accepted *13 Sep 2023*
Published *06 Feb 2024*

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Abstract

Furrow irrigation systems have been widely evaluated around the world. However, there is no national data indicating how efficient furrow irrigation is under Uruguayan conditions. The objective of the present work was to evaluate the performance of a system of furrow irrigation in two different soils texture. Seventeen irrigation events were analyzed in sugar-cane cultivation in northern Uruguay during 2016-17 and 2017-18 irrigation seasons. The water advance and recess curves were determined; flow rate during irrigation and runoff were monitored. The maximum furrow length studied was 100 m and the average slope was 0.24%. Application efficiencies in both types of soils were observed above 75%. These field data were compared with data simulated by the WinSRFR model, where high correlations were observed in the results of water application efficiency, distribution uniformity and runoff. These first results encourage to continue working in the efficient use of water, not only thinking about a better use of the resource but also in less loss by run-off, and therefore, less possibility of contamination and lower cost of energy and labor.

Keywords: furrow irrigation, application efficiency, irrigation evaluation, WinSRFR, water management

Resumen

Los sistemas de riego por surcos han sido ampliamente evaluados en todo el mundo. Sin embargo, no hay datos nacionales que indiquen cuán eficiente es el riego por surcos. El objetivo del presente trabajo fue evaluar el desempeño de un sistema de riego por surcos en dos suelos de diferente textura. Se analizaron 17 eventos de riego en cultivos de caña de azúcar en el norte de Uruguay durante las temporadas de riego 2016-17 y 2017-18. Se determinaron las curvas de avance y retroceso del agua, se monitoreó el caudal durante el riego y el escurrimiento. La longitud máxima de surco estudiada fue de 100 m y la pendiente promedio fue de 0,24%. Se observaron eficiencias de aplicación en ambos tipos de suelos superiores al 75%. Estos datos de campo fueron comparados con datos simulados por el modelo WinSRFR, donde se observaron altas correlaciones en los resultados de eficiencia de aplicación de agua, uniformidad de distribución y escorrentía. Estos primeros resultados alientan a seguir trabajando en el uso eficiente del agua, no solo pensando en un mejor aprovechamiento del recurso, sino también en menores pérdidas por escurrimiento y, por ende, menor posibilidad de contaminación y menor costo de energía y de mano de obra.

Palabras clave: riego por surcos, eficiencia de aplicación, evaluación del riego, WinSRFR, manejo del riego

Resumo

Os sistemas de irrigação por sulcos têm sido amplamente avaliados em todo o mundo. No entanto, não há dados nacionais que indiquem quão eficiente a irrigação por sulcos é nas condições uruguaias. O objetivo do presente trabalho foi avaliar o desempenho de um sistema de irrigação por sulcos em dois solos de texturas diferentes. Foram analisados 17 eventos de irrigação em cultivos de cana-de-açúcar no norte do Uruguai durante as temporadas de irrigação de 2016-17 e 2017-18. Foram determinadas as curvas de avanço e retrocesso da água, o fluxo durante a irrigação e o escoamento. O comprimento máximo do sulco estudado foi de 100 m e a inclinação média foi de 0,24%. Foram observadas eficiências de aplicação em ambos os tipos de solos superiores a 75%. Esses dados de campo foram comparados com dados simulados pelo modelo WinSRFR, onde foram observadas altas correlações nos resultados de eficiência de aplicação de água, uniformidade de distribuição e escoamento. Esses primeiros resultados incentivam a continuar trabalhando no uso eficiente da água, não apenas pensando em um melhor aproveitamento do recurso, mas também em menores perdas por escoamento e, portanto, menor possibilidade de contaminação e menor custo de energia e mão de obra.

Palavras-chave: irrigação por sulcos, eficiência de aplicação, avaliação da irrigação, WinSRFR, gestão da irrigação

1. Introduction

Worldwide, agriculture uses more than 70% of freshwater with great pressure from other sectors seeking to improve sustainable water resource management to increase water productivity in food and agriculture[1]. In Uruguay, 86% of the extracted volume of water is used for crop irrigation, 9% for drinking and water supply, 3% for industries, and 2% for recreation and other uses[2]. Agriculture in Uruguay is mostly rainfed, except for rice, intensive vegetables, citrus, and sugarcane, which are irrigated by furrows[3]. The total irrigated area in Uruguay increased fourfold in the last 45 years, from 52,000 hectares in 1970 to 205,000 hectares in 2015[4]. Surface irrigation is the most extended irrigation method in the world, having the advantage of lower investment and operating costs[5]. Irrigation in Uruguay has developed with the expansion of rice, sugarcane, fruits, and vegetables[6]. Surface irrigation represents between 70 and 80% of the irrigated area[4].

The cultivation of sugarcane (*Saccharum officinarum*) takes place in the northwest of the country. The total area of this crop is 7,100 ha^{-1}, with an average yield reaching 55.27 t ha^{-1} per year[4]. The world cultivates 25 million hectares with an average of 70 t ha^{-1} per year[7].

The main water losses in surface irrigation are usually due to water percolation beyond the effective root zone of the crop, and when furrows or strips are open at the end, leading to surface runoff[8]. The analysis of the application efficiency (AE) data for surface irrigation by the National Resources Conservation Service (NRCS) and the International Commission on Irrigation and Drainage (ICID) showed that values are between 50 and 80%[9].

In Australia, the efficiency of application in commercial premises generally varies between 31 and 62% with individual efficiencies that can reach 90%[10]. In the commercial areas of sugarcane of South America, an irrigation AE of 59% was observed, reaching values of 70% with water salinity management[11].

Studies by Gonzalez and others[12] attribute the causes of low distribution uniformity (UD) in surface irrigation to the different opportunity times for water infiltration between the areas closest to the supply point and the furthest end of the water outlet. The WinSRFR model developed by USDA-Agricultural Research Service is an integrated software package for analyzing surface irrigation performance. The model also allows estimating infiltration properties and simulating new irrigation scenarios[13]. Assessments of surface pasture irrigation in southern Uruguay using WinSRFR concluded that the model predicted very well the volume of water infiltrated and runoff[14].

The traditional areas of surface irrigation in Uruguay are rice and sugarcane crops, with low efficiency (EA and UD) and high volume of fresh water consumed[15]. So it is important to improve efficiency in water management, since this aspect is critical to ensure high productivity, and reduce losses due to percolation and runoff. In this way, pumping costs can be reduced. Another crucial aspect lies in the examination of hydraulic variables, as our country lacks scientific data that can provide the necessary technical irrigation criteria for designing effective furrow irrigation systems. Additionally, we lack tools such as simulation models to analyze these irrigation hydraulics variables, especially in the context of furrow irrigation for our specific production conditions.

The specific objective of the present work was to study the performance of the irrigation system by furrow in sugarcane through soil physics variables characteristics in each irrigation event. Because there is no scientific data in our country that contribute to having technical irrigation criteria and there are no tools for the hydraulic analysis of furrow irrigation.

2. Materials and methods

2.1 Sites and experimental treatment

The study was carried out in three sites at the Bella Union region of northeast Uruguay. Soils on site I (30° 33' S; 57° 60' W) and site III (30° 30' S; 57° 58' W) were fine, mixed, superactive, thermic Typic Argiudolls, and site II (30° 36' S; 57° 64' W) was fine, mixed, superactive, thermic Pachic Vertic Argiudolls[16]. Total annual rainfall ranges between 1100 and 1600 mm. There is no rainfall season, but some years water deficit occurs from mid-spring to summer, which evapotranspiration (ET) exceeds the soil water available[6]. The irrigation events analyzed correspond to the 2016-17 and 2017-18 seasons. A total of 24 irrigation evaluations were conducted, 17 of which were analyzed.

2.2 Crop management

The variety of sugarcane used was TUC 77-42, because it is the most planted one in this region and with more local research. The crop agronomic management was representative farm practice of the region (ALUR Sugarcane Industry instructive recommendation). Table 1 shows some crop characteristics and some climate variables.

2.3 Irrigation management and soil water measurement

Soil texture, bulk density and water retention curve were evaluated from samples collected in October 2016 at three depths (0-0.20; 0.20-0.40, and 0.40-0.60 m). Texture was determined using the international pipette method[17]. The soil water retention curve was characterized from measured water content at tensions of -0.01, -0.033, -0.1, and -1.5 MPa using the Richards and Weaver methods[18]. The measurements at -0.033 and -1.5 MPa were interpreted as the water content at field capacity (FC) [L^3/L^3], and permanent wilting point (PWP), respectively, with their difference equal to the available water.

Table 1. Crop characteristics, rainfall, temperature and evapotranspiration during irrigation seasons (2016-17 and 2017-18)

Plant crop	Site I	Site II	Site III
Start date	August	August	August
Harvest date	May	May	May
Growing period (days)	280	280	280
Weather variable (Sep.- April)	2016-17		2017-18
Rainfall (mm)	1125.4		1151.5
Radiation (cal cm^{-2} day^{-1})	76533		83355
T max (°C)	32.7		30.2
T min (°C)	14.1		12.5
T average (°C)	21.6		22.8
ETo (mm)	846		534.2

T max: maximum daily temperature; T min: minimum daily temperature; Radiation: sum of daily sun radiation; ETo: FAO 56-Penman Monteith reference evapotranspiration.

Irrigation evaluations were carried out in furrows with open end, furrow length 100 m or less and 1.2 m between rows. The average slopes recorded at each site were: 0.05 m m^{-1} for site I, 0.024 m m^{-1} for site II, and 0.0175 m m^{-1} for site III. During each irrigation event, three continuous furrows were selected to evaluate. The irrigation events were carried out in two irrigation seasons, 2016-17 and 2017-18. Irrigation water was applied using poly-pipe with slide gates spaced at 2.40 m.

The total length of the furrow was divided into 10 sections to determine advance and recession times. Opportunity time was defined as the difference between the advance and recession times along the furrow.

Profile of each furrow was determined following the methodology of the profilometer[8]. Each measure was replicated three times along the furrow (head, middle and bottom). For each irrigation, event irrigation depth to be applied at each site was calculated using the gravimetric procedure for the effective root exploration. The effective root depth was assumed to be constant throughout the irrigation experiment season. Prior research conducted in

Uruguay has indicated that the majority of the effective root zone is located in the top layer of the soil profile (0.30 m), as reported by De la Peña Ruiz and Martínez Correa[19], and Dapueto Firpo and Rodríguez Roig[20].

Field irrigation evaluations were carried out according to that described by Morábito[21]. Washington State University flumes[22] were used to measure both inflow and runoff rates in each furrow and each irrigation event. Infiltrated depth was calculated as the difference between the applied and run-off volume divided by the plot area.

Determined infiltration with double ring NRCS-USDA was used in the head, middle and tail of each furrow. In addition, infiltration was determined by volume balance and adjusted by modified[23]. The measurement was taken prior to irrigation.

The cumulative infiltration was measured using a double-ring infiltrometer and adjusted to a potential curve of the form:

$$\mathbf{Icum} = \mathbf{A} * \mathbf{t}^{\mathbf{B}} \quad [1]$$

where $\mathbf{Icum}$ is the cumulative infiltration as a function of time in mm; A and B are the coefficient and exponent of the potential equation, respectively, and t is the time of water entry into the soil in minutes.

Subsequently, based on the data provided by the irrigation evaluation, the coefficient A of equation [1] was corrected using a volume balance. This is the methodology used by the WinSRFR model when selecting the Merriam and Keller option in the Event Analysis module[13][24].

According to the following relationship:

$$\boldsymbol{Amodif} = \mathbf{A} * \mathbf{Linf}/\mathbf{Icum} \quad [2]$$

where $\boldsymbol{Amodif}$ is the modified infiltration equation coefficient; A is the infiltration equation coefficient obtained using the double-ring infiltrometer; $\mathbf{Linf}$ is the average infiltrated depth calculated by volume balance, and $\mathbf{Icum}$ is the average infiltrated depth calculated using the double-ring infiltrometer equation. The infiltration rate, in mm/min, was obtained by deriving the accumulated infiltration over time.

The basic soil infiltration rate, ib, was determined using the following formula[25-26]:

$$\mathbf{ib} = (\mathbf{600} * b)^{b} * a * 60 \quad [3]$$

where ib is the basic soil infiltration in mm/h; a is the coefficient of the infiltration rate equation; and b is the exponent of the infiltration rate equation.

The required depth of irrigation (Dreq) is equal to the water content in the root zone. The irrigation times were defined based on the volume required to apply the gross depth of water[27]. A fixed application flow rate was used, and the irrigation time was calculated according to the following equation:

$$\mathbf{t} = \frac{\mathbf{d\,x\,a}}{\mathbf{q}} / \mathbf{60} \quad [4]$$

where t = time in seconds, d = gross depth of water to be applied in m, a = plot area in m^2, q = inflow rate m^3 s^{-1}. Since the same inflow rate was used for all irrigations, the application time varied depending on the water replacement depth.

Based on the soil moisture before and after irrigation, the required depth of water (Dreq), AE (application efficiency), and DUlq (distribution efficiency) were calculated. AE was calculated as the net depth of water (Dz) divided by the applied depth of water (Dapp)[24].

$$\mathbf{AE} = \mathbf{Dz} / \mathbf{Dapp} \quad [5]$$

where Dz was the depth of water that effectively remained in the root zone, measured in mm, and was calculated according to Bautista and others[13]:

$$\mathbf{Dz}: \mathbf{Xa} - \mathbf{Xb} \quad [6]$$

where Xa is the water content in mm before irrigation, and Xd is the average water content in mm after irrigation.

Dapp corresponds to the total applied depth of water in mm and was calculated according to Bautista and others[13]:

Dapp = Volume applied/area [7]

DUlq was calculated as the infiltrated depth of water in the quarter of the furrow with the least amount of water divided by the average infiltrated depth of water in the entire furrow[8].

$$\mathbf{DUlq} = \mathbf{Dlq} / \mathbf{Dinf} \quad [8]$$

where Dlq is the average infiltration depth of the lowest quarter, corresponding to one-fourth of the area of the plot that receives the least amount of water, and Dinf is the average infiltration depth of the entire furrow.

2.4 Statistical analysis

The variables studied were: irrigation time (t), required depth (dreq); applied depth irrigation (Dapp); average depth of infiltrated water (infiltrated volume/area) (dinf); average depth of runoff, or runoff volume expressed as an equivalent average depth (Dr); infiltrated depth contributing to the irrigation target (Dz). These variables allow to calculate AE, DUlq, EAL (storage efficiency), dz (percentage of deep percolation), Ep (percentage of runoff), as described by Bautista and others[24].

Infiltration of water in the soil, water holding capacity, irrigation time, advance and recession curve, uniformity of wetting in the soil profile and runoff in each of the applied irrigation were determined.

The RMSE (root means square) error was calculated using the statistical software package SAS/STAT[28].

3. Results

3.1 Description and analysis of soil

Soil characteristics of each site, soil type, depth of each layer, soil texture, bulk density, field water capacity, permanent wilting point and available water are presented in Table 2. Total available water for the effective root exploration (0-30 cm) of sites I, II and III is 47.7 mm, 65.6 mm, and 54.8 mm, respectively.

Table 2. Physic properties of soils of three experimental sites

Site	Soil	Horizon	Depth	Soil Texture	Bulk density	FC	PWP	TAW
			(m)		g cm^{-3}	% by volume		mm
I	Mollisols (Udolls)	A	0-0.3	SCL	1.36	18.7	7	11.7
		B	0.3-0.45	SL	1.50	22.0	13.0	9.0
II	Vertisol (Uderts)	A	0-0.25	CL	1.15	28.0	9.0	19.0
		B	0.25 -0.40	Clay	1.35	26.3	13.0	13.3
III	Mollisols (Udolls)	A	0-0.25	SCL	1.39	29.3	16.1	13.2
		B	0.25 -0.40	Clay	1.30	31.9	21.5	10.4

*Trapezoidal; SCL: sandy clay loam; CL: clay loam; SL: sandy loam; TAW: total available water; FC: field capacity; PWP: permanent wilting point

3.2 Irrigation system

Table 3 shows the characteristics of furrows in each experimental site. Lengths varied between 48 and 100 m, and wide of each furrow was 1.2 m.

Table 3. Characteristics of furrows in each experimental site

Variable	Site I	Site II	Site III
Length, L (m)	100-90	100	48-60
Width, W (m)	1.2	1.2	1.2
Downstream boundary	Open	Open	Open
Cross - Section	Tr*	Tr*	Tr*
Bottom slope So (m m^{-1})	0.05	0.024	0.0175
Mannign's n	0.04	0.04	0.04-0.06
Inflow rate, Q (l s^{-1})	0.5	0.5	0.5

Furrows shape was trapezoidal and open end. Table 3 also presented variables used into the model in each soil site. Manning's n value used for both sites was 0.04 due to the fact that the soil conditions were of low roughness and without the presence of weeds along the furrow. The flow of 0.5 l s^{-1} was used considering the most used by the irrigators in the area under study.

WinSRFR program, Event Analysis and Operation Analysis modules were used to analyze the information collected at the field during each irrigation event. Collected information at the field was processed and analyzed for each irrigation event during two irrigation seasons, 17 irrigation events in two different texture soils.

3.3 Description and analysis of events

Performance indicators of each irrigation event in each site (I, II and III) are presented in Table 4. Irrigation depth varies from 19 to 41 mm according to soil water content in the effective root exploration. Irrigation performances of the different events are presented.

Irrigation events 1, 2, and 3 were better indexes of AE and application depth. The required application depth was 17 mm in events 1, 2 and 3 to reach field capacity, corresponding to 40% of the water available into the root zone of the crop. The depth irrigation applied for these first three events was on average 21 mm and average runoff of 3.3 mm. Application efficiencies were 76% (average), and distribution uniformity 0.84. In irrigation events 4 and 6, depth irrigation applied exceeded the required application depth, AE index down and the distribution uniformity in the low quarter increased. In the average of all irrigation events, high values were obtained of AE (69%) and DUlq 0.84. The average opportunity time was 98.6 min in order to replace required depth irrigation of 20 mm. At site I, best performances were obtained applying 20 mm of irrigation depth. In this case, required depth was 17 mm and flow rate 0.5 l s^{-1} reached application efficiencies 78% and uniformity of 0.78 with an opportunity time of 79 minutes.

Table 4. Irrigation performance indicators from site I

Events	depth (mm)	Dapp (mm)	Infiltrated depth (mm)	Runoff (mm)	AE	DUlq	Opportunity Time (min)
1	17	20	18	4	78	0.86	79.3
2	17	23	20	3	75	0.82	86.0
3	17	23	20	3	75	0.84	76.2
4	23	41	35	6	56	0.88	140.0
5	23	19	14	5	77	0.91	76.0
6	23	39	39	1	58	0.67	78.0

The following figure (Figure 1) represents irrigation event 3, that shows hydraulic summary of this event. These data are based in field data and simulated data, irrigation required depth and infiltrated depth to replace requirement soil water.

As can be observed in Figure 1 advance and recession curves are in the upper part of the figure. Observed data and simulated data matched very well. The area between advance and recession is the opportunity time (min). In the low part of the figure the blue line describes required irrigation depth and observed and simulated data of irrigation depth. It was observed good relationship reaching good performance.

At site II the soil was heavier, which allowed a contrasting irrigation blade management to have different indicators of irrigation performance. The following table (Table 5) summarizes the main variables and index of performance irrigation on site II.

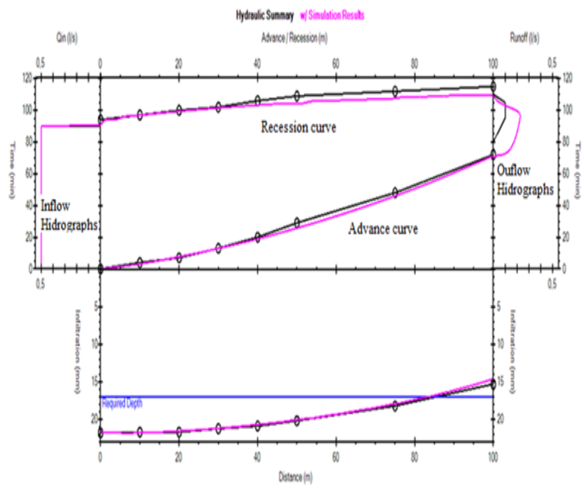

Figure 1. Hydraulic summary with field data and simulated data (irrigation event 3)

*black line is observed data, rose line is simulated data, blue line is required depth irrigation.

Table 5. Irrigation performance indicators from Site II

Events	depth (mm)	Dapp (mm)	Infiltrated depth (mm)	Runoff (mm)	AE	DUlq	Opportunity Time (min)
1	30	33	29	4	87	0.83	105.7
2	30	33	32	2	86	0.76	112.0
3	30	38	34	4	77	0.81	131.4
4	18	20	14	6	72	0.93	106.0
5	18	23	17	6	75	0.94	95.0
6	18	20	14	7	68	0.94	98.0

Required irrigation depth in 1, 2 and 3 irrigation events presented in Table 5 was 30 mm; only in events 2 and 3 irrigation depth applied attended water requirements; however, this was not possible in event 1. Average application efficiency was 83%, and average opportunity time 116 min.

In events 4, 5 and 6 it was not possible to attend required irrigation depth, runoff was 6.3 mm on average and application efficiency 71.6%, and average opportunity time 100 min. A better uniformity of distribution was observed to the detriment of greater loss due to runoff.

In the average of 6 irrigation events for this site (site II), it was observed that application efficiency was 77% and the distribution uniformity of 0.87 for the fourth most affected.

The best performance of site II was obtained by irrigation depth of 33 mm when water required was 30 mm, runoff 4 mm and opportunity time 105 min. It was observed application efficiency 87% and distribution uniformity of 0.73.

Figure 2 shows observed and simulated data infiltrated by Modified Kostiakov Infiltration equation on site II from irrigation event number 3. It can be observed a good correlation along the furrow. Also in the other irrigation event (data not presented).

In this figure (Figure 2) we can observe the adjust parameters of the infiltration function to match the predicted infiltration to the values derived from volume balance.

In site III, irrigation depth ranged from 16 to 33 mm depending in each irrigation event to the soil and weather conditions. In two of the five irrigation events runoff was 1 mm and maximum runoff was 4 mm. Table 6 presented the main performance irrigation indicators on site III.

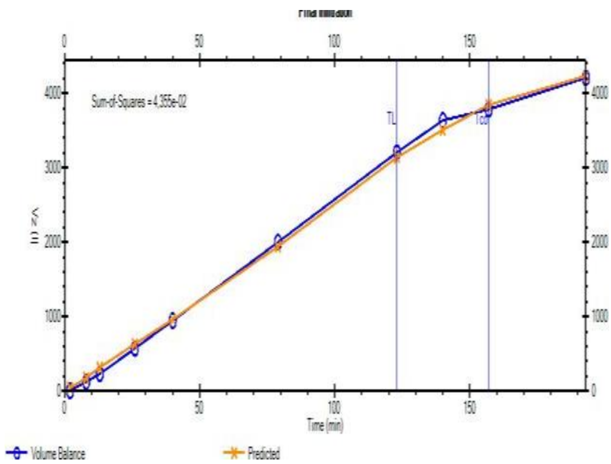

Figure 2. Infiltrated irrigation depth as function of time predicted with Modified Kostiakov Infiltration equation (irrigation event 3, site II)

Table 6. Output of the irrigation performance indicators (Site III)

Events	depth (mm)	Dapp (mm)	Infiltrated depth (mm)	Runoff (mm)	AE	DUlq	Opportunity Time (min)
1	10	17	16	1	58	0.71	32
2	10	33	32	1	30	0.77	50
3	10	16	14	2	62	0.79	55
4	10	20	16	4	49	0.71	55
5	10	19	15	4	54	0.78	59

Furrows length in this site are shorter compared to site I and II. This makes opportunity times shorter to complete irrigation depth required. Although water infiltrated was larger in event 2 than irrigation depth required, probably it was a mistake to estimate soil moisture content by gravimetric sampling at the time of irrigation, or furrows did not receive the correct irrigation depth in the previous irrigation.

Table 6 shows that the average AE was 51% in site III, lower than that obtained in sites I and II. Although soil texture and deep are similar to site I, hydraulic behavior was not the same, probably because furrows were shorter (not exceeding 50 m) and also with larger slopes, which could be causing this lower efficiency. Applying irrigation flows of less than 0.5 l/s could contribute to improving AE. For this reason, the lower values of AE obtained in the events of site 3 would be explained.

The distribution of the average uniformity of the five events was 0.75, the lowest 25%.

Infiltrated depth as function of distance predicted with Modified Kostiakov Infiltration equation (event 1, site III) is presented in Figure 3.

It was observed high relationship between measured and estimated infiltration by volume balance, mainly at the head of the furrow; at the end of it there is a difference between the observed and estimated infiltration of 3 mm.

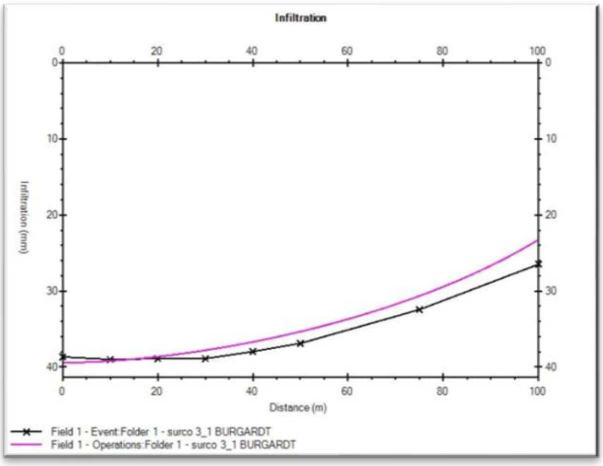

Figure 3. Hydraulic simulation of the irrigation event number 3

4. Discussion and sensitivity analysis

Application efficiency (AE) and distribution uniformity (DUlq) depend on several factors such as soil roughness, weeds, furrow profile, soil water infiltration characteristics, flow rate, slope and furrow length, and irrigation cutoff time. AE values observed in the field and simulated by WinSRFR software for all events were processed and analyzed (Figure 4). A high and positive correlation were observed (r^2 = 0.9), where the maximum application efficiency values reach values of 87%. These values are similar and agree with those found by Raine and Bakker[10].

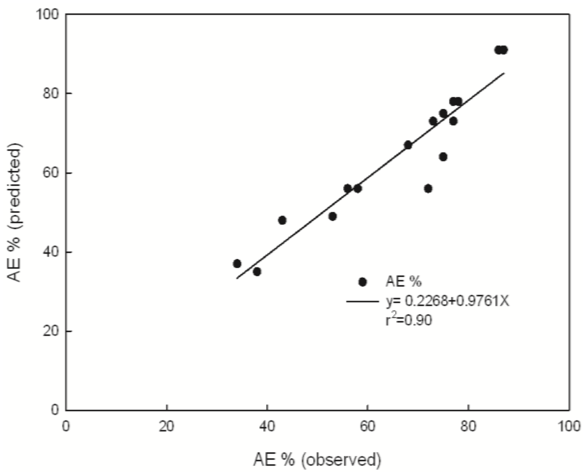

Figure 4. Relationship between application efficiency (AE) from Event Analysis and AE from the Operation Analysis

WinSRFR Operations analysis was used changing variables that affect application efficiency to determine how performance could be improved. In general terms, it was observed that by reducing irrigation cutoff time it was possible to improve AE. On the other hand, when high flow rates are used, better DUlq is achieved, but losses due to runoff increase; otherwise when flow rate is reduced, DUlq become worst.

The following figure (Figure 5) presents the relationship between DUlq observed and Dulq simulated from the total irrigation events, showing that good correlation (r^2=0.76) data reached 0.94 indicates good water distribution along the furrow. Similar data were found by Bautista and others[13].

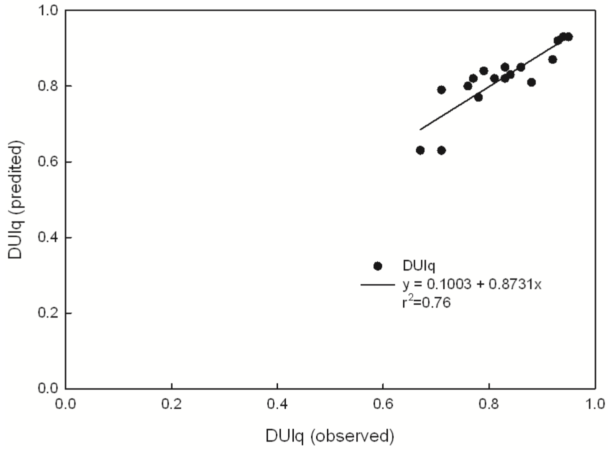

Figure 5. Relationship between distribution uniformity (low quarter) from Event Analysis and distribution uniformity (low quarter) from the Operation Analysis

Ranged value between 1 and 37% on runoff water was observed. Similar runoff data is reported by Carrol and others[29] working with Vertisol soils in Australia. Although they are not excessively high values for the irrigation depth applied, it is interesting to know these indicators for the purposes of an improvement in the hydraulic analysis of the system. The lower these runoff values are, the lower the probability of incurring in excess of runoff water, energy, and potential erosion and contamination problems. Figure 6 below shows the runoff measured in the field during the two irrigation seasons and the runoff predicted by the model. There is a good correlation between the observed and the predicted (r^2 = 0.64).

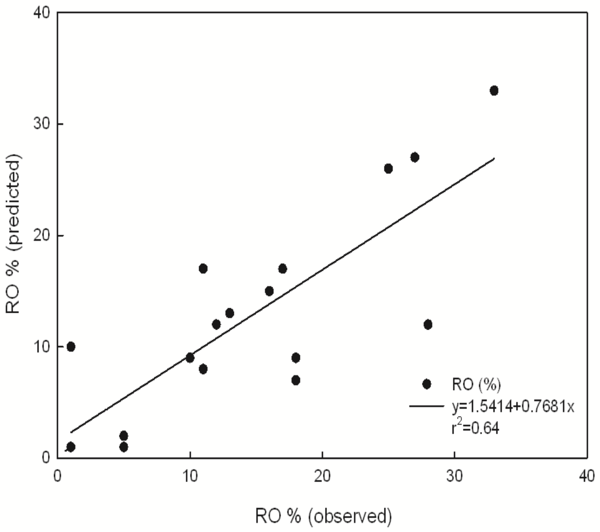

Figure 6. Relationship between runoff (predicted) and runoff observed from each irrigation event

Likewise, important information is presented in the root means square error (RMSE) and the correlation (r^2), as good sensitivity indicators in the variables for this study (Table 7).

Table 7. Sensitivity indicators for variables AE, DUlq and RO

Performance indicators	r^2	RMSE*
AE (%)	0.90	5.38
DUlq	0.76	0.058
RO (%)	0.64	5.57

*RMSE= root means square error

The relationship observed and the simulated data of the application efficiency (AE) showed a high value of r^2 and low value of RMSE. The goodness-of-fit indicators for the distribution uniformity indicator (Dulq) showed a good performance, reaching r^2 of 0.76 and 0.058 for RMSE. In the case of runoff indicators (RO), r^2 was not so high; however, the goodness of fit value (RMSE) was very good.

5. Conclusions

The required average depth in site I was 20 mm, where it applied 27.5 mm and only 24.3 mm were infiltrated. Application efficiency (AE) on site I was 70% and distribution uniformity (DUlq) was 0.83. Applying required depth in most of the cases in 89.2 min in average (opportunity time), runoff was 3.6 mm in the average of all the events.

The required average depth in site II was 24 mm, where it applied 27 mm and only 23.3 mm were infiltrated. Application efficiency was 77.5% and distribution uniformity was 0.86. Average runoff of irrigation events was 4.8 mm.

The average depth required at site III was 10 mm, where between 21 and 18.6 mm was applied and infiltrated. The application efficiency (AE) was 51% and the distribution uniformity (DU) was 0.75. Applying the depth required in most cases in 50 min on average (opportunity time), runoff was 2.45 mm on average for all events. In the case of site III, the length of the furrows was shorter than in the other two sites (48-60 m).

It was observed very good relationship between observed field data and simulated data by WinSRFR program. For AE (%) r^2 was 0.9; for DUlq r^2 was 0.76, and RO (%) was 0.64.

These results allow to conclude that high irrigation performances could be achieved, as well as efficient water use and saving power and labor. In addition, it is highly probable that environmental pollution could be decreased.

These results would contribute to the producers having criteria for the management of furrow irrigation, achieving high irrigation efficiencies and uniformities. Researchers and field technicians will be able to obtain improvement tools in the design of the irrigation system and the criteria for its hydraulic analysis. Although it would be necessary to continue studying irrigation system performances in order to improve EA and DUlq in soils with different physics properties and different slopes.

Acknowledgements

The authors wish to thank the Department of Agriculture of ALUR, SOFORUCE, and especially their technicians, farmers, and field personnel, who made it possible to carry out this experiment in the Bella Unión area. This work was supported by SOFORUCE and the National Agriculture Research Institute (INIA) from Uruguay.

Transparency of data

The entire data set that supports the results of this study was published in the article itself.

Author contribution statement

Gabriel Ribas: Methodology, design of analysis, collection of data, investigation, formal analysis, writing of original draft, review and editing. **Claudio García**: Conceptualization, methodology, design of analysis, collection of data, investigation, writing of original draft, review and editing.

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