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Optimum use of the irrigational water in a wide-spaced irrigation technology

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Abstract

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A six-year field experiment with wide-spaced irrigation of corn was conducted in Sofia region. Three irrigation depths, based on 80%, 75% and 70% of field capacity, and their 50% and 66% reductions, distributed on every furrow, every-other fixed furrow and every-third fixed furrow were tested. The soil was Chromic Luvisols (LVch). Multiple regression analysis was developed to establish the combined effect of three factors: irrigation depth, number of applications and space between the irrigated furrows on the parameters: relative additional yield (RAdY) and relative irrigation water use efficiency (RIWUE). Statistica, Mathcad and Excel software were used for data processing and illustration. A generalized parameter of optimization: an average utility function (AUF) was developed in order to establish the conditions for obtaining maximum RAdY at maximum relative irrigation water use efficiency (RIWUE). It was found that $RAdY_{max}$ can be obtained when distributing in every-other-fixed-furrow (EOFF) the maximum irrigation depth through a maximum number of applications. The number of applications has the biggest effect on the additional yield, while the irrigation depth has almost half of that effect. $RIWUE_{max}$ is obtained when maximum irrigation depth is distributed in ETFF through a maximum number of applications. The spatial pattern of water distribution has the biggest effect on RIWUE. The number of applications has the least effect. $RAdY_{max}$ and $RIWUE_{max}$ are simultaneously obtained through the EOFF technology. The irrigation depth and the number of applications should be maximal. When EOFF is applied, around 10% of the irrigation depth can be saved, while RAdY and RIWUE are nearly maximal.

Keywords: wide-spaced irrigation; corn; yield; irrigation water use efficiency; multiple regression analysis; optimization

Introduction

The irrigation practices, which satisfy the total crop water needs, require significant water amounts and, in most cases, are economically inefficient. The farmers can enhance their production and reduce the environmental harm (Levidow et al., 2014) if they are familiar with some recent improvements of the irrigation technologies and optimization methods. One possibility for achieving higher water use efficiency is the application of small irrigation depths. This seems impossible for surface irrigation, but it could work when water is distributed in every-other furrow (EOF) or every-third furrow (ETF). This so-called wide-spaced technology was tested and found applicable for row crops and capillary soils (Eneva, 1975; Crabtree et al., 1985; Sepaskhah and Kamgar-Haghighi, 1997; Kang et al., 2000; Sepaskhah and Afshar-Chamanabad, 2002). It was established that it contributes for substantial increase of the irrigation water use efficiency (IWUE): a 15-20% yield reduction can be tolerated with 20 to 50% less evapotranspiration losses, which results in 40-50% irrigational water savings (Stone et al., 1982, Crabtree et al., 1985; Kang et al., 2000; Moteva, 2005). Stone et al.

(1982) obtained nearly maximum yields by applying only 50-80% of the optimum irrigation depths. Sepaskhah and Kamgar-Haghighi (1997) obtained 16% more yield from the EOF plots than from the EF ones with 73% of the optimum irrigation depth.

A technology with a localizing irrigation effect, the wide-spaced irrigation maintains soil relatively dry, keeps the soil structure proper and minimizes the deep percolation water losses. It also contributes to a relatively uniform watering over the irrigated territory. The results from Sepaskhah and Afshar-Chamanabad (2002) experiments provide evidence for the soil's higher absorption of irrigational water. The infiltration properties of the EOF water distribution, as estimated by Hodges et al. (1989), were better vs. those of the ordinary every-furrow distribution (EF): the down-furrow advance rate of the water stream was as low as 0.68-0.81 for different combinations of soil type and terrain slope. According to Welde and Gebremariam (2016), for sustainable crop production with sustainable and efficient utilization of limited water resources in a particular area, specific furrow and plant spacing recommendation is very crucial. They concluded that the water was more productive in grain yield using 30 cm plant spacing, in terms of biomass productivity – 20 cm plant spacing but with combination of 70 cm furrow distance, which showed best results, compared to 50 and 90 cm furrow distance.

Some authors tested the wide-spaced irrigation technology at different durations of the in-between application intervals, different application depths, and alternated wet furrows (Stone et al., 1982; Crabtree et al., 1985; Sepaskhah and Kamgar-Haghighi, 1997; Kang et al., 2000). Different durations of the in-between application intervals in EOF were performed on sugar beet. The 6-day interval with smaller application depths appeared to have better effect on the productivity of the crop than the 10-day irrigation interval with greater application depths. It contributed for a similar root yield but for only 23% water savings. The water use efficiency (IWUE) in the case of EOF and smaller irrigation intervals was 43% higher than in the case of EF and the longer intervals. The evapotranspiration losses were limited to some 20-50%. Mintesinot et al. (2004) found enhanced root development and higher grain yield of corn by applying up to 50% of the optimum irrigation depth in alternate furrow irrigation (AF) in comparison with the same water quantity applied in every-other-fixed-furrow (EOFF) or EF irrigation. The IWUE increased was some 58%. This proved that AF irrigation, especially in water deficit conditions, can produce economically better yield than EOFF or EF irrigation.

Alternate furrow irrigation and deficit irrigation are appropriate methods to increase WUE, allowing application of less irrigation water, particularly, for green gram production (Webber et al., 2006). The deficit irrigation increases both the IWUE and the economic profitability of the water. According to English (1981) the farmers are open to adjust their water use with some degree of yield risk in order to gain economic profits. The management of the deficit irrigation is crucial to reducing the crop yield-associated risks and securing the farmer's income. The basic criterion for planning and management of deficit irrigation scheduling is the maximum IWUE, estimated in the yield-water relationship. Oweis et al. (1999), as cited by Mintesinot et al. (2004), tested two levels of deficit irrigation (satisfying 67% and 33% of the full crop water requirement). They concluded that economically reasonable yields can be obtained when the irrigation dose and the intervals are well-monitored, in the sense that the deficit irrigation requires more control over the amount and timing of the water application than the full irrigation. Also, they concluded that the parameters of the deficit irrigation should be optimized in order to obtain minimum yield reduction. An optimization procedure can be performed if the water production functions and the water-stress sensitive stages of the crop are well-known.

Recently, wide-spaced furrow irrigation with different levels of water deficit was tested on several different soil types in Bulgaria – Vertisols, Luvisols and Fluvisols. Chromic Luvisols occupy 2.8 million ha, which is approximately 25.28% of the country surface area. Around 41.1% of them are used for agricultural production and 1 million ha are deep soils, mainly in South Bulgaria. They have heavy texture, especially in the subsurface horizon and peculiar for high water holding capacity and side infiltration (Koynov et al., 1998; Teoharov, 2009).

The above-mentioned experiments were conducted on corn. The crop produced around 85% of the maximum yield when irrigated in EOFF with 50% of the optimum irrigation depth. The IWUE was increased with 71-79% (Eneva, 1975; Moteva, 2005). It was theoretically proven that irrigation has an effect of the corn yield when the distance between the wetted furrows is up to 2.8 m. The economic results were dependent on both the irrigation depth and the pre-irrigation soil moisture. Most efficient was the irrigation in EOFF with 50% of the maximum irrigation depth (Moteva, 2005; Vidinova and Moteva, 2009).

Nowadays, soil water deficit is one of the reasons for reducing the corn cropped area of the country. Since the crop is very sensitive to the soil and the atmospheric moisture, breaking its normal water supply causes productivity deceleration and serious yield decrease (Dimitrova et al., 2005). The unsuitable current climate and economic agents of the agricultural production, comprised of warmth and drought tendencies (Kazanjiev et al., 2011), the recently destroyed irrigation and drainage network, and the high irrigational water prices makes spreading knowledge of irrigation technologies that accelerate the IWUE a necessity. So far, the approaches in establishing the different factors' impact on the yield and on IWUE have been founded in single-regression analyses. In the previous research, the separate factors have been studied individually, but their combined effect has not been determined. The yield-water relationship, for example, accounts only for the effect of the irrigation depth. It does not consider the number of applications, the irrigation application depth, the pre-irrigation soil moisture or the wetting pattern. These parameters may have complimentary effects on the yield and on the economic results. We believe that the farmers can make reasonable decisions about the irrigation process if they rely on a decision tool that accounts for more than one yield factor.

The objective of the paper is to suggest facilitating tools for managing corn irrigation scheduling under wide-spaced irrigation technology with fixed wetted furrows. The tools were developed by means of multiple regression analysis and optimization.

Materials and Methods

Description of the experiment

A 6-year field experiment with wide-spaced irrigation of corn was conducted in the periods 1987-1989 and 1996-1998 in the Sofia region, 42.6° N and 550 m a.s.l. The climate of the site is temperate continental with monthly maximum of the rainfalls in June. The moderately late corn hybrids are usually irrigated in July and August.

The studied hybrid was moderately late (FAO 500): suitable and well-adapted to the natural conditions of the region. Every experimental year was applied the same agricultural practices – date of planting, plant density, quality and type of fertilizers and herbicides, etc.

Three irrigation depths were tested: 1) M_1 = MAD at 80% of field capacity (FC) (the irrigation depth was equal to the maximum allowable deficit) – full irrigation; 2) M_2 = MAD at 75% of FC; 3) M_3 = MAD at 70% of FC. Each of these irrigation depths were distributed in every furrow (EF) (var. 2, 11 and 14) (Table 3). Once the water deficits in var. 2, 11 and 14 reached their respective MADs, the M_1, M_2 and M_3 irrigation applications were given, respectively, to achieve zero water deficits in the plots. Together with the three plots of scheduled irrigation in EF, application depths like M_{11} = 50%M_1, M_{12} = 33%M_1, M_{21} = 50%M_2, M_{22} = 33%M_2, M_{31} = 50%M_3 and M_{32} = 33%M_3 were given in EF, every-other fixed furrow (EOFF) and every-third fixed furrow (ETFF) to other plots, as described in Table 3. The wetted furrows in the wide-spaced irrigation plots were fixed for the entire period of irrigation. Var. 2 was considered the optimum one, since Boyanov et al. (1970) proved that the optimum irrigation scheduling for corn on Chromic Luvisols can be maintained when the pre-irrigation soil moisture is 80% of FC. Hence, $M_1 = M_{opt}$. The pre-irrigation soil moisture in var. 11 and 14 caused certain water deficit in the soil.

The experiment was conducted in randomized complete block design in three replications. The land preparation, the weed control and the fertilizer amount were in compliance with the usual agricultural practices in the region. The soil moisture in var. 2, 11 and 14 was measured through the gravimetric method. Soil samples from every 10 cm-layer within a 1-m soil profile were taken. The net application depths were calculated according to Kostyakov (1956) (eq. 1):

$$m = 10H\alpha(\sigma_W^{FC} - \sigma_W^{80\%FC}), \tag{1}$$

where: m – net irrigation application depth, mm; H – depth of the active root zone (we assumed H = 1 m); a – bulk density of the soil; $\sigma_W^{FC} - \sigma_W^{80\%FC}$ – deficit of available water at 80%, 75% and 70% of FC, respectively, %. The net application depth was multiplied by a coefficient *K,* that reflects the water efficiency of the irrigation system (*K* = 1.3 for surface irrigation systems (Zhivkov, 2013)). The water amount that was delivered within an application was measured by a water meter.

The yields were recalculated for 14% standard grain dampness and were statistically rated by analysis of variance (Shanin, 1977).

The IWUE for every irrigated plot was calculated as (eq. 2):

$$IWUE_n = \frac{Y_n - Y_o}{M_n}, \text{kg/m}^3, \tag{2}$$

where: $IWUE_n$ – the irrigation water use efficiency in the *n* irrigated plot (variant), kg/m³; Y_n – the yield from the *n* irrigated plot (variant), kg/ha*,* Y_o – the yield from the rain-fed plot, kg/ha, M_n – the irrigation depth of the n irrigated plot (variant), mm (m³/ha).

The combined effect of the three factors: the irrigation depth, the space between furrows, and the number of applications on the relative yield and relative IWUE, were studied. By distributing the irrigation water in EOFF and ETFF, the runoff and seepage loss through the soil cracks were minimized because the lateral infiltration of the soil was activated.

Weather and soil data

The meteorological conditions in the years of the experiment were very diverse, therefore the summary results were considered representative. Two of the experimental years were very dry (1987 and 1988), two of them were moderately dry (1996 and 1998), one of them was moderate (1989) and one is moderately wet (1997) (Fig. 1). The probability of exceedance was calculated in a 30-year (1969-1998) statistical row. It ranges from 1.3% to 97.7% for the period of study. The rainfall totals varied from 189 to 616 mm for the vegetation period of corn (April-September), and from 33 to 280 mm for the irrigation period (generally July-August).

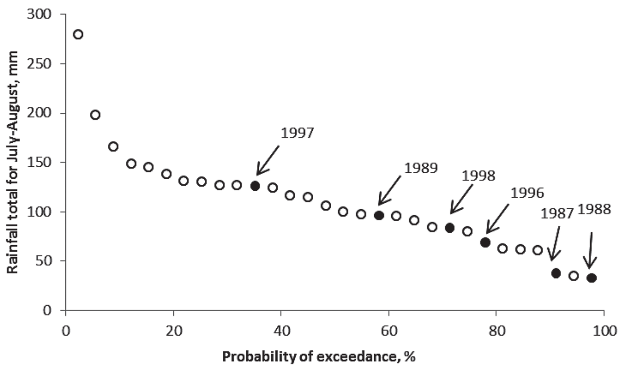

Fig. 1. Empirical curve of the probability of exceedance of the rainfalls occurring during the irrigation season (July-August) in Sofia, period 1969-1998

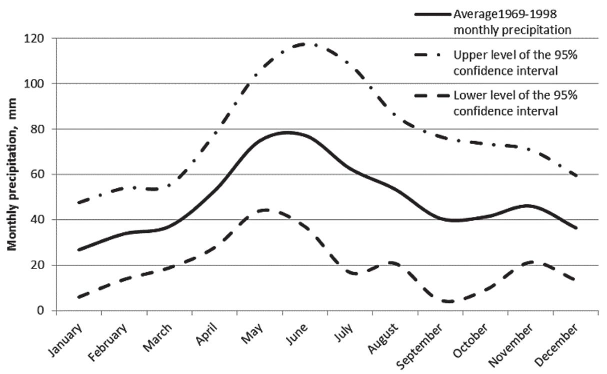

Fig. 2. Average monthly precipitation amount in Sofia region, period 1969-1998

The monthly precipitation was highly variable, as shown on Fig. 2. The April-September air temperature totals varied from 2681°C to 3402°C, average 3030°C. The solid line in Fig. 2 represents the average monthly precipitation; the dashed lines represent the 95% confidence interval for the period 1969-1998.

The soil type in the Sofia region is Chromic Luvisols, clay-loamy, typical for the irrigated areas in South Bulgaria (Table 1). The B-horizon of the soil has good water holding capacity and moderate hydraulic conductivity with good side infiltration. The saturation conductivity of the 0-35-cm soil layer is much less in depth. In a precise multiple-layer investigation (Koleva, 1974), it was found that the 20-40 cm layer has higher conductivity and intensive moisture exhaustion.

The total water content at FC is TWC = 327 mm, the total available water content is TAWC = 165 mm, and the bulk density is α = 1.5 Mg/m^3.

Description of the numerical investigation

Multiple regression analysis of the combined effect of the three factors: irrigation depth, number of applications, and space between the irrigated furrows on the yield and on the IWUE, was developed. The conditions for obtaining maximum RAdY and maximum IWUE were established through optimization of the multiple regression models.

The irrigation depth, the number of irrigation applications and the space between the irrigated furrows were considered factors of the regression model, while the relative additional yield (RAdY) and the relative irrigation water use efficiency (RIWUE) were considered parameters for estimation.

In order to isolate the impact of the meteorological conditions, the estimated parameters were introduced in relative values (%). The additional yield due to irrigation was calculated in relative units (eq. 3):

$$RAdY_n = \frac{Y_n - Y_0}{Y_0} 100 \qquad (3)$$

where: $RAdY_n$ – relative additional yield from the n variant, %; n – number of the irrigated plot (variant) (n=2, 3…16); Y_n – the yield from the n variant, kg/ha; Y_0 – the yield from the rain-fed plot (var. 1), kg/ha; Y_n-Y_o – the additional yield in kg/m^3.

Table 1. Soil texture and hydraulic properties of Chromic Luvisols in Sofia region, period 1969-1998 (Varlev and Popova, 1999)

Depth	Texture	Particle size distribution, %			Hydraulic conductivity at saturation (K_s) (cm/d)	Soil water (cm^3/cm^3)	
		Clay <0.001	Silt 0.05-0.001	Sand >0.05		Field capacity	Permanent wilting point
0-30	SL	32.0	32.0	36	93.0	0.22	0.10
30-60	SCL	41.5	27.0	31.5	17.6	0.23	0.11
60-100	SL	33.0	20.0	47.0	30.5	0.21	0.11

The relative IWUE was calculated as (eq. 4):

$$RIWUE = \frac{IWUE_n}{IWUE_2} 100, \% \quad (4)$$

where: RIWUE – the relative IWUE, %; $IWUE_2$ – the IWUE in var. 2.

A generalized parameter of optimization: an average utility function (AUF) was developed in order to establish the conditions for obtaining maximum RAdY at maximum RIWUE. The following average utility function (AUF) was chosen:

$$AUF = \frac{1}{n}\sum_{i=1}^{n} U_i \quad (5)$$

where: AUF – average utility function; U_i – the utility function (UF) for each of the two parameters RAdY and RIWUE; n – number of the parameters considered, the maximum and minimum values of the experimental results were selected as utility limits.

The utility function of the relevant parameters was determined through the equation:

$$U_i = \frac{Z_i - Z_{min}}{Z_{max} - Z_{min}} \quad (6)$$

where: Z_i – the value of the parameter at a random point in the experiment, Z_{min} and Z_{max} – the minimum and maximum values.

The yield, obtained under rain-fed conditions, was the base for calculation of the additional yield (AdY). The IWUE of the full irrigation variant (var. 2) was considered an IWUE standard. The irrigation depth of var. 2 (full irrigation) was considered an irrigation depth standard.

Table 2. Levels of variation of the independent factors

Factors		Coded value of the factor			Natural value of the factor		
		Lower level	Basic level	Upper level	Lower level	Basic level	Upper level
Spatial pattern of water distribution	X_1	-1	0	1	EF	EOFF	ETFF
Number of irrigation applications	X_2	-1	-	1	2	-	5
Irrigation depth	X_3	-1	0	1	30%	70%	110%

Table 3. Number of applications and irrigation depths, experiment of wide spaced irrigation of corn in Sofia region, 1987-1989 and 1996-1998

Var.	Irrigation schedule	Irrig. Depth Code	Relative Irrig. Depth	Appl. Depth	Wat. Dis-tribut. pattern	1987		1988		1989		1996		1997		1998	
						Appl. nb	Irr. Dpth	Appl. nb	Irr. Dpth	Appl. nb	Irr. Dpth	Appl. nb	Irr. Dpth	Appl. nb	Irr. Dpth	Appl. nb	Irr. Dpth
			%	Mm		nb	mm	nb	mm	nb	mm	nb	mm	nb	mm	nb	mm
1	Rain-fed	-	-	-		-	-	-	-	-	-	-	-	-	-	-	-
2	M_1=MAD at 80% of FC	M_1	100%M_1	60	EF	5	300	4	240	3	180	3	180	3	180	3	180
3	Irrigated together with Var.2	M_1	100%M_1	60	EOFF	-	-	-	-	-	-	3	180	3	180	3	180
4		M_1	100%M_1	60	ETFF	-	-	-	-	-	-	3	180	3	180	3	180
5		M_{11}	50%M_1	30	EF	-	-	-	-	-	-	3	90	3	90	3	90
6		M_{11}	50%M_1	30	EOFF	5	150	4	120	3	90	3	90	3	90	3	90
7		M_{11}	50%M_1	30	ETFF	-	-	-	-	-	-	3	90	3	90	3	90
8		M_{12}	33%M_1	20	EF	-	-	-	-	-	-	3	60	3	60	3	60
9		M_{12}	33%M_1	20	EOFF	-	-	-	-	-	-	3	60	3	60	3	60
10		M_{12}	33%M_1	20	ETFF	5	100	4	80	3	60	-	-	-	-	-	-
11	M_2=MAD at 75% of FC	M_2	100%M_2	80	EF	4	320	3	240	2	160	-	-	-	-	-	-
12	Irrigated together with Var.11	M_{21}	50%M_2	80	EOFF	4	160	3	120	2	80	-	-	-	-	-	-
13		M_{22}	33%M_2	80	ETFF	4	104	3	78	2	52	-	-	-	-	-	-
14	M_3=MAD at 70% of FC	M_3	100%M_3	100	EF	3	300	2	200	2	200	-	-	-	-	-	-
15	Irrigated together with Var.14	M_{31}	50%M_3	100	EOFF	3	150	2	100	2	100	-	-	-	-	-	-
16		M_{32}	33%M_3	100	ETFF	3	99	2	66	2	66	-	-	-	-	-	-

The factors were coded as shown in Table 2. The minimum values noted as (-1) and the maximum values as 1. A second power polynomial was chosen to describe the regression model surface of distinctiveness. Its general appearance was (eq. 5):

$$Y = b_0 + b_1x_1 + b_2x_2 + b_3x_4 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 + + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 \quad (7)$$

Statistica, Mathcad and Excel software were used for the data processing and illustration. The full model was optimized without removing the insignificant coefficients because they contain certain process information. The effect of each factor by itself on the parameters was estimated through a procedure of consecutive cutoff.

Results and Discussion

Results for the yield and IWUE from the field experiment

The results in Table 3 show that, depending on the wetting pattern of the year, the number of applications varied from 3 to 5 and the irrigation depth in the full irrigation variant (var. 2) varied from 60 mm to 180 mm. The maximum irrigation depth in the experiment M_{max} = 320 mm was obtained in the very dry 1987 through four EF applications (var. 11). The minimum irrigation depth M_{min} = 52 mm was obtained in 1989, a year of moderately dry conditions, through two ETFF applications (var. 13, Table 3).

The highest yield was obtained through full irrigation (M_{opt}, var. 2) in the very dry 1988. It was 14.24 Mg/ha. The yields obtained through M_{opt} were significantly higher in all the years. They varied from 9.34 Mg/ha to 14.34 Mg/ha. All wide-spaced irrigation variants had lower yields. The main reason for that was either water loss by deep percolation, insufficiency of water for meeting the crop water needs, or both (Table 4).

The IWUE was highest in the very dry 1988 in No. 10 and No. 16 ETFF variants. It was 8.0 kg/m^3 and 8.3 kg/m^3, respectively. Depending on the wetting pattern of the year, the IWUE in the full irrigation variant (var. 2) varied from 0.81 kg/m^3 to 4.59 kg/m^3 (Table 4).

Table 4. Yield and irrigation water use efficiency (IWUE), experiment of wide spaced irrigation of corn in Sofia region, 1987-1989 and 1996-1998

Var.	Irrigation schedule	Irrig. Depth Code	Relative Irrig, Depth %	Appl. Depth mm	Water distr. pattern	Yield, Mg ha^{-1}						IWUE$_n$, kg m^{-3}					
						1987	1988	1989	1996	1997	1998	1987	1988	1989	1996	1997	1998
1	Rain-fed	-	-	-	-	2.69	3.70	6.91	4.13	7.14	5.21	-	-	-	-	-	-
2	M_1=MAD at 80% of FC	M_1	100%M_1	60	EF	12.24	14.34	9.34	9.79	8.53	12.57	3.21	4.59	1.35	2.54	0.81	4.09
3	Irrigated together with Var.2	M_1	100%M_1	60	EOFF	-	-	-	10.74	8.04	11.90	-	-	-	5.71	1.51	5.3
4		M_1	100%M_1	60	ETFF	-	-	-	9.15	8.19	12.58	-	-	-	6.28	2.65	7.61
5		M_{11}	50%M_1	30	EF	-	-	-	7.52	7.95	8.55	-	-	-	3.05	0.47	3.72
6		M_{11}	50%M_1	30	EOFF	9.25	11.63	9.01	8.80	7.72	9.98	4.4	6.84	2.33	6.17	1.57	4.82
7		M_{11}	50%M_1	30	ETFF	-	-	-	7.85	7.56	9.68	-	-	-	5.73	1.72	7.44
8		M_{12}	33%M_1	20	EF	-	-	-	6.02	7.69	6.78	-	-	-	1.45	0.77	4.09
9		M_{12}	33%M_1	20	EOFF	-	-	-	6.69	7.20	7.68	-	-	-	2.87	0.77	4.96
10		M_{12}	33%M_1	20	ETFF	5.91	8.80	8.30	-	-	-	3.24	8.0	2.32	-	-	-
11	M_2=MAD at 75% of FC	M_2	100%M_2	80	EF	10.21	12.26	9.09	-	-	-	2.37	3.64	1.37	-	-	-
12	Irrigated together with Var.11	M_{21}	50%M_2	80	EOFF	8.07	10.40	8.81	-	-	-	3.39	5.78	2.38	-	-	-
13		M_{22}	33%M_2	80	ETFF	5.59	7.67	8.12	-	-	-	2.71	5.21	2.28	-	-	-
14	M_3=MAD at 70% of FC	M_3	100%M_3	100	EF	9.88	12.03	9.28	-	-	-	2.42	4.31	1.19	-	-	-
15	Irrigated together with Var.14	M_{31}	50%M_3	100	EOFF	7.44	9.36	8.12	-	-	-	3.19	7.12	1.21	-	-	-
16		M_{32}	33%M_3	100	EOFF	4.66	7.26	7.90	-	-	-	1.99	8.3	1.47	-	-	-
$LSD_{5\%}$							2.33			2.13							
$LSD_{1\%}$							3.19			2.93							
$LSD_{0.1\%}$							4.34			4.02							

Estimating the effect of the irrigation depth, the number of irrigation applications and the space between the irrigated furrows on RAdY

The results of the regression analysis for the parameter RAdY are presented in Table 5. This table was extracted from Statistica software. It shows that the coefficient of determination is R^2 = 0.56 and the Fisher's test result is F (9, 41) = 5.8397 at a probability $p < 0.00003 < 0.05$. These statistical features are sufficient grounds to consider the model adequate to the behavior of the studied parameter. This model describes more than 56% of the parameter's variation.

The data in Table 5 shows that there is no combined effect on RAdY between the studied factors. Each factor has its own individual effect on the yield. In order to estimate the effect of each factor, a consecutive cutoff procedure was applied. The results show that the number of applications had the greatest effect on the yield, while the irrigation depth had almost half of that effect. The spatial pattern of the water distribution had the least effect.

After suspending the insignificant coefficients, the relative additional yield (in an encoded mode) can be calculated as (eq. 8):

$$RAdY = 162.71 + 122.79\,X_2 + 72.55\,X_3 \qquad (8)$$

The lines of identical response indicate the cross-section of the response surface area at the optimum value of the factor X_1 (Fig. 3). Since the optimal value is close to zero (X_1 = 0.43), we assume that X_1 is identical to the EOFF. The figure below illustrates the combined effect of the main factors on the yield when the water is distributed in EOFF. It also shows that a yield close to $RAdY_{max}$ can be obtained if the irrigation

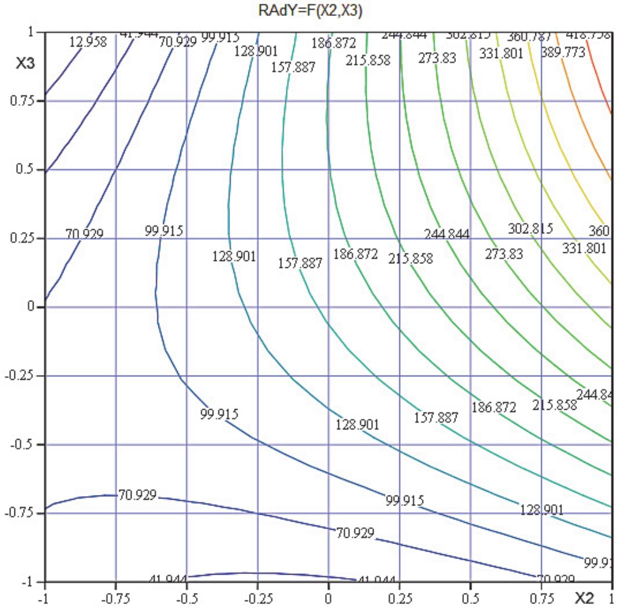

Fig. 3. Dependence of the relative additional yield on the irrigation depth (X_3) and on the number of applications (X_2), experiment of wide spaced irrigation of corn in Sofia region, 1987-1989 and 1996-1998

Table 5. Results from the regression analysis for relative additional yield (RAdY) experiment of wide spaced irrigation of corn in Sofia region, 1987-1989 and 1996-1998

N=51	Regression Summary for Dependent Variable: RAdY,% R= ,74951001 R^2= ,56176526 Adjusted R^2= ,46556738 F(9,41)=5,8397 p<,00003 Std.Error of estimate: 64,861					
	Beta	Std.Err. of Beta	B	Std.Err. of B	t(41)	p-level
Intercept			162,7122	24,12922	6,74337	0,000000
X1	0,023328	0,251290	2,5545	27,51719	0,09283	0,926489
X2	0,675712	0,147935	122,7941	26,88350	4,56764	0,000045
X3	0,567198	0,254506	72,5489	32,55326	2,22862	0,031382
X12	0,213837	0,374481	40,9116	71,64618	0,57102	0,571101
X13	-0,200241	0,121067	-31,2828	18,91374	-1,65397	0,105770
X23	0,501387	0,390690	109,0919	85,00634	1,28334	0,206580
X11	-0,077535	0,117106	-14,2531	21,52747	-0,66209	0,511618
X22	0,137516	0,113487	32,0317	26,43470	1,21173	0,232554
X33	-0,148771	0,117751	-51,4347	40,71005	-1,26344	0,213568

depth is in the interval $98\%M_{max} - M_{max}$ and the number of applications is at a maximum.

After maximization of RAdY functional, it was obtained:

$$f_{max} = \begin{pmatrix} 0.427 \\ 1 \\ 1 \end{pmatrix}$$

The value of the function at the issued point is f_{max} = 450.348. It means that the maximum relative additional yield is $RAdY_{max}$ = 450,348% and it is obtained when watering in EOFF with maximum number of applications (i.e. 5 applications) and maximum irrigation M_{max} (i.e. 320 mm).

The graph on Fig. 4 shows the nature of the interaction between factors X_1 (the spatial pattern of water distribution) and X_3 (the irrigation depth) at an optimal X_2 (the number of applications) value. The figure illustrates that the spatial pattern of the irrigation water distribution has no significant effect on the additional yield when the irrigation depth is in the range $98\%M_{max} - M_{max}$ (M_{max} = 110%). This means that when the irrigation depth is in the interval $98\%M_{max} - M_{max}$, there is enough water for deep and side infiltration and for root expansion in every part of the root zone. A yield close to $RAdY_{max}$ can be obtained if the irrigation depth is in the interval $98\%M_{max} - M_{max}$ regardless of the water distribution spatial pattern (Fig. 4).

Estimating the effect of the irrigation depth, the number of irrigation applications and the space between the irrigated furrows on the irrigational water use efficiency

The results of the regression analysis for RIWUE are presented in Table 6. This table was extracted from Statistica software. The coefficient of determination is R^2 = 0.61. The Fisher's test result is F (9, 41) = 7.1 at a probability

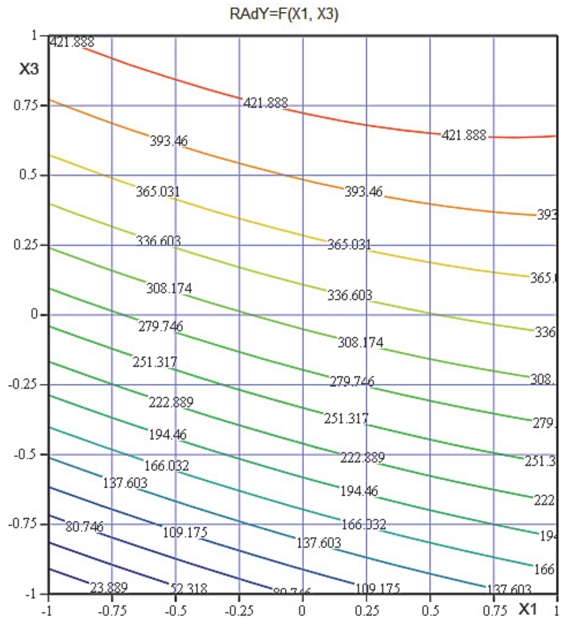

Fig. 4. Dependence of the relative additional yield on the irrigation depth (X_3) and the spatial pattern of irrigation water distribution (X_1), experiment of wide spaced irrigation of corn in Sofia region, 1987-1989 and 1996-1998

Table 6. Results from the regression analysis for relative irrigation water use efficiency (RIWUE), experiment of wide spaced irrigation of corn in Sofia region, 1987-1989 and 1996-1998

	Regression Summary for Dependent Variable: RIWUE,% R= ,78050170 R^2= ,60918291 Adjusted R^2= ,52339379 F(9,41)=7,1009 p<,00000 Std.Error of estimate: 39,201					
N=51	Beta	Std.Err. of Beta	B	Std.Err. of B	t(41)	p-level
Intercept			166,5686	14,58347	11,42174	0,000000
X1	0,828214	0,237306	58,0438	16,63113	3,49007	0,001169
X2	-0,070477	0,139702	-8,1969	16,24813	-0,50448	0,616625
X3	0,507968	0,240343	41,5831	19,67488	2,11351	0,040687
X12	-0,014923	0,353641	-1,8272	43,30227	-0,04220	0,966547
X13	0,316586	0,114329	31,6540	11,43128	2,76907	0,008404
X23	0,115483	0,368949	16,0813	51,37702	0,31301	0,755863
X11	-0,051209	0,110589	-6,0248	13,01100	-0,46305	0,645774
X22	-0,008131	0,107172	-1,2121	15,97688	-0,07587	0,939893
X33	-0,133160	0,111198	-29,4642	24,60477	-1,19750	0,237989

p < 0.00000 < 0.05. These statistical features are sufficient grounds to consider the model adequate to the behavior of the studied parameter. This model describes 61% of the parameter's variation. The effects of the individual factors on RIWUE were estimated through a procedure of consecutive cutoff. The spatial pattern of the water distribution has the greatest effect on RIWUE; the irrigation depth has less effect; the number of applications has the least effect, which is 13 times less than that of the water distribution spatial pattern. Table 6 shows that the number of applications is an insignificant factor, while the combined effect of the water distribution spatial pattern and the irrigation depth (reflected in coefficient X_{13}) is significant.

After suspending the insignificant coefficients, the relative irrigation water use efficiency (in an encoded mode) can be calculated as (eq. 9):

$$RIWUE = 166.57 + 58.04\,X_1 + 41.58\,X_3 + 31.65\,X_1X_3 \quad (9)$$

After maximization of RIWUE functional, it was obtained:

$$f_{max} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

The value of the function at the issued point is f_{max} = 267.205. It means that the maximum relative water use efficiency is $RIWUE_{max}$ = 267.205%. It is obtained when watering in ETFF with maximum number (i.e. 5 applications) of applications and maximum irrigation M_{max} (i.e. 320 mm).

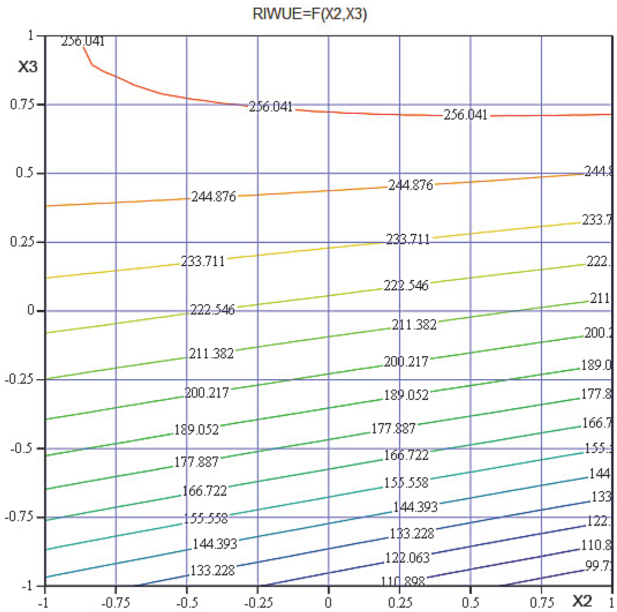

Fig. 5. Dependence of the relative irrigation water use efficiency on the number of applications (X_2) and the irrigation depth (X_3), experiment of wide spaced irrigation of corn in Sofia region, 1987-1989 and 1996-1998

The graph in Fig. 5 illustrates that a close to $RIWUE_{max}$ value can be obtained at X_3 = 0.75, which corresponds to 90%M_{max}, regardless of the number of applications.

Table 7. Results from the regression analysis for Average Utility Function (AUF), experiment of wide spaced irrigation of corn in Sofia region, 1987-1989 and 1996-1998

N=51	Regression Summary for Dependent Variable: AuF R= ,76085746 R²= ,57890408 Adjusted R²= ,48646839 F(9,41)=6,2628 p<,00002 Std.Error of estimate: ,10645					
	Beta	Std.Err. of Beta	B	Std.Err. of B	t(41)	p-level
Intercept			0,432177	0,039602	10,91297	0,000000
X1	0,608115	0,246327	0,111494	0,045163	2,46873	0,017818
X2	0,519660	0,145013	0,158115	0,044123	3,58354	0,000892
X3	0,839150	0,249480	0,179710	0,053428	3,36360	0,001678
X12	0,169697	0,367085	0,054359	0,117589	0,46228	0,646323
X13	0,056099	0,118676	0,014674	0,031042	0,47271	0,638927
X23	0,504801	0,382974	0,183898	0,139517	1,31811	0,194785
X11	-0,101758	0,114793	-0,031320	0,035332	-0,88645	0,380547
X22	0,110171	0,111246	0,042967	0,043386	0,99034	0,327819
X33	-0,220048	0,115425	-0,127378	0,066815	-1,90641	0,063623

Estimating the effect of the irrigation depth, the number of irrigation applications and the space between the irrigated furrows on the average utility function

The results from the regression analysis for the parameter Average Utility Function (AUF) are presented in Table 7. This table was extracted from Statistica software. The coefficient of determination is $R^2 = 0.58$. The Fisher test result is F (9, 41) = 6.26 at a probability $p < 0.00002 < 0.05$. These statistical features are sufficient grounds to consider the model adequate to the behavior of the studied parameter. This model describes 58% of the parameter's variation. The effect of the individual factors on AUF was estimated through a procedure of consecutive cutoff. The irrigation depth has the greatest effect on RIWUE and RAdY. The spatial pattern of water distribution and the number of applications have a similar effect, which is less than that of the irrigational depth.

After suspending the insignificant coefficients, the utility function (in an encoded mode) can be calculated as (eq. 10):

$$AUF = 0.43 + 0.11\ X_1 + 0.15\ X_2 + 0.17\ X_3 \qquad (10)$$

The optimization of this utility function shows that maximum yield at maximum irrigation water efficiency can be obtained when the values of all three factors are maximum. The graph in Fig. 6, which illustrates the effects of the number of irrigation applications and the irrigation depth, shows that optimum results can be obtained in the interval $90\%M_{max} - M_{max}$. Nearly maximum additional yield at maximum irrigation water use efficiency can be obtained by saving around 10% of the irrigation depth.

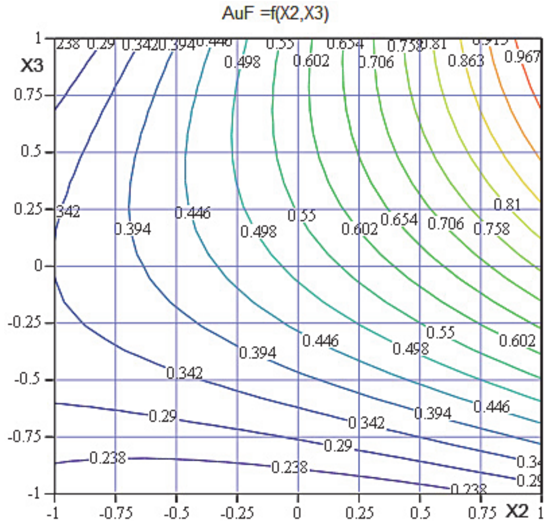

Fig. 6. Dependence of AUF on the irrigation depth (X_3) and the number of applications (X_2), experiment of wide spaced irrigation of corn in Sofia region, 1987-1989 and 1996-1998

The graph on Fig. 7 shows that the water distribution spatial pattern and the irrigation depth have similar effect on AUF within the optimal area.

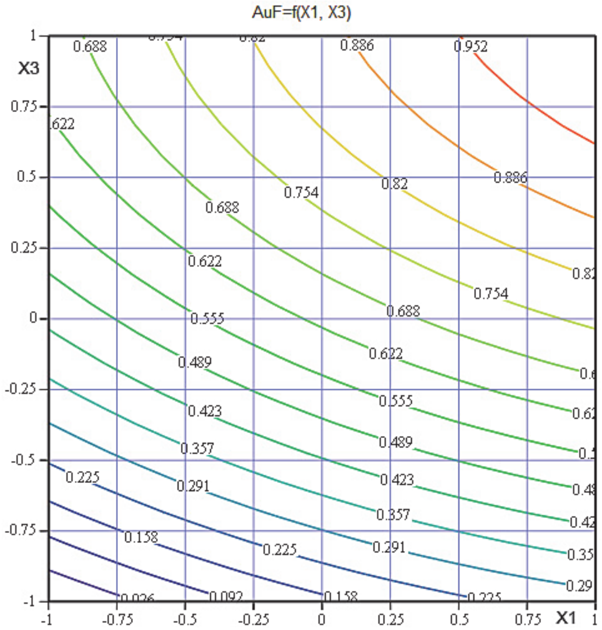

Fig. 7. Dependence of the average utility function on the irrigation depth (X_3) and the spatial pattern of irrigation water distribution (X_1), experiment of wide spaced irrigation of corn in Sofia region, 1987-1989 and 1996-1998

Conclusions

The present study evaluates the combined effect of three factors: the water distribution spatial pattern, the number of irrigation applications and the irrigation depth on the yield and water use efficiency under furrow irrigation of corn.

Maximum additional yield can be obtained when distributing the maximum irrigation depth in every-other-fixed-furrow (EOFF) through a maximum number of applications. Nearly maximum yield can be obtained at an irrigation depth in the interval $98\%M_{max} - M_{max}$, through a maximum number of applications. The number of applications has the greatest effect on the additional yield, while the irrigation depth has almost half of that effect. This is valid for all water distribution spatial patterns: every furrow (EF), every-other-fixed-furrow (EOFF) or every-third-fixed-furrow (ETFF). A regression equation for RAdY calculation on the base of the irrigation depth applied and the number of irrigation applications was derived.

Maximum irrigation water use efficiency can be obtained when the irrigation depth is in the interval 90% M_{max}

– M_{max} and is distributed in every-third-fixed furrow (ETFF) through a maximum number of applications. The spatial pattern of water distribution has the greatest effect on the irrigation water use efficiency. The number of applications has the least effect: 13 times less than that of the water distribution spatial pattern. A regression equation for RIWUE calculation on the base of the water distribution spatial pattern and the number of irrigation applications was derived.

The wide-spaced irrigation technology demonstrates its advantages at every-other-fixed furrow (EOFF) irrigation. Nearly maximum additional yield at maximum irrigation water use efficiency can be obtained by saving around 10% of the irrigation depth. A regression equation for AUF calculation on the base of the three factors: water distribution spatial pattern, irrigation depth and number of irrigation applications was derived. It can be used for determining the field of maximum results in an EOFF irrigation technology.

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