14 - SURGE-FLOW IRRIGATION FOR WATER SAVING

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Abstract: To improve water saving and conservation in irrigated agriculture, a range of field evaluation experiments was carried out with various furrow irrigation treatments in cotton fields to estimate the possibilities of improving furrow irrigation performances under conditions of Central Fergana Valley, Uzbekistan. The research consisted in comparing surge and continuous flow in long furrows and adopting alternate-furrow irrigation. The best results were achieved with surge flow irrigation applied to alternate furrows. Field data allowed the calibration of a surface irrigation model that was used to identify alternative management issues. Results identified the need to better adjust inflow rates to soil infiltration conditions, cutoff times to the soil moisture deficits and improving irrigation scheduling. The best irrigation water productivity (0.61 kg/m^3) was achieved with surge flow on alternate furrows, which reduced irrigation water use by 44% (390 mm) and led to high application efficiency, near 85%. Results demonstrated the possibility for applying deficit irrigation in this region.

Keywords: Water productivity, Application efficiency, Distribution uniformity, Alternate-furrow irrigation, Deficit irrigation.

Introduction

A first study on cotton furrow irrigation has shown that cutting the volumes applied by controlling the cut-off times and the adoption of alternate-furrow irrigation could lead to considerable water savings relative to traditional every-furrow irrigation (Horst *et al.*, 2005). The same study also identified the need to better adjust the irrigation timings because the traditional irrigation results in small soil moisture deficits at time of irrigation, thus leading to high percolation and runoff volumes. The need to assess the potential water saving when adopting surge flow was then identified.

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The surge flow technology was first developed and used in Bulgaria (Varlev, 1971; Varlev *et al.*, 1998) and in the former USSR, namely in Kyrgyzstan and Uzbekistan (Penzin and Terpigorev, 1977; Khamrayev and Yusupov, 1980; Terpigorev, 1983; Pavlov and Horst, 1995). However, the lack of effective interest by users did not allow for a wide application of this advanced technology in the practice. Thus, despite it was developed later in USA (Stringham and Keller, 1979), this technique became worldwide known after it was extensively applied in USA since the 80's (Walker and Skogerboe, 1987; Humpherys, 1989). Surge irrigation can decrease labour (automatic irrigation of two sets at one setting), improve distribution uniformity (faster advance), and reduce runoff (quasi-cutback flows).

Studies developed in Uzbekistan (Horst *et al.*, 1990) identified an area of about 1 million ha, or 24% of total national irrigated area as potentially suitable for the surge flow technology. This research, based upon those former studies, aims at assessing the potential water savings in furrow irrigation for cotton when using surge flow and alternate-furrow irrigation.

Material and Methods

Treatments

The field studies on surge flow irrigation were conducted in a cotton field in the farm «Azizbek-I» located in the Central Fergana Valley during the growing season 2002. Three treatments were analysed (Table 1).

Table 1. Surge and continuous flow treatments in alternate-furrow irrigation.

Irrigation treatments	Furrow number	Length (m)	Slope (m/m)	Inflow rate (l/s)	Soil compaction
Fa - Surge flow	17	320	0.0028	2.4/1.2	Compacted
	18	320	0.0028	2.4/1.2	Compacted
Fb - Surge flow	21	320	0.0028	3.0/1.5	Compacted
	22	320	0.0028	3.0/1.5	Compacted
G - Continuous flow	19	320	0.0028	2.4	Compacted
	20	320	0.0028	2.4	Compacted

* Furrow spacing was 0.9 m.

Dates and duration of water application for the control treatment G were decided by the farmer. Water was applied when it was available for that given field, thus reflecting the actual irrigation delivery rotation among several farms.

Due to lack of gated pipes to deliver the water to the furrows, surge flow was not automated but adapted to the existing conditions, where water is supplied to the furrows through an earth distribution ditch, which is supplied by a field ditch (Fig. 1). To do so, the water supplied by the field ditch is flowing to the left or the right side of the distribution ditch with help of a manually controlled disk valve. The procedure is labour consuming but similar to the current continuous flow practice. The present lack of capital to invest in automation has lead to develop such a simplified technique.

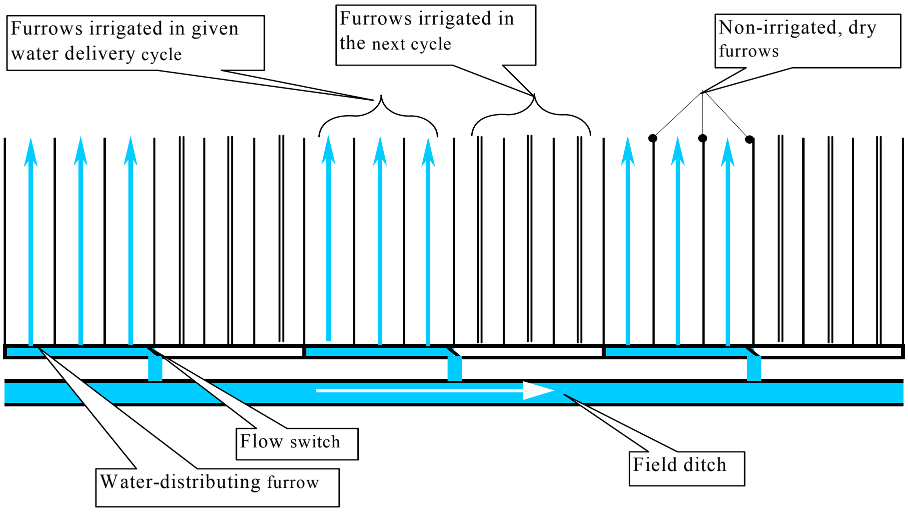


Fig. 1. Schematic diagram of surge flow applied to alternate-furrow irrigation.

The surge-flow irrigation was managed following the one-fourth rule. The first surge was started by applying water to the right and lasted until the advance was completed over one fourth of the field. Then water was applied to the left until the first fourth was completed and then successively to the right and the left to complete the full advance over the field (Fig. 2). When the advance was completed in the furrows at left, the valve was re-shifted in such a way that the furrows on right received half of initial discharge and, after a period of time equalling the duration of the fourth surge, the discharge was increased twofold and divided into both sides, which were irrigated at the same time. When finishing irrigation of the furrows on the right, the discharge was reduced and only the furrows on left were irrigated until the irrigation was completed (Fig. 2).

Field evaluation procedures

Soil characteristics referring to 6 genetic horizons selected from soil survey are presented in Table 2. The soil bulk density (γ_d, g/cm^3) was determined by the methodology described by Walker (1989). The soil water content at field capacity (FC) and wilting point (WP) (mm/m) were determined in laboratory using the pressure membrane at -1/3 atm and –15 atm suction pressure, respectively. Data in Table 2 show that the soil has high soil water holding capacity and is very appropriate for surface irrigation using high application depths and low irrigation frequencies.

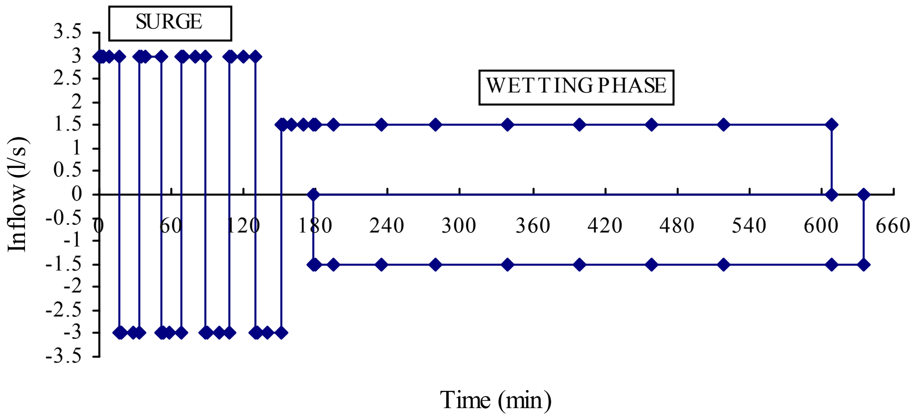


Fig. 2. Surge flow irrigation schedule for treatment Fb (positive values refer to irrigation on the left side and negative to the right side).

Table 2. Soil water and physical characteristics.

Genetic horizon (cm)	Layer thickness (cm)	Bulk density (g/cm^3)	Porosity (%)	Field capacity (m^3 m^{-3})	Field capacity (mm)	Wilting point (m^3 m^{-3})	Wilting point (mm)	Available soil water (m^3 m^{-3})	Available soil water (mm)
0-25	25	1.24	52.3	0.335	83.8	0.170	42.5	0.165	41.3
25-45	20	1.47	42.5	0.325	65.0	0.165	33.0	0.160	32.0
45-66	21	1.43	47.4	0.297	62.4	0.165	34.7	0.132	27.7
66-83	17	1.54	41.5	0.241	41.0	0.108	18.4	0.133	22.6
83-94	11	1.30	49.0	0.318	35.0	0.187	20.6	0.131	14.4
94-100	6	1.58	37.4	0.35.0	21.0	0.190	11.4	0.160	9.6
0-100	**100**	**1.40**	**46.2**	**0.308**	**308.1**	**0.161**	**160.5**	**0.148**	**147.6**

The methodology used for the evaluation of furrow surge irrigation follows that by Walker and Skogerboe (1987), Walker (1989), ASAE (2003) and Pavlov and Horst (1995). The measurements included assessment of: land levelling conditions, furrow discharges, furrow cross-sections, advance and recession, hydraulics roughness and infiltration. Related methodologies are those referred in the companion paper by Horst *et al.* (2005).

The Kostiakov infiltration equation, which is adopted in the surface irrigation simulation model SIRMOD (ISED, 1989), was used:

$$Z = k\tau^{\alpha} + f_o\tau \qquad [1]$$

where Z is cumulative infiltration per unit length of furrow (m^3/m), τ is intake opportunity time (min); α and k are empirical parameters, and f_o is the empirical base infiltration rate ($m^3/min/m$). The best parameter values were obtain after several iterations with the simulation model SIRMOD aiming at minimizing the sum of the squares of the deviations between observed and simulated advance and recession times (Calejo *et al.*, 1998). The roughness parameter n was kept constant.

The initial values for the infiltration parameters f_o, α and k were determined using the "two-point" method (Walker and Skogerboe, 1987). The SIRMOD model uses also a Kostiakov infiltration equation to the soil under surge effect conditions (referred below with the subscript s), which is supposed to happen after the third wetting:

$$Z_s = k_s \cdot \tau^{\alpha_s} + f_s \cdot \tau \qquad [2]$$

During the second wetting, both equations 1 and 2 are applied and they are balanced by a distance based factor FP:

$$FP = \left\{ \begin{array}{ll} \left(\dfrac{x_{i-1} - x}{x_{i-1} - x_{i-2}} \right)^{\lambda} & (\text{if } x_{i-2} \le x \le x_{i-1}) \\ 0 & (\text{if } x < x_{i-2}) \\ 1 & (\text{if } x > x_{i-1}) \end{array} \right\} \qquad [3]$$

where x is the distance of the calculation section to the origin during time step i, and λ is an empirical factor, taking usually the value of 3 (ISED, 1989). It results the equation:

$$Z = [k + (k - k_s)\, FP]^{\,\tau[\alpha + (\alpha - \alpha s)\, FP]} + [f_0 + (f_0 - f_s)\, FP]\, \tau \qquad [4]$$

Soil water content measurements were performed before and 2-3 days after irrigation. The methodology applied is referred by Horst *et al.* (2005). Soil water data were used through a simplified soil water balance to estimate the irrigation depths required (Z_{recq}). The maximum soil moisture deficit, SMD (mm), observed was assumed as the best estimate of Z_{recq}. For all irrigation events, the root zone depth, RD (m), was assumed equal to 0.7 m based on phenological estimations of the maximum development of cotton roots.

Performance indicators

The performance indicators are the same as for the previous study (Horst *et al.*, 2005): the application efficiency, E_a (%), and the distribution uniformity, DU (%). DU characterizes the irrigation system and E_a is a management performance indicator (Pereira and Trout, 1999; Pereira *et al.*, 2002a, b). In addition, the indicators E_r (%), water requirement efficiency, IE (%), infiltration efficiency, TWR (mm or %), tail water runoff, and DPR (mm; %), deep percolation, were also used to characterize surge irrigation (Walker and Skogerboe, 1987; ASAE, 2003).

E_r (%) was estimated by

$$E_r = \frac{Z_{\text{avg (root zone)}}}{Z_{\text{recq}}} \times 100 \qquad [5]$$

and IE (%) was derived from:

$$IE = \frac{Z_{\text{avg}}}{D} \times 100 \qquad [6]$$

DPR was computed from the difference between Z_{avg} and $Z_{avg(root\ zone)}$, which were estimated from computing the depth of water infiltrated during the intake opportunity time relative to each location i at each 20 m along the furrows using the calibrated Kostiakov equation:

$$\mathrm{Z_i = k[t_r - (t_a)_i]^a + f_0[t_r - (t_a)_i]} \qquad [7]$$

where t_r and t_a are respectively the recession and the advance times (min) at the location i. SIRMOD computations were used. A similar procedure was applied to estimate Z_{lq}.

The average depth of water applied, D (mm), was computed from:

$$D = \frac{q_{avf} \times 60 \times t_{co}}{L \times s} \qquad [8]$$

where q_{avf} is the average furrow inflow rate (l/s) during an irrigation event, t_{co} is the cutoff time or duration of the inflow (min), and s is the furrows spacing (m).

The average outflow depth at the tail end of the furrow, V_{out} (mm), was calculated from:

$$V_{out} = \frac{q_{out} \times 60 \times t_{out}}{L \times s} \qquad [9]$$

where q_{out} is the average runoff rate at the tail end of the furrow (l/s) during the runoff time tout (min). TWR was computed from V_{out}.

Results

Furrow slopes and forms

The average furrow slope observed was S_{avg} = 0.00284 m/m. Typical furrow cross profiles for surge flow and continuous flow, before and after irrigation, are shown in Fig. 3. It can be noted that continuous flow erodes the -bottom part of the furrow (Fig. 3a) while under surge flow the profile is subjected only to reformation and the -bottom part is filled with the soil from furrow sides (Fig. 3b). Alternate surges and pauses make that the furrow bottom is less subject to erosion. This ensures better conditions to preserve the soil fertility even at high inflows, such as $q_{inflow} = 2.4 - 3.0$ l/s.

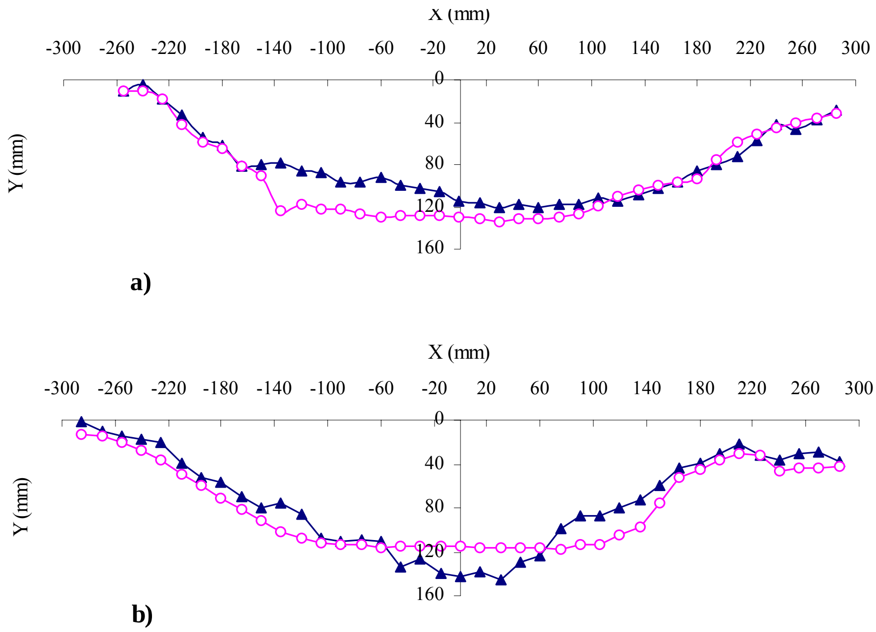


Fig. 3**.** Typical furrow cross profiles before (▲) and after (○) irrigation: a) continuous-flow; b) surge-flow.

Inflow-outflow hydrographs

Measured inflows and outflows for the both types of irrigation and all options are given in Table 3. An example of Inflow-outflow hydrographs is given in Fig. 4.

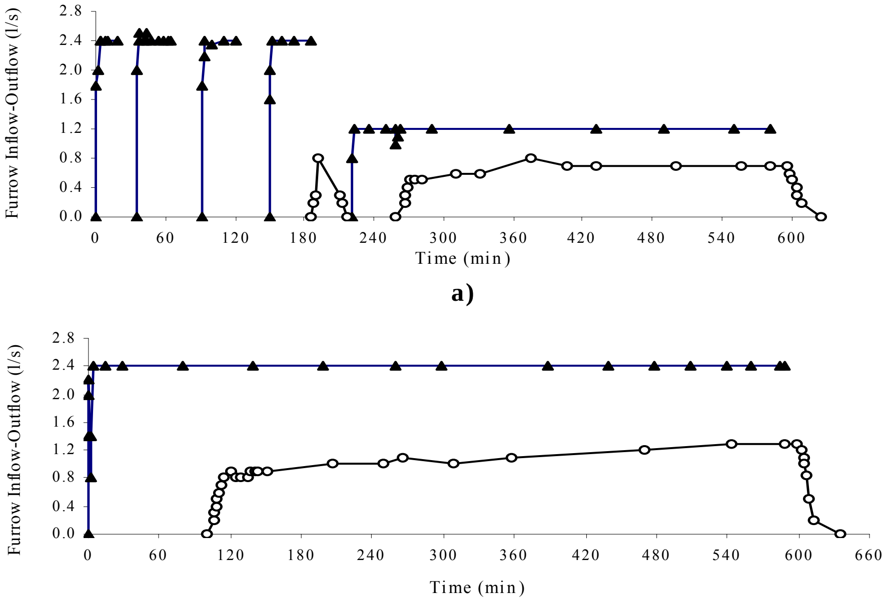
Advance and recession curves for continuous and surge flow

The comparison of the advance curves for q = 2.4 l/s relative to the first and fourth irrigation events (Fig. 5) indicates that the advance is faster for surge flow at the beginning of growing season, when soil clods are yet formed. Later in the growing season, the advance times are practically the same because the furrows are then smoothed.

Table 3. Main measured irrigation parameters for continuous and surge flow.

		First irrigation						Fourth irrigation					
	Treatment	Surge Fa		Contin G		Surge Fb		Surge Fa		Contin. G		Surge Fb	
	Furrow nº	17	18	19	20	21	22	17	18	19	20	21	22
	$q_{in(project)}$	2.40	2.40	2.40	2.40	3.00	3.00	2.40	2.40	2.40	2.40	3.00	3.00
	$q_{in(average)}$	1.45	1.45	2.41	2.41	1.79	1.79	1.47	1.52	2.40	2.35	1.71	1.71
	$p_{(project)}$	0.69		0.67		0.68		0.67		0.69		0.67	
	$p_{(befor\ irr)}$	0.45		0.50		0.49		0.42		0.44		0.40	
	t_{co}	522	518	568	568	502	502	470	469	589	589	533	533
I Cycle	t_{surge}	18	18	155	149	16	16	18	18	101	94	17	17
	$q_{in\text{-}flow}$	2.22	2.39	2.43	2.42	2.98	3.02	2.22	2.37	2.37	2.19	3.01	2.98
	L_{adv}	84	88	320	320	80	78	80	90	320	320	80	92
II Cycle	t_{surge}	26	26			22	22	28	28			17	17
	$q_{in\text{-}flow}$	2.39	2.45			2.99	2.98	2.41	2.39			2.98	2.95
	L_{adv}	160	180			160	160	160	174			160	163
III Cycle	t_{surge}	29	29			29	29	29	29			20	20
	$q_{in\text{-}flow}$	2.33	2.34			2.95	2.95	2.32	2.32			2.87	2.99
	L_{adv}	240	268			240	242	240	240			236	240
IV Cycle	t_{surge}	29	24			31	31	36	36			22	22
	$q_{in\text{-}flow}$	2.39	2.38			3.00	2.98	2.38	2.38			3.00	2.95
	L_{adv}	320	320			320	320	320	316			320	300
Wetting	t_{inflow}	421	421	413	419	404	404	359	359	488	495	457	457
	$q_{in\text{-}flow}$	1.20	1.20	2.40	2.40	1.50	1.50	1.20	1.20	2.40	2.38	1.50	1.50
	t_{adv}	31	34			34	41	37	50			27	22
	L_{adv}	320	320			320	320	320	320			320	320
Out flow	$t_{out\text{-}flow}$	502	491	445	452	472	464	440	437	535	534	518	516
	$q_{out\text{-}flow}$	0.68	0.77	0.95	1.10	0.34	0.50	0.62	0.59	1.11	1.12	0.88	0.88

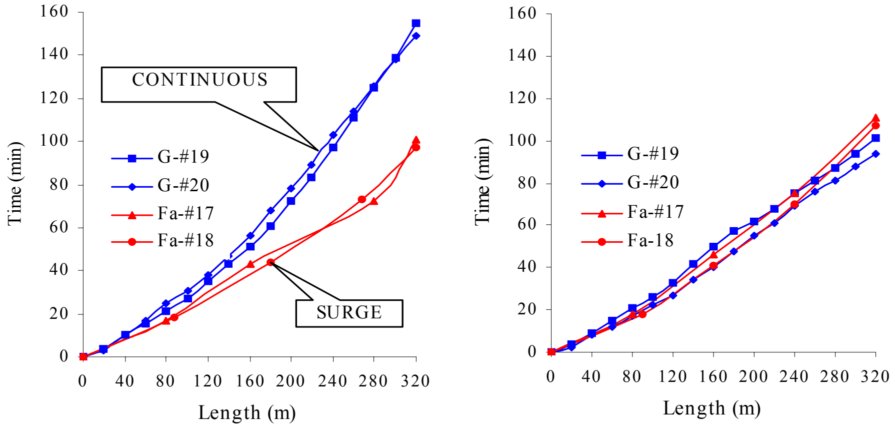
$q_{in(project)}$	design inflow rate, l/s;
$q_{\ in(average)}$	average actual inflow rate, l/s;
$p_{(project)}$	depletion fraction for no stress (Allen *et al.*, 1998);
$p_{(befor\ irr)}$	actual depletion fraction for no stress;
t_{co}	cutoff time, min;
t_{surge}	duration of a surge, min;
$q_{in\text{-}flow}$	actual inflow to furrow, l/s;
L_{adv}	distance of advance, m;
$t_{out\text{-}flow}$	duration of outflow, min;
$q_{out\text{-}flow}$	actual outflow rate, min.



a)

b)

Fig. 4. Typical inflow (▲) and outflow (○) hydrographs for surge (a) and continuous flow (b).

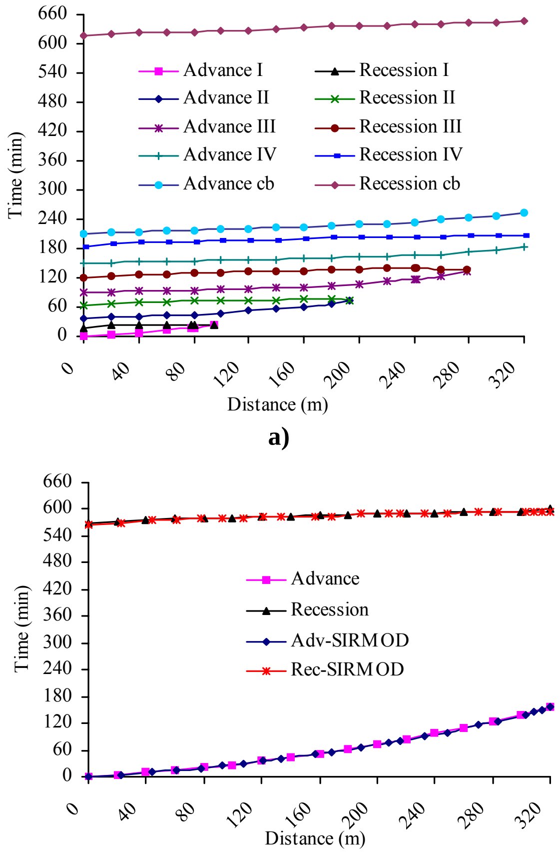


a)

b)

Fig. 5. Comparison of the advance curves for continuous-flow and surge-flow for q=2.4 l/s relative to a) first irrigation; b) fourth irrigation.

Typical advance and recession curves for continuous and surge-flow irrigation are shown in Fig. 6.



a)

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Fig. 6. Typical advance-recession curves: a) surge-flow; b) continuous-flow.

Hydraulic roughness and infiltration

The observed hydraulic roughness coefficient n are quite similar for all treatments. For surge flow, the roughness coefficient varied from n = 0.020 to n = 0.022, while for continuous flow varied from n = 0.020 to n = 0.021.

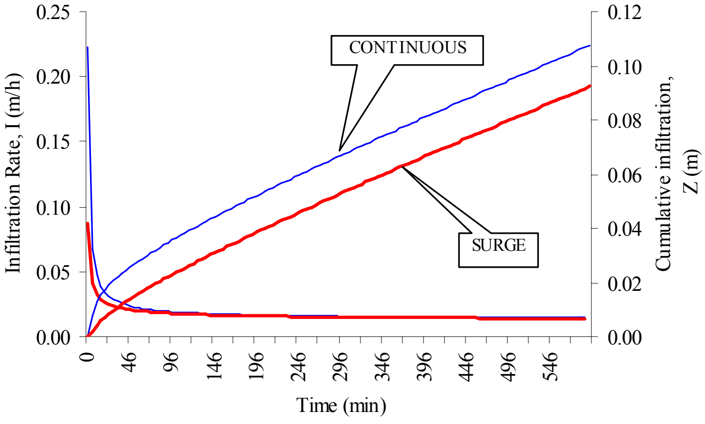
The estimated final infiltration rate f_o and the infiltration parameters k and α are presented in Table 4. The final infiltration rate f_o for furrows irrigated with surge flow was half as large as that for continuous flow, with averages ranging from 0.000128 m^3/min/m (first irrigation) to 0.000098 m^3/min/m (fourth irrigation). A considerable variation of f_o in the first irrigation (CV = 0.48) is probably related to different degrees of furrow compactness and clods at that time. For the fourth irrigation it was much smaller (CV = 0.15). In case of continuous flow, f_o varied from 0.000210 to 0.000220 m^3/min/m, much less than for surge.

Table 4. Estimated infiltration parameters.

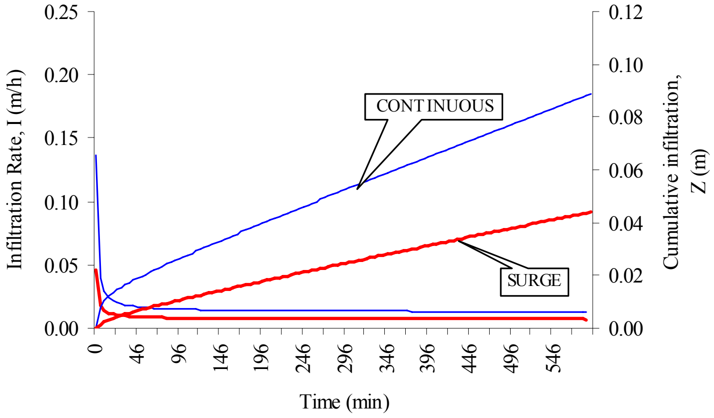
	Statistical indicators	f_o (m^3/min/m)	k(m^3/min^{α}/m)	α
All surged furrows and all irrigation events	Average value	0.000113	0.0028	0.353
	Standard deviation	0.00004	0.0004	0.114
	CV	0.36	0.14	0.32
All surge furrows, first irrigation	Average value	0.000128	0.0030	0.383
	Standard deviation	0.00006	0.0005	0.152
	CV	0.48	0.15	0.40
All surged furrows, fourth irrigation	Average value	0.000098	0.0026	0.322
	Standard deviation	0.00001	0.0003	0.069
	Value of CV	0.15	0.10	0.21
All control furrows and all irrigation events	Average value	0.000215	0.0159	0.166
	Standard deviation	0.00001	0.0048	0.058
	CV	0.05	0.30	0.35
All control furrows, first irrigation	Average value	0.000210	0.0185	0.194
	Standard deviation	0.000	0.0063	0.081
	CV	0.00	0.34	0.42
All control furrows, fourth irrigation	Average value	0.000220	0.0132	0.138
	Standard deviation	0.00001	0.0007	0.018
	CV	0.06	0.06	0.13

The surge infiltration parameter k, averaged for both surging phases («advance» and «wetting», this one with continuous half-inflow), was 5 to 6 times smaller than that for continuous-flow irrigation. The average parameter k varied between 0.0030 $m^3/min^{\alpha}/m$ (first irrigation) and 0.0026 $m^3/min\alpha/m$ (fourth irrigation) with CV = 0.10 and 0.15, respectively. For continuous flow, it was k = 0.0185 $m^3/min^{\alpha}/m$ (first irrigation) and k = 0.0132 $m^3/min^{\alpha}/m$ (fourth irrigation). The infiltration parameter showed a larger variation for the first irrigation for both surge-and continuous-flow. The parameter α for surge irrigation was twice as that for continuous, which is explained by the specific characteristics of surge-flow irrigation.

The above mentioned differences in infiltration parameters for surge-flow and continuous-flow irrigation produced different infiltration curves as shown in Fig. 7.



a)



b)

Fig. 7. Typical infiltration curves for continuous (furrow 19) and surge-flow irrigation (furrow 21): a) first irrigation; b) fourth irrigation.

For all furrow irrigation treatments, the general trend was to decrease the variability of the infiltration parameters from the beginning to the end of the growing season due to «levelling» effects of successive irrigations on rearranging the soil aggregates.

Irrigation performance and water productivity

Irrigation performances

The first irrigation was undertaken when the soil moisture deficit (SMD) in the rooting zone was relatively small, from 55.2 mm (treatment Fa) to 62.0 mm (treatment G) and the allowable soil water depletion, corresponding to the readily available water (Allen *et al.*, 1998), ranged from RAW = 83.1 mm (treatment G) to 84.7 mm (treatment Fb). The fourth irrigation was also performed with small SMD, between 50.0 mm (treatment Fb) and 55.0 mm (treatment G) while RAW ranged from 83.3 mm (treatment Fa) to 86.3 mm (treatment G). These data identifies a situation where irrigation scheduling is poor and is a cause for low irrigation efficiency. Results for both irrigations are given in Table 5.

Table 5. Performance characteristics of the first and fourth cotton irrigations.

		First irrigation						Fourth irrigation					
Date		11.06.02		13.06.02		12.06.02		31.07.02		02.08.02		01.08.02	
Treatment		Fa		G		Fb		Fa		G		Fb	
Flow condition		Surge		Contin		Surge		Surge		Contin		Surge	
Furrow nº		17	18	19	20	21	22	17	18	19	20	21	22
$q_{in(rated)}$ (l/s)		2.4/1.2	2.4/1.2	2.4	2.4	3.0/1.5	3.0/1.5	2.4/1.2	2.4/1.2	2.4	2.4	3.0/1.5	3.0/1.5
$q_{in(average)}$ (l/s)		1.45	1.45	2.41	2.41	1.79	1.79	1.47	1.52	2.40	2.35	1.71	1.71
t_{co} (min)		522	518	568	568	502	502	470	469	589	589	533	533
D (mm)		79.0	78.0	143	142	93.8	93.4	71.9	74.4	147	144	95.0	94.9
Z_{recq} (mm)		55.2	55.2	62.0	62.0	61.0	61.0	52.2	52.2	55.0	55.0	50.0	50.0
Z_{avg} (mm)		43.6	38.5	98.4	90.8	76.9	71.5	43.5	47.8	85.2	81.8	47.3	47.8
Z_{lq} (mm)		40.2	36.5	91.0	84.2	71.7	65.7	39.3	42.3	81.8	78.5	45.5	45.4
TWR	(mm)	35.4	39.5	44.1	51.6	16.9	24.3	28.4	26.6	61.9	62.5	47.7	47.1
	(%)	45	51	31	36	18	26	40	36	42	43	50	50
DPR	(mm)	0.0	0.0	46.4	28.8	15.9	8.2	0.0	0.0	30.1	26.8	0.0	0.0
	(%)	0	0	26	20	17	9	0	0	20	19	0	0
IE (%)		55	49	69	64	82	76	60	64	58	57	50	50
E_r (%)		79	70	100	100	100	100	83	92	100	100	95	96
E_a (%)		51	47	43	44	65	65	55	59	37	38	48	48
DU (%)		92	95	92	93	93	92	90	88	96	96	96	95

Data relative to the first irrigation suggests the following comments:

- The uniformity DU is high for all treatments, ranging from 92 to 95%. On the contrary, the efficiency E_a is generally low because the small SMD would require accurate control of the irrigation time duration, which is difficult under the existing delivery scheduling practices. Therefore, the irrigation depths D are much greater than Z_{recq}. Over-irrigation is explained by farmer's attempts to avoid soil water stress between irrigations. Therefore, possible improvements of irrigation performances, mainly $E_{a,}$ relate to optimizing irrigation scheduling;
- For continuous flow (treatment G) D was 1.5 times higher than for surge flow. This is due to the fact that the inflow rate was reduced to half during the wetting phase and the cutoff time t_{co} was smaller for the surge treatments;

- The tail end runoff was considerable larger in the continuous flow treatment (treatment G) originating TWR>30%. However, a higher TWR was observed with surge flow treatment Fa due to low values of steady infiltration in these furrows ($f_o = 0.000075$ m^3/min/m). The expected advantage of surge flow could not be confirmed there while the problem of variability of soil hydraulic properties was evidenced as a difficulty to appropriately manage irrigation in these soils;
- Due to low infiltration, the infiltrated depth in treatment Fa was less than required. Consequently, deep percolation (DPR) was null. On the contrary, DPR for the continuous flow treatment G exceeded 20%. For the treatment Fb the entire field received Z_{recq}, thus at expenses of some deep percolation (Fig. 8).

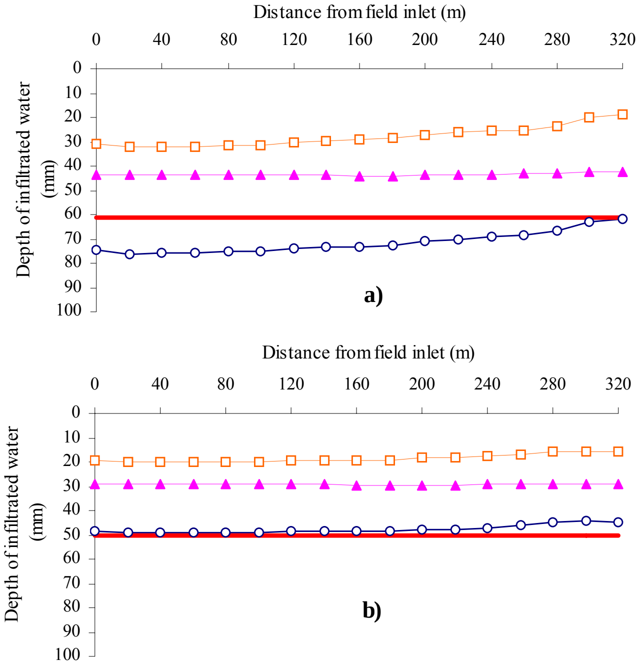


Fig. 8. Infiltrated depths profiles for the surge-flow treatment Fb with discrimination of infiltration surging the surging (□) and the wetting (▲) phases; (○–○ total infiltrated water); (: ▬ - target application): a) first irrigation; b) fourth irrigation.

The data on the fourth irrigation (Table 5) shows similar performances and problems:

- DU is high (DU>95%) for all but the surge treatment Fa due to problems caused by poor infiltration; results show that the inflow rate is excessive for those soils;

- E_a is generally low, mainly for the continuous flow treatment, due to excessive cutoff times that originate very high irrigation depths, much higher than Z_{recq}. These are quite low due to poor irrigation scheduling as pointed out above;
- The tail water runoff is substantially high in the continuous flow treatment G and in surge flow treatment Fb. For the latter, this mainly results from a notable decrease of the infiltration after the first irrigation associated with a large inflow rate;
- Deep percolation is very high for the continuous flow treatment G, as it happens to the first irrigation, but is about null for surge flow irrigation (Fig. 8).

Issues to improve irrigation performances

The factors by which a farmer may manage a system in order to improve DU and E_a may be expressed by simplified functional relationships (Pereira and Trout, 1999) such as:

$$DU = \mathrm{f}\,(q_{in}, t_{co}) \qquad [10]$$

and

$$E_a = \mathrm{f}\,(q_{in}, t_{co}, SMD) \qquad [11]$$

which symbols were previously defined. Therefore, from the precedent analysis it becomes evident that the following factors may be considered to improve the irrigation performances:

- *Continuous flow irrigation*: (a) reducing the cutoff time (t_{co}) in proportion to the inflow rate used in order to reduce the excessive difference between Z_{recq} and D; (b) adopt smaller inflow rates, particularly for the soils with low infiltration and therefore reducing the tail end runoff. In a former study (Horst *et al.*, 2005) the best results were obtained for q_{in} = 1.8 l/s for alternate-furrow irrigation and q_{in} = 1.2 l/s when irrigating every furrow; however, in this experiment the traditional inflow discharges were used and revealed to be excessive;
- *Surge flow irrigation*: (a) reducing the inflow rates in case of low infiltration soils similarly to above; (b) surging during the wetting phase in alternative to diving the inflows among the right and left hand furrows;
- *Surge and continuous flow irrigation*: delay irrigations until SMD becomes close to the RAW, thus increasing Z_{recq} to a level close to the more common values for D in the traditional practice. A depletion fraction p from 0.6 to 0.7 should be considered.

Simulations were performed for the continuous flow treatment G considering t_{co} reduced by 160-180 min. Results are given in Table 6 comparing the performance indicators relative the actual and improved situations; infiltrated depths curves relative to the actual and the simulated conditions are shown in Fig. 9.

Table 6. Simulated characteristics for the continuous flow treatment G when the cutoff time is improved.

		First irrigation				Fourth irrigation			
Dates		13.06.2002				02.08.2002			
Condition		Actual		Improved		Actual		Improved	
Furrow nº		19	20	19	20	19	20	19	20
$q_{in(rated)}$ (l/s)		2.4	2.4			2.4	2.4		
$q_{in(average)}$ (l/s)		2.41	2.41	2.41	2.41	2.40	2.35	2.39	2.30
t_{co} (min)		568	568	390	412	589	589	430	410
D (mm)		143	142	98	103	147	144	107	98
Z_{recq} (mm)		62.0	62.0	62.0	62.0	55.0	55.0	55.0	55.0
Z_{avg} (mm)		98.4	90.8	73.7	70.9	85.2	81.8	59.4	59.7
Z_{lq} (mm)		91.0	84.2	65.9	64.2	81.8	78.5	56.2	56.4
TWR	(mm)	44.1	51.6	24.2	32.4	61.9	62.5	37.2	34.4
	(%)	31	36	25	31	42	43	35	35
DPR	(mm)	46.4	28.8	11.7	8.9	30.1	26.8	15.0	8.7
	(%)	26	20	12	9	20	19	14	9
E_a (%)		43	44	63	60	37	38	51	56
DU (%)		92	93	89	91	96	96	95	94

Reducing t_{co} by 160-180 min results in decreasing the applied depths in about 40-45 mm, i.e., producing water savings of about 30%, which sums near 200 mm when cumulated the entire season. Both percolation and runoff were reduced. Consequently E_a is improved by more than 15% but DU is decreased by about 2%, which is negligible.

Issues to improve water productivity

When land is scarce farmers aim at increasing land productivity and not water productivity. This is the reason why they tend to over-irrigate as shown in this study. In Fergana the water is not felt by farmers to be scarce contrarily to farmers located downstream in the basin, but they consider that land is scarce. Under these circumstances, it is difficult to implement water saving techniques.

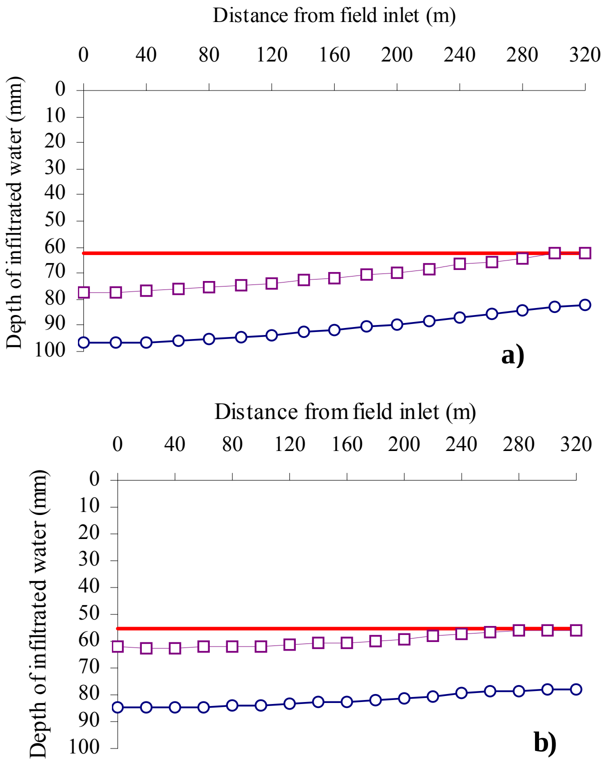


Fig. 9. Infiltrated depth curves for the continuous-flow treatment G comparing actual (○) and improved (□) inflow rates (▬ - application) or the first (a) and fourth (b) irrigation.

Shreder *et al.* (1977) developed a yield-water relation for cotton Y_a/Y_{max} =f (Z_a/Z_{max}), where Y_a is actual cotton yield (kg/ha), Y_{max} is maximum cotton yield (kg/ha), Z_a is actual cotton water consumption, and Z_{max} is cotton water consumption when maximal yield is attained (Fig. 10). It shows that deficit irrigation may be feasible because 5 to 10% decrease in water use reduces cotton yields by 2 to 4% only.

Basing upon the irrigation performance studies described above and in previous ones (Horst *et al.*, 2005), field studies relative to four cotton irrigation treatments on water-yield and water productivity (WP) relations were performed during the growing season 2003 which are referred in Table 7. Treatments compared surge *vs*. continuous flow and alternate *vs*. every-furrow irrigation: EC – continuous flow on every furrows; ES - surge flow on every furrows; AC - continuous flow on alternate furrows; AS - surge flow on alternate furrows. Each treatment referred to a different furrow irrigation system, i.e. three replications per treatment were used and the area of a replication was 0.36 ha. Six irrigations were applied to all treatments, from 15.06.03 to 12.09.03.

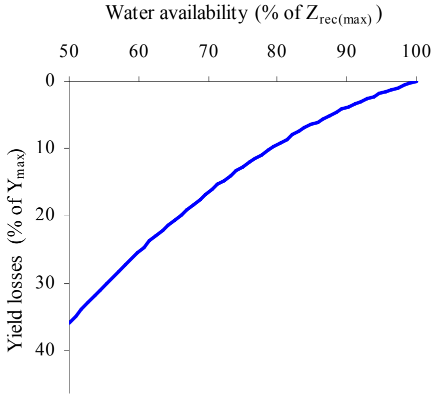


Fig. 10. Water-yield relationship for cotton (Shreder *et al.*, 1977).

Table 7. Water depths applied (D), actual yields (Ya) and water productivity (WP) relative to four cotton irrigation systems.

Irrigation treatments	D (m^3/ha)	Changes in applied water relative to average (%)	Ya (kg/ha)	Yield changes relative to average (%)	WP (kg/m^3)	Changes in productivity relative to average (%)
EC	8813	31	3391	9	0.38	-20
ES	6925	3	3041	-2	0.44	-8
AC	6225	-7	2988	-4	0.48	0
AS	4922	-27	3010	-3	0.61	28
Average	6721		3108		0.48	

The largest irrigation water productivity WP = 0.61 kg/m^3 was achieved with surge flow on alternate furrows (AS), which also used less water and yielded only 100 kg less than average. When compared with the traditional continuous flow applied to every furrow (EC), that treatment AS used 3890 m^3/ha (44%) less than the EC treatment but yields decreased by 380 kg/ha (11%). The treatments ES and AC used about the same water, and had similar yields and water productivity. Results indicate that considerable water savings may be achieved with alternate-furrow irrigation and adopting surge flow.

Water use performances at field level

The consumed fraction of water used at field level for the growing season, $WCF_{(field)}$, representing the consumed fraction of total water used by the crop (Pereira *et al.*, 2002a) was estimated by the following relationship:

$$WCF_{(field)} = \frac{ET_a}{(D+P)} \qquad [12]$$

where, ET_a is the actual water consumption of the cotton crop (mm) that provides for the cotton yield Ya; D is the total irrigation depth applied (mm); and P is the total rainfall (mm), all relative to the time duration of the growing season.

Considering that for the Fergana soils a leaching fraction LF is required, the beneficial water use fraction $BWUF_{(field)}$ is

$$BWUF_{(field)} = \frac{ET_a(1+\frac{LF}{100})}{(D+P)} \qquad [13]$$

where LF corresponds to about 5% for the most common soils in the area.

Estimates of $WCF_{(field)}$ and $BWUF_{(field)}$ for every furrow irrigation and continuous flow (EC) compared with alternate furrow irrigation with continuous flow (AC) and alternate furrow irrigation with surge flow (AS) are shown in Table 8. Also included the ET_a/ET_{max} ratio where ET_{max} is the cotton water consumption for maximum yield (ET_{max} = 693 mm according to Cholpankulov *et al.*, 2005); Y_a is the actual cotton yield (kg/ha); and Y_{max} is maximum cotton yield for Fergana conditions (3600 kg/ha).

Table 8. Comparative water use effectiveness, at field level, under every and alternate furrow irrigation treatments.

Irrigation treatment	ET_a (mm)	ET_aET_{max} (%)	Y_a (kg/ha)	Ya/Ymax	D (mm)	P (mm)	$WCF_{(field)}$	$BWUF_{(field)}$
EC	598	86	3 391	0.94	881	70	0.63	0.66
AC	480	69	2 988	0.83	623	70	0.69	0.72
AS	480	69	3 010	0.84	492	70	0.85	0.89

The highest water use consumed fraction and beneficial water use fractions were for surge flow applied to alternate furrows (AS), with respectively 0.85 and 0.89 with a relative ET deficit of 31% and a relative yield deficit of 16%. The next best results concern continuous flow applied to alternate furrows (AC), which show similar relative ET and relative yield but lower $WCF_{(field)}$ and $BWUF_{(field)}$. These results show a clear advantage of alternate furrow irrigation over every furrow irrigation, as well as advantage of surge over continuous flow.

Conclusions

This study, in line with that described by Horst *et al.* (2005), shows that several improvements in surface furrow irrigation are required and are feasible, not requiring heavy investments in equipment. Considerable water savings may be achieved when adopting surge flow and alternate-furrow irrigation, from 200 up to 390 mm for the total irrigation season of cotton. However, the improvement of farm irrigation systems need to be combined with improved irrigation scheduling because farmers tend to anticipate the irrigation dates and to apply excessive irrigation depths.

Field studies allowed the parameterization of irrigation simulation models which provide for an extensive use of modelling to improve the systems in accordance to the prevailing land conditions, namely for using the SADREG decision support tool (Gonçalves *et al.*, 2005).

Studies have shown that the distribution uniformity is generally high but application efficiencies are low. This indicates that the priority of interventions has to be related to adopt more appropriate furrow inflow rates and time duration of irrigations in agreement to prevailing infiltration conditions, as well as to delay the timing of irrigations aiming at having larger SMD at time of irrigation, that better match with the more common and easy to apply water depths.

Surge flow has demonstrated the ability to reduce both deep percolation and tail end runoff. Advantages of surging are particularly visible for the early season irrigations. However, the variability of soil hydraulic properties along the irrigated lands constitutes an additional difficulty to decide inflow rates and timings.

Surge flow on alternate furrows shows to be the best technique for water saving and increased water productivity. When compared with the traditional every-furrow irrigation with continuous flow, water use was reduced by 3890 m^3/ha (44%) with a decrease in yield of 380 kg/ha (11%), while the water productivity was 0.61 kg/m^3 against 0.38 kg/m^3 for the traditional one. Moreover, the consumed fraction of water used at field level was 0.85.

Finally, it is important to recognize these results in the context of a water scarce region prone to desertification and where climatic change consequences may be disastrous (Horst, 2002).

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