13 - ASSESSMENT OF FURROW IRRIGATION IMPROVEMENTS AND WATER SAVING IN COTTON IRRIGATION

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Abstract: To assess the potential for improving the performance of furrow irrigation in the central part of the Fergana Valley, Uzbekistan, a set of evaluation experiments was carried out in cotton fields relative to several irrigation options. These included a variety of furrow inflow rates, from 1.2 to 2.4 l/s/furrow; furrow lengths, 130 m and 400 m; and comparing every-furrow irrigation with water saving alternate-furrow irrigation. Results were evaluated through the application efficiency (E_a), the distribution uniformity (DU) and total applied irrigation depths. The best performances were obtained for alternate long furrows adopting the inflow discharge 1.8 l/s/furrow, which produced high E_a and DU, superior to 80 and 83% respectively, and led to seasonal water savings from 200 to 300 mm when compared with actual water use in every-furrow irrigation. Large water saving also resulted from reducing the irrigation cutoff times in every-furrow irrigation, corresponding 150 to 200 mm through the irrigation season. Also, improving the multi-tier reuse method when adjusting the cutoff times in agreement with the inflow rates produced high irrigation performances and water savings larger than 300 mm for the season.

Keywords: Alternate furrow irrigation, Application efficiency, Cutoff times, Distribution uniformity, Multi-tier irrigation, Water saving, Irrigation Water Management.

Introduction

The Aral Sea basin is world widely known as a water scarce region where problems due to man made desertification add to aridity and drought. Water scarcity is intensified by poor operation and management of irrigation systems (Dukhovny and Umarov, 1999). Issues for solving the problems are of very

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different nature and preferably should be such that minimize the impacts from both aridity and desertification (Pereira *et al.*, 2002a). This includes the control of irrigation demand through improved farm irrigation performance (Laktaev, 1978; Djurabekov and Laktaev, 1983; Horst, 1989).

Research is focused on the farm scale because the improvement of water management at the conveyance and distribution systems needs further consideration due to the complexity of problems related to changing from the centralized state farms into private farms. Water saving, considered herein as the policies and practices that lead to reduce the water resources mobilized for irrigation, concentrate on improved farm demand management and increased water productivity (Pereira *et al.*, 2002b).

The objective of this paper is to present and discuss alternative improvements to the furrow irrigation systems that lead to less irrigation water use and higher irrigation performances, but do not require heavy investments and may be adopted in the farmers practice. Therefore, the reported research bases upon field evaluations and experiments performed in farmer fields, while the discussion is supported by model simulation.

Material and methods

Field experiments

Field studies were carried out in the farm "Azizbek-1" in central Fergana Valley during the 2001 irrigation season. Four furrow irrigation treatments were evaluated in cotton fields as described in Table 1. The furrow spacing was 0.9 m for all treatments. The irrigation scheduling was decided by the farmers because it was intended to evaluate the farmers practices to later define improvements to be introduced in both scheduling and furrow systems.

Table 1. Design factors in furrow irrigation experiments.

Irrigation treatments	Furrow number	Length (m)	Slope (m/m)	Inflow (l/s)	Soil compaction	Furrow irrigation management	Drainage conditions
A	1	130	0.0025	2.4	compacted	Irrigation	Normal
	2	130	0.0025	1.8	compacted	every furrow	
	3	130	0.0025	1.2	compacted		
	4	130	0.0025	1.8	n/compacted		
B	5	400	0.0020	2.4	compacted	Irrigation	Normal
	6	400	0.0020	1.8	compacted	every furrow	
	7	400	0.0020	1.2	compacted		
	8	400	0.0020	1.8	n/compacted		
C	9	400	0.0020	2.4	n/compacted	Alternate	Normal
	10	400	0.0020	1.8	compacted	furrows	
D	11	400	0.0026	1.8	compacted	Irrigation	Improved
	12	400	0.0026	1.8	n/compacted	every furrow	drainage

Irrigation with short furrows (treatment A) may be improved when using multi-tier irrigation (Fig. 1). With this field layout, the runoff from a set of furrows in the first tier is collected into a ditch across the field, which acts as surface drain for the upstream furrows and as distributor for the furrows in the second tier. At the same time, this ditch receives water from the distributor located upstream of the field, which amount should correspond to the difference between the volumes supplied and flowing out of the first furrows' tier. This supply is conveyed through the «shokh-aryk» ditch, which runs parallel to the irrigated furrows (Fig. 1). Similarly, the runoff from the second tier is collected in a second ditch across the field and is supplied by another «shokh-aryk» to distribute water for the third tier. Therefore, only the runoff from the last tier is not reused.

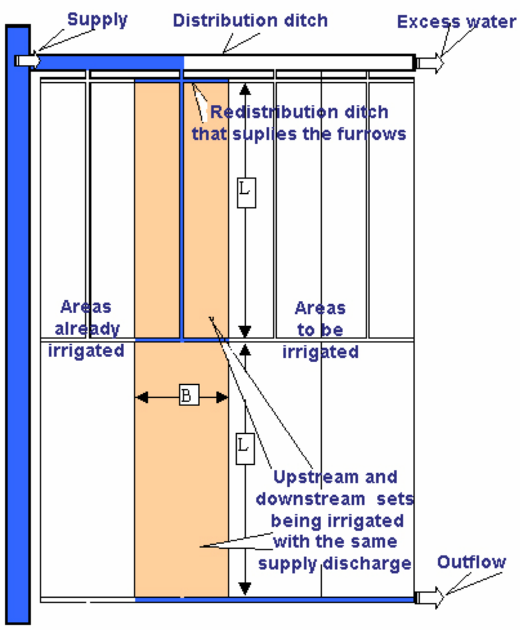

Fig. 1. Scheme of multi-tier irrigation to reuse runoff in successive furrow sets.

Soil characteristics referring to 7 genetic horizons selected from the 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 and wilting point (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 appropriate for surface irrigation using high application depths and low irrigation frequencies.

Table 2. Soil physical and hydraulic properties.

Genetic horizon (cm)	Layer thickness (cm)	Bulk density (g/cm^3)	Porosity (%)	Field capacity ($m^3\ m^{-3}$)	(mm)	Wilting point ($m^3\ m^{-3}$)	(mm)	Available soil water ($m^3\ m^{-3}$)	(mm)
0-15	15	1.47	43.2	0.38	56	0.21	31	0.17	26
15-35	20	1.40	44.0	0.32	64	0.17	34	0.15	.30
35-50	15	1.32	48.8	0.33	49	0.19	29	0.14	20
50-62	12	1.28	50.4	0.34	41	0.19	23	0.15	18
62-76	14	1.41	45.0	0.36	50	0.19	27	0.17	23
76-91	15	1.45	43.9	0.37	55	0.19	29	0.17	26
91-100	9	1.52	42.8	0.38	34	0.20	18	0.18	16
0-100	100	1.40	45.4	0.35	348	0.19	189	0.16	159

Field evaluation procedures

The methodology used for the evaluation of furrow irrigation follows that by Merriam and Keller (1978) as adapted by Calejo *et al.* (1998). Measurements included land levelling conditions, furrow discharges, furrow cross-sections, advance and recession, hydraulics roughness and infiltration.

Deviations from actual to target field elevations were measured using a square grid 20x20 m in a field with 400x250 m. The standard deviation of field elevation differences S_{dp} (m) was computed as:

$$S_{dp} = \left[\sum_{i=1}^{N} (h_i - h_{ti})^2 / (N-1) \right]^{0.5} \qquad [1]$$

where h_i are the field elevations (m) at the grid points i; h_{ti} are the target elevations at the same points (m) and N is the number of observations.

Along with S_{dp}, the relative non-uniformity indicator Δ_y (%), adopted by Li and Calejo (1998), was also used:

$$\Delta_y = \frac{100 \sum_{i=1}^{N} |y_i - \hat{y}|}{NL} \qquad [2]$$

where y_i are the observed elevations (m); $\hat{y}$ is the desired elevation (m) at the same point i, which is derived from the fitted slope line; N is the number of observations; and L is the length of the field (m).

Discharges into the furrows were measured with portable flumes, modified broad crested weirs (Replogle and Bos, 1982; Clemmens *et al.*, 2001), which were placed at the upstream end, center and tail end of the furrows evaluated as indicated in Table 1 (Fig. 2). A wide variation of discharges was observed during the first minutes of water application to furrows. Therefore, flow rates were initially measured every 1 or 2 minutes until the flow became stable. After the stabilization, measurement intervals increased up to 20-30 minutes; in case of abrupt changes of the flow rate in the upstream water supply ditch, measurements were taken more frequently until the flow rate was stabilized.

Fig. 2. Portable flumes at the head-end of a furrow set.

The furrow inflow rates were characterized by the time weighted average inflow rate Q_{avg} (l/min):

$$Q_{avg} = \frac{\sum_{i=1}^{N} A_{qi}}{t_{ap}} \qquad [3]$$

where A_{qi} are the inflow volumes (l) during the time intervals from t_i to t_{i-1} computed by

$$A_{qi} = 30(Q_i + Q_{i-1})(t_i - t_{i-1}) \qquad [4]$$

and t_i and t_{i-1} are the times of two successive inflow rate measurements (min), which start at the moment when the irrigation was started; Q_i and Q_{i-1} are the measured furrow flow rates (l/s) at those times t_i and t_{i-1}; N is the number of flow rate measurements; and t_{ap} is the total time of water application (min).

The variation of inflow rates during an irrigation event was estimated for every furrow by the sum of the squares of the deviations of the current inflow measurements to the average rate Q_{avg}:

$$SSD_q = \sum_{i=1}^{N} (Q_i - Q_{avg})^2 \qquad [5]$$

The furrows cross sectional areas were measured with furrow profilometers (Walker and Skogerboe, 1987). Observations were performed at the furrow upstream end before and after every irrigation event. Measurements in each cross-section location were averaged, and the cross section was described by a parabola type equation as a function of the furrow depth.

Advance and recession times **(**t_{av} and t_{rec}**)** were measured every 10 m in case of short furrows and every 20 m for the long furrows. Recession times were recorded at the times when water fully infiltrated the soil at the observation sections; however, when unevenness of the furrow bed caused the water to pond for long time, t_{rec} were recorded when water disappeared from the furrow bed in the areas nearby the measurement section. It resulted that advance time measurements were more accurate than recession ones, the later depending upon observer subjective factors.

The Manning's roughness coefficient n ($m^{-1/3}s$) was calculated from observations of the furrow cross-sectional area, flow rates, flow water depths and water surface width:

$$n = \frac{AR^{\frac{2}{3}} S_o^{\frac{1}{2}}}{Q_{\inf}} \quad [6]$$

where Q_{inf} is the inflow rate to the furrow (m^3/s); A is the cross-sectional area of the furrow flow (m^2); R is the hydraulic radius (m); and S_o is the hydraulic gradient, which was assumed to equal the furrow slope (m/m).

The Kostiakov infiltration equation, which is adopted in the model SIRMOD (ISED, 1989), was used in this research:

$$Z = k\tau^{\alpha} + f_o\tau \quad [7]$$

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 empirical base infiltration rate ($m^3/min/m$).

The infiltration parameters were estimated using the inverse method (Katopodes *et al.*, 1990) in which observed advance and recession data are compared with those computed with the simulation model SIRMOD. The best parameter values were obtained after several iterations aiming at minimizing the sum of the squares of the deviations between observed and simulated advance and recession times as proposed by Calejo *et al.* (1998). The roughness parameters (n) obtained with Eq. 6, the observed furrow discharges and the furrow shape parameters were kept constant during the search procedure.

The initial values for the infiltration parameters f_o, α and k (Eq. 7) were determined using the "two-point" method (Elliott & Walker. 1982). The estimation procedure starts with the definition of the final infiltration rate f_o

from the inflow-outflow hydrograph for each of the studied irrigation treatments as described by Walker and Skogerboe (1987).

Soil water content measurements were carried out in each furrow irrigation field at three locations at distances of 0.25 L; 0.5 L and 0.75 L from the furrow upstream end. Neutron probe access tubes were located in the middle of the furrow bed and on the ridges. Readings with a calibrated neutron probe (threefold repeated) were recorded for every 20 cm, from 40 cm depth until 120 cm, or 140 cm for measurements taken on the ridges. Soil samples were taken from the surface and at a depth of 20 cm; observations were performed before and 3-5 days after irrigation. Soil water data were used through a simplified soil water balance to estimate the irrigation depths required (Z_{req}).

Performance indicators

The performance indicators considered in this study are the application efficiency, E_a (%), and the distribution uniformity, DU (%). DU characterizes the irrigation system and generally corresponds to an even crop (Fig. 3), and E_a is a management performance indicator (Pereira and Trout, 1999; Pereira *et al.*, 2002b). They are described by the following relationships:

$$E_a = \begin{cases} \dfrac{Z_{req}}{D} \times 100 & Z_{lq} > Z_{req} \\ \dfrac{Z_{lq}}{D} \times 100 & Z_{lq} < Z_{req} \end{cases} \qquad [8]$$

$$DU = \frac{Z_{lq}}{Z_{avg}} \times 100 \qquad [9]$$

where Z_{req} is the average depth (mm) required to refill the root zone in the quarter of the field having higher soil water deficit; D is the average water depth (mm) applied to the irrigated area; Z_{lq} is the average depth of water infiltrated in the lower quarter of the field (mm); and Z_{avg} is the average depth of water infiltrated in the whole irrigated area (mm).

Z_{req} were estimated from field measurements of the soil water content before the irrigation, which were used to compute the soil moisture deficit, SMD (mm), in the root zone. Measurements were carried out at the distances of one quarter, one half and three quarters from the upstream end of the furrows. The maximum SMD observed were assumed as the best estimates of Z_{req}.. For all irrigation events, the root zone depth was assumed equal to 0.7 m based on phenological estimations of the maximum development of cotton root masses. Z_{avg} was estimated from computing the depth of water infiltrated during the intake opportunity time relative to each location i, at each 10 or 20 m for short and long furrows respectively. The Kostiakov equation was used with the estimated infiltration parameters as referred above:

$$Z_i = \mathrm{k}\left[(t_r)_i - (t_a)_i\right]^{\mathrm{a}} + f_0\left[(t_r)_i - (t_a)_i\right] \qquad [10]$$

where k, α and f_0 are the infiltration parameters characterizing each irrigation, and $(t_r)_i$ and $(t_a)_i$ are respectively the times of advance and recession relative to the location i (min). Z_{lq} was estimated from the average relative to the quarter of the furrow where infiltration was smaller.

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

$$D = \frac{q_{avf} \times 60 \times t_{co}}{L \times s} \qquad [11]$$

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 spacing between furrows (m).

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

$$V_{out} = \frac{q_{out} \times 60 \times t_{out}}{L \times s} \qquad [12]$$

where q_{out} is the average discharge rate at the tail end of the furrow (l/s) during the runoff time t_{out} (min).

Fig. 3. View of the experimental field by the late season showing that the cotton crop performed well.

Results and Discussion

Furrow slopes and forms

The average slope in the furrow flow direction was S_{long} = 0.00212 m/m, ranging from 0.00158 to 0.00275 m/m. The standard deviation was S_d = 0.00030 and the coefficient of variation was CV=0.14, i.e. the variations of the longitudinal slope are generally small along the furrows (Fig. 4a).

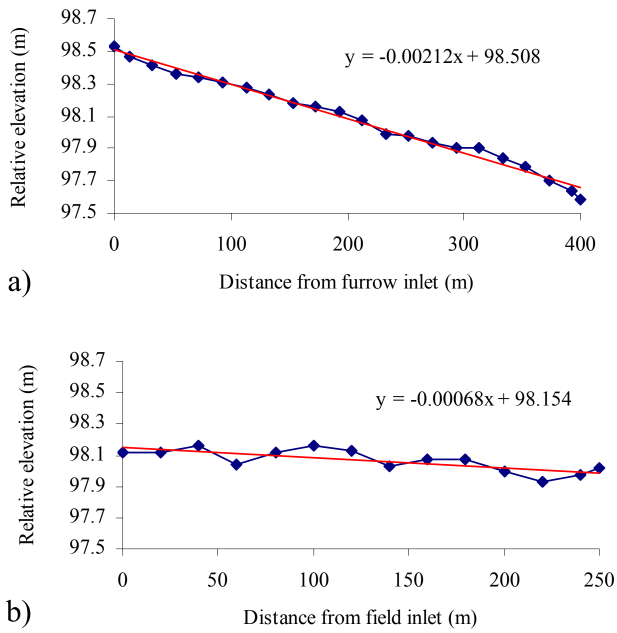

Fig. 4. Typical slopes: (a) longitudinal and (b) across the field.

The average slope across the field was S_{across} = 0.00065 m/m (Fig. 4b), with standard deviation S_d = 0.00035 m/m and coefficient of variation CV=0.55. The range of variation was from 0.00004 to 0.00089 m/m.

The effect of inflow-rate on furrow erosion is, generally, very significant in Fergana soils. The small and medium inflow rates tested (1.2 and 1.8 l/s) were non-erosive, but the high one (2.4 l/s) produced some erosion on furrows upstream end, particularly on first irrigation. Typical furrow cross-sections before and after irrigation are shown in Fig. 5. A parabolic equation was adjusted. Comparing the cross sections before and after irrigation (Fig. 5), results show that relatively high erosion and deposition occur inside the field, which is related to the fine soil materials and the large inflow rates used for long furrows (Table 1). However, sediment transport out of the field was very small.

Inflow rates varied differently among treatments, with coefficients of variation ranging from 0.06 to 0.28. A larger variation was observed for treatments A and B. Typical inflow-outflow hydrographs are presented in Fig. 6, where variations in the inflow rates are well apparent as well the respective impacts on outflows.

Typical advance and recession curves measured and simulated with SIRMOD model are presented in Fig. 7. They show that the recession curve is about linear with very small differences between the upstream and the downstream sections. Results also show that the SIRMOD model adequately describes advance and recession when the parameters search referred in Field Evaluation Procedures is applied.

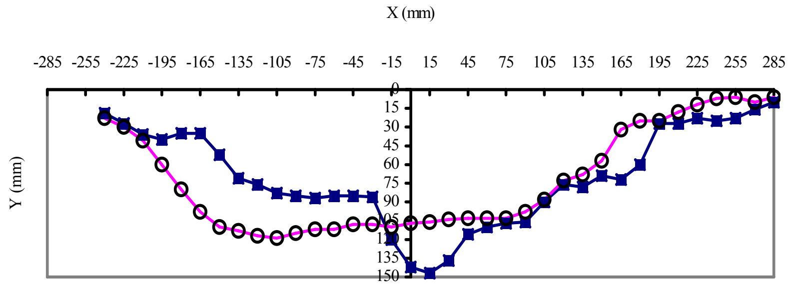

Fig. 5. Typical furrow cross sections before (■) and after irrigation (O) (furrow # 9, treatment C, first irrigation).

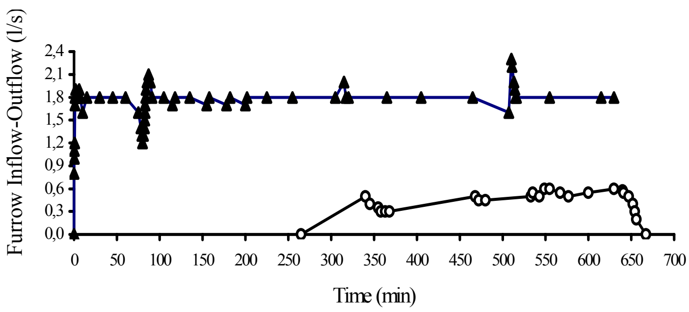

Fig. 6. Typical inflow (▲)-outflow (○) hydrographs (furrow 12, treatment D, third irrigation).

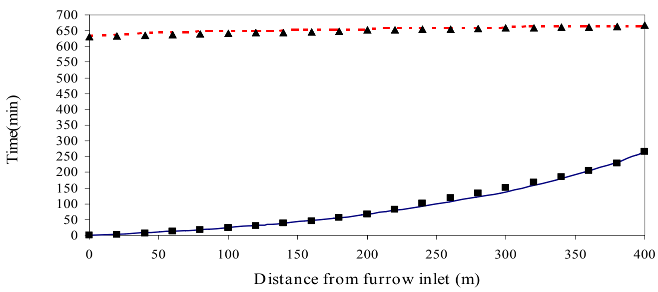

Fig. 7. Observed advance (■) and recession (▲) versus simulated advance (▬) and recession (---) curves (furrow 12, Treatment D, third irrigation).

Hydraulics roughness and infiltration

The hydraulics roughness n had a small variation from the first to the last irrigation event but decreasing from the first to the last irrigation events (Table 3) as it is currently observed. The average value was n = 0.018 $m^{-1/3}$ s and varied 0.020 to 0.017 $m^{-1/3}$ s from the first to the third irrigation events for the long furrows (400 m).

Table 3. Estimated Manning's roughness n from flow observations in cotton fields.

	Statistical indicators	n ($m^{-1/3}$ s)
All furrows and all irrigation events	Average	0.018
	Standard deviation	0.002
I irrigation, long furrows	Average	0.020
	Standard deviation	0.002
II irrigation, long furrows	Average	0.019
	Standard deviation	0.002
III irrigation, long furrows	Average	0.017
	Standard deviation	0.002

The estimated final infiltration rate, f_o, and the infiltration parameters k and α are presented in Table 4. The variability of all parameters is quite large when all irrigations and all the irrigation treatments are considered. This variability is smaller for the final infiltration rate f_o in the long furrows. The variability of the parameters k and α is large for all irrigation events and reduces only for the third irrigation.

Table 4. Estimated infiltration and respective statistical indicators of their variability.

	Statistical indicators	f_o (m^3/min/m)	k ($m^3/min^a/m$)	α
All furrows and all irrigations	Average	0.000224	0.0106	0.250
	Standard deviation	0.000116	0.0058	0.113
	CV	0.52	0.55	0.45
Long furrows (400 m)	Average	0.000192	0.0109	0.231
	Standard deviation	0.000042	0.0060	0.101
	CV	0.22	0.55	0.44
I irrigation, long furrows	Average	0.000206	0.0138	0.187
	Standard deviation	0.000050	0.0076	0.086
	CV	0.24	0.55	0.46
II irrigation, long furrows	Average	0.000206	0.0109	0.235
	Standard deviation	0.000035	0.0060	0.077
	CV	0.17	0.55	0.33
III irrigation, long furrows	Average	0.000193	0.0116	0.204
	Standard deviation	0.000027	0.0020	0.060
	CV	0.14	0.17	0.30

The average final infiltration rate f_o in long furrows decreased from the first to the third irrigation, from 0.000206 to 0.000193 m^3/min/m. This may be related to the rearrangement of soil particles due to transport and deposition inside the furrows, as referred relative to changes in furrow cross-sections in Fig. 5, which becomes more stable only after the second irrigation. The parameters k and α did not have clear trends when comparing the respective average values from the first to the last irrigation but a trend existed for k to decrease after the first irrigation, and inversely for α to increase. Differences related to treatments and soil compaction by the tractor wheels (Table 1) may explain part of this k and α variation.

In agreement with the variability of infiltration parameters, considerable differences were observed in infiltration curves computed from field measurements of advance and recession in treatments B, C and D. Thus, the infiltration parameters were grouped to create families of infiltration cumulative curves Z = f(t) relative to each of the three irrigations representing low, medium and high soil infiltration (Fig. 8). The infiltration parameters relative to these families were later used with SIRMOD to evaluate the irrigation systems performance and to design better solutions. It may be observed (Fig. 8) that differences among Z = f(t) curves are larger for the first irrigation, with the low and medium infiltration soils tending to behave similarly for the last irrigation when influences of crop residues, clods and soil compaction are lesser.

Soil water observations

The average soil water content before and after irrigation and the average soil moisture deficit (SMD) at time of irrigation are shown in Table 5.

The soil water depletion fraction ranged from 0.43 to 0.56, generally much smaller than the commonly recommended soil water depletion fraction for no stress p = 0.65 (Allen *et al.*, 1998). Thus, an irrigation schedule excluding crop water stress was adopted by the farmer, which influenced the results of the evaluations described below because the timings of irrigations were anticipated to those optimal. In other words, the SMD at time of irrigation were smaller than those aimed when water saving irrigation is practiced. As a consequence of the irrigation scheduling adopted, the depth of water added to root zone storage observed 3 or 4 days after irrigation is generally small. These conditions indicate a large potential to increase the application efficiency when the irrigation intervals are enlarged.

Irrigation performances

The results of the first and third cotton irrigations are used to analyze the observed irrigation performances. Those for the first irrigation are in Table 6.

The first irrigation was carried out when the SMD in the least moist quarter of the field varied from 73.5 mm (treatment A) to 74.2 mm (treatment C). Results in Table 6 show that DU is generally high to very high, with only the furrows 6 and 12 having DU<83%. This is related to slope and infiltration conditions, which are due to prolonged advance times. Irrigation depths D are generally much above those required, Z_{recq}. This is related to the commonly long advance times t_{av} (e.g. Fig. 7) and the excessive times for cutoff t_{co}. In fact, to avoid crop water stress farmers use a long duration of irrigation, which results in over irrigation. Despite D is excessive, the lower quarter depth infiltrated is for some cases smaller than the target Z_{req}. This is explained through the uneven infiltrated depths (e.g. Fig. 9) despite DU keeps high.

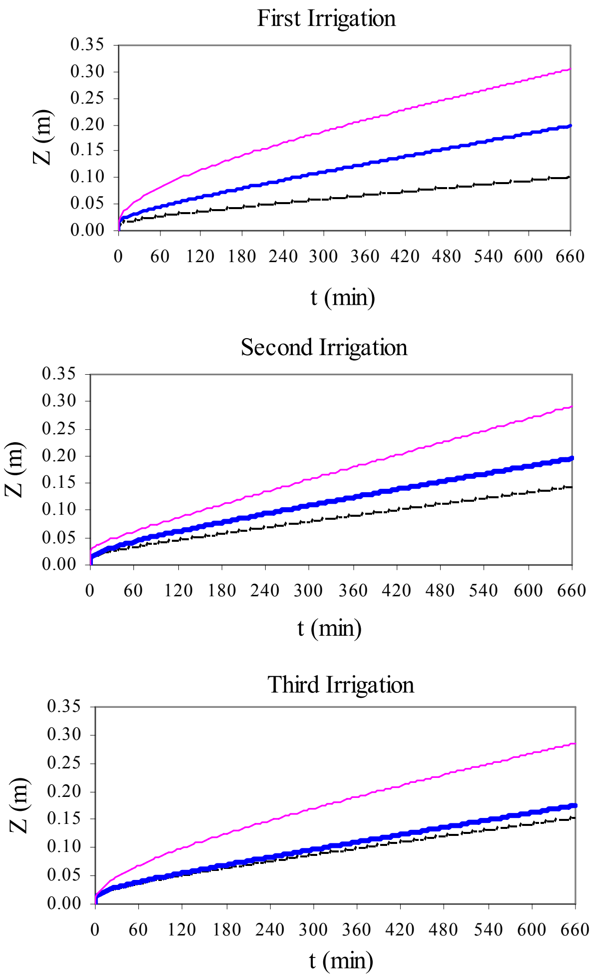

Fig. 8. Average cumulative infiltration curves relative to high ( ), medium ( ) and low ( ) soil infiltration families relative to the three irrigations events (treatments B, C, and D).

Table 5. Soil water content before and after irrigation and moisture deficit (SMD) before irrigation.

Irrigation event	Treatment	Observation before irrigation			Observation after irrigation		
		Dates	Soil water content (% FC)*	SMD (mm)	Dates	Days after irrigation	Soil water content (% FC)
I	B	03.06	75.8	57.6	07.06	4	87.7
	C	01.06	69.0	73.9	05.06	3	93.2
	D	06.06	71.5	67.8	09.06	3	88.7
II	B	25.06	72.9	64.5	30.06	4	101.1
	C	24.06	75.9	57.5	29.06	4	91.9
	D	27.06	76.4	56.2	01.07	3	98.1
III	B	11.07	71.6	67.6	17.07	4	102.4

* FC: soil water content at field capacity

Table 6. Performances of the first irrigation event.

	Long furrows (L = 400 m)							Multi-tier (3L=130 m)		
	Target inflow rates							Average inflow rates		
	2.4 l/s		1.8 l/s				1.2 l/s	1.8 l/s	1.3 l/s	0.96 l/s
Treatment	B	C	B	C	D		B	A		
Furrow nº	5	9	6	10	11	12	7	1	2	3
q_{in}	2.35	2.34	1.74	1.78	1.79	1.79	1.17	2.30*	1.75*	1.17*
(l/s/furrow)								1.67	1.09	0.87
t_{co} (min)	360	540	565	540	505	505	500	145	178	210
t_{av} (min)	152	224	476	284	233	452	256	30	54	65
q_{out} (l/s)	0.90	0.56	0.16	0.27	0.15	0.06	0.33	0.95	0.99	0.44
t_{out} (min)	266	351	169	292	313	101	304	144	162	170
D (mm)	141	105	164	80	151	151	97	134	118	104
Z_{avg} (mm)	108	91	163	77	142	148	82	80	79	91
Z_{req} (mm)	73.5	74.2	73.5	74.2	73.9	73.9	73.5	73.5	73.5	73.5
Z_{lq} (mm)	98.6	80.4	117.0	64.6	122.0	96.8	70.2	79.8	77.9	85.0
E_a (%)	52.2	70.6	44.8	80.8	48.9	49.0	72.1	55.0	62.4	70.9
DU (%)	91.4	88	71.9	83.6	85.8	65.3	85.8	99.3	98.8	93.9

* Inflow rates during advance and maintenance

The tail-end runoff is not very high for most cases, particularly for alternate furrow irrigation, but the runoff time (t_{out}) is often quite long, also in relation to the excessive t_{co} observed. Application efficiencies are generally low, often $E_a < 50\%$, due to both excess irrigation and small SMD at time of irrigation. A large fraction of the applied water percolates then below the root zone since it cannot be stored there.

When comparing results relative to inflow rates utilized, it may be concluded that high inflow rates are not the most appropriate, including for the short furrows used in multi-tier irrigation. Relative to long furrows, it was observed that for q_{in} = 2.4 l/s, the best E_a and DU were obtained for the treatment C, with alternate irrigation of the furrows (E_a = 70.6% and DU = 88%). When q_{in} = 1.8

l/s, the best E_a and DU were also obtained for the same treatment C with E_a = 80.8% and DU = 83.6% (Fig. 9). This show to be the best inflow rate for alternate furrows' irrigation. For q_{in} = 1.2 l/s the best E_a and DU combination corresponds to the treatment B, also with long furrows but with irrigation in every furrow (E_a = 72.1% and DU = 85.8%).

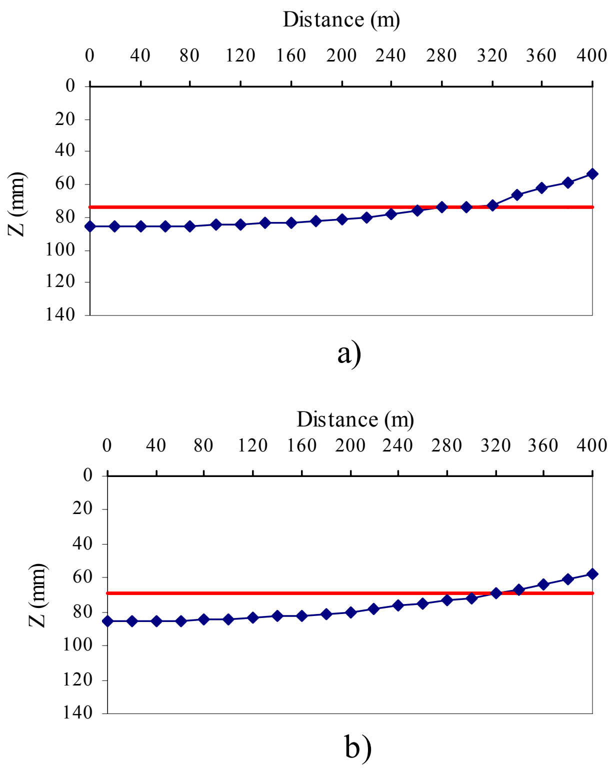

Fig. 9. Infiltration profiles of furrow 10, treatment C: a) first irrigation, and b) third irrigation.

Relative to multi-tier irrigation, good results were achieved for the design inflow q_{in}= 1 l/s (furrow 3), which produced E_a = 70.9% and DU = 93.9%.

When the third irrigation was carried out the SMD ranged between 69.0 mm for treatment C and 78.9 mm for treatment B (Fig. 10). The respective evaluation results are presented in Table 7.

Results in Table 7 show that DU generally improved relatively to the first irrigation event, with only one case having DU<85%. Higher DU were mainly due to the fact that the furrow bed surfaces were smoothed after the preceding irrigations, thus having smaller advance times that positively influenced DU.

Table 7. Performances of the third irrigation event.

	Long furrows (L = 400 m)							Multi-tier (3L=130 m)		
	Target inflow rates							Average inflow rates		
	2.4 l/s		1.8 l/s				1.2 l/s	2.07 l/s	1.21 l/s	0.87 l/s
Treatment	B	C	B	C	D		B	A		
Furrow nº	5	9	6	10	11	12	7	1	2	3
q_{in}	2.39	2.36	1.79	1.78	1.79	1.78	1.21	2.36*	1.79*	1.19*
(l/s/furrow)								1.94	1.02	0.74
t_{co} (min)	540	540	660	540	630	630	720	275	275	309
t_{av} (min)	143	118	297	251	230	265	457	27	41	56
q_{out} (l/s)	0.97	0.95	0.33	0.22	0.27	0.42	0.20	1.19	1.29	0.73
t_{out} (min)	457	459	412	335	439	402	315	297	273	288
D (mm)	215	106	197	80	188	187	145	332	250	189
Z_{avg} (mm)	141	76	177	77	173	167	143	172	88	103
Z_{req} (mm)	78.9	69.0	78.9	69.0	75.1	75.1	78.9	71.3	69.3	71.3
Z_{lq} (mm)	132.2	72.0	151.3	65.0	153.4	144.4	113.0	169.8	86.8	100.7
E_a (%)	36.7	65.0	40.1	80.8	39.9	40.1	54.5	21.5	28.6	37.8
DU (%)	93.5	94.5	85.5	84.5	88.5	86.6	78.9	98.9	98.9	97.5

* Inflow rates during advance and maintenance

Fig. 10. View of the cotton experimental field at the third irrigation (treatment B).

The irrigation depths D were generally much above those required because the t_{co} times were generally larger than for the first irrigation while Z_{req} were not larger. This is explained, as for the first irrigation, by the common farmers practice aimed at avoiding crop water stress, thus preferring to over irrigate to better control risks relative to water deficiencies This practice makes that the lower quarter infiltrated depth was generally much larger than the target Z_{req}, thus resulting in very low application efficiencies, often E_a <40%.The tail end runoff was higher, for some cases much higher than for the first irrigation, increasing when high inflow rates were used. Alternate furrow irrigation produced less runoff than other practices.

Comparing results relative to different inflow rates, it was confirmed that high inflow rates are not appropriate to short furrows, with low E_a for all multi-tier experiments. Results were aggravated by the excessive depths D applied. For long furrows with q_{in}= 2.4 l/s, the best E_a and DU were again obtained for the treatment C, with irrigation in alternate furrows (E_a = 65.0% and DU = 94.5%). Adopting a smaller q_{in}= 1.8 l/s, the best E_a and DU were also obtained for alternate furrows (treatment C), with E_a = 80.8% and DU = 84.5%. This inflow rate is probably the most appropriate for alternate furrow irrigation. For q_{in}= 1.2 l/s, the best E_a and DU combination were for treatment B, with long furrows and irrigation in every furrow (E_a = 54.5% and DU = 78.9%); this inflow-rate is the most appropriate for every furrow irrigation but performances are worst than those obtained for alternate furrows with q_{in}= 1.8 l/s.

Discussion on improving irrigation performances

The distribution uniformity DU and the application efficiency depend upon a large number of factors such as the unit inflow rate, the hydraulics roughness, the intake characteristics of the soil, the cross-sectional characteristics of the furrow, time of cutoff and the longitudinal slope of the furrows (Pereira and Trout, 1999). In addition, E_a depends on the soil water deficit at time of irrigation. However, attention must be given to land levelling conditions since these play a major role for achieving uniform flow along the field, particularly in basin irrigation (Playan *et al.*, 1996; Fangmeier *et al.*, 1999; Pereira *et al.*, 2002b). In this study, because it aims at field assessment of water saving potential when adopting easy accessible technologies related to furrow irrigation, and distribution uniformities assessed are good, precision of land levelling was not considered. Therefore, the factors by which a farmer may manage a system in order to improve the distribution uniformity, DU, and the application efficiency, E_a, may be expressed by simplified functional relationships (Pereira and Trout, 1999):

$$DU = \mathrm{f}\,(q_{in},\ t_{co}) \qquad [13]$$

and

$$E_a = \mathrm{f}\,(q_{in},\ t_{co},\ SMD) \qquad [14]$$

which symbols were previously defined along this paper.

Relative to the furrow inflow rates, the results analyzed above show that adopting q_{in} = 1.8 l/s for alternate furrow irrigation and q_{in} = 1.2 l/s when irrigation in every furrow is practiced seem to be appropriate. In case of multi-tier irrigation with short furrows, the best E_a and DU combination refer to q_{in} = 1.2 l/s during advance and q_{in} = 0.75 l/s during the maintenance phase, after the advance is completed. However, these results may need further confirmation from field. Results also show that other main factors leading to improve the performances are, first, to reduce the duration of irrigation, t_{co}, and, secondly, to delay the irrigation events to have a larger SMD at time of irrigation. The later depends upon adopting an improved irrigation scheduling (Fortes *et al.*, 2005). Adjusting t_{co} may be adopted easily in the farmers practice together with improved inflow rates as a best management practice.

Aiming at verifying these hypotheses, a simulation was performed relative to the third irrigation event (Table 7) decreasing t_{co} but keeping all other variables constant. Simulation results in Table 8 show that adopting smaller cutoff times generally leads to better adjust the average infiltrated depths to those required and to decrease the applied depths D. However, results differ among treatments, being more effective for the multi-tier irrigation and, in long furrows, for every-furrow irrigation treatments.

For treatment C – irrigation of alternate furrows – responses to changes in t_{co} would decrease the infiltrated depth below target, thus these changes are not considered in Table 8. This behaviour is related to the fact that soil water storage is much larger than in case of every-furrow irrigation (Fig. 11).

Fig. 11. Cotton irrigation by alternate furrows (1st irrigation, treatment C).

Comparing results from C with those relative to B and D treatments (Table 7), the applied depths for the C cases were already about half of those relative to every furrow irrigation. A similar but less drastic reduction of D was also observed for the first (and second) irrigation (Table 6). Therefore, water savings due to the use of alternate furrow irrigation instead of every furrow irrigation represent about 200 mm when q_{in}= 1.8 l/s/furrow, and 300 mm when q_{in}= 2.3 l/s/furrow. Nevertheless, further improvements leading to reduce the advance time and to make infiltration more uniform using surge-flow need to be considered (Horst *et al.*, 2005).

Table 8. Simulated performances of the third irrigation when the cutoff time is improved.

	Long furrows (L = 400 m)							Multi-tier (3L=130 m)		
	Target inflow rates							Average inflow rates		
	2.4 l/s		1.8 l/s				1.2 l/s	2.07 l/s	1.21 l/s	0.87 l/s
Treatments	B	C**	B	C**	D		B	A		
Furrow nº	5	9	6	10	11	12	7	1	2	3
q_{in} (l/s/furrow)	2.39	2.36	1.79	1.78	1.79	1.78	1.21	2.36* 1.94	1.79* 1.02	1.19* 0.74
t_{av} (min)	143	118	297	251	230	265	457	27	41	56
t_{co} (min)	310	540	410	540	384	420	673	85	170	192
q_{out} (l/s)	0.74	0.95	0.23	0.22	0.16	0.28	0.18	0.63	1.15	0.66
t_{out} (min)	209	459	162	335	193	193	268	107	168	171
D (mm)	123	106	121	80	115	125	136	90	105	86
Z_{avg} (mm)	93	76	116	77	111	116	133	73	69	74
Z_{req} (mm)	78.9	69.0	78.9	69.0	75.1	75.1	78.9	71.3	69.3	71.3
Z_{lq} (mm)	83.0	72.0	90.0	65.0	89.8	90.7	103.0	71.1	68.1	71.4
E_a (%)	64.1	65.0	65.0	80.8	65.3	60.2	58.2	78.7	64.8	82.9
DU (%)	89.7	94.5	77.4	84.5	81.1	78.3	77.3	97.1	98.4	96.2

* Inflow rates during advance and maintenance
** Field, not simulated results

In multi-tier irrigation, t_{co} may be reduced to about one third of actual ones when the average q_{in} is about 2 l/s/furrow and to about 2/3 when a smaller q_{in} close to 0.9 l/s/furrow is used. Then, the applied depths D are reduced from 332 to 90 mm or from 189 to 86 mm respectively. Water savings in this third irrigation could then range between 103 and 242 mm. For the 3 irrigations of cotton, the total water savings could be larger than 300 mm. Results also point out that good performances may be achieved with various inflow rates, but the best correspond to those identified in field experiments, q_{in}= 1.2 l/s during advance and q_{in}= 0.75 l/s as the maintenance discharge after the advance is completed. However, multi-tier irrigation is difficult to adopt in farmers practice because it requires additional labour inputs for setting the «shokh-aryk» ditch (Fig. 1) and needs a relatively complex field water management.

For long furrows where the alternate irrigation technique is not applied, reducing t_{co} by about 1/3 leads to drastic water savings, about 90 mm when q_{in}= 1.8 l/s/furrow was applied, and near 70 mm when q_{in} = 2.4 l/s/furrow was used. Similar but small savings are attainable for the first and second irrigation, thus leading to the season's potential water saving of 150 to 200 mm if cutoff times are better adjusted. Further water savings are expected from adopting surge-flow irrigation (Pavlov and Horst, 1995; Horst *et al.*, 2005).

Conclusions

Furrow irrigation systems in Fergana Valley were characterized relative to furrow slopes and geometry, inflow rates, hydraulic roughness, infiltration characteristics, and advance and recession times. Field evaluations performed in farmer managed fields have shown that the distribution uniformities are generally high, indicating good system performances, but the application efficiencies are low, thus indicating poor system management. Farmers may be interested in high DU because this results in more uniform crops. Causes for low E_a relate to very high advance times, less good irrigation timings, and excess water application related to large cutoff times. Both irrigation timings and duration reflect the farmers' preference to over-irrigate to avoid crop water stress. The collaboration with farmers to enhance the transfer of research findings is therefore essential since they are strongly tied to traditional practices.

The best performances for long furrows were observed for alternate furrow irrigation, which season potential for water savings relative to every-furrow irrigation is about 200 mm when q_{in}= 1.8 l/s/furrow, and 300 mm when q_{in}= 2.4 l/s/furrow. Alternate furrow irrigation may be recommended as a water saving practice to be widely spread in Central Fergana Valley considering the favourable lateral redistribution of the infiltrated water in the flat silty loam soils in the area.

A practice to be considered for long furrows is a reduction in the irrigation cutoff times when every-furrow irrigation is used. For the conditions observed, reducing t_{co} by about one third leads to a season's potential water savings of 150 to 200 mm.

The multi-tier irrigation, where three tiers of furrows with 130m long operate successively to reuse the upstream runoff, shows to perform well when inflow discharges and, mainly the cutoff times are well adapted. Season's potential water savings observed exceeds 300 mm. However, this irrigation method requires additional labour inputs and thorough regulation and repeated re-regulation of inflow. Further research should focus on surge-flow irrigation using non-automated and low-cost surge control equipment for long furrows, including when irrigation of alternate furrows is adopted. Surge-flow has the potential to reduce the advance times, to produce more uniform infiltration and to reduce tail end runoff. Adopting more adequate irrigation timings requires better approaches to irrigation scheduling as referred by Cholpankulov *et al.*, 2005.

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