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Field assessment of the water saving potential with furrow irrigation in Fergana, Aral Sea basin

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Abstract

The Aral Sea basin is a region that faces water scarcity due to aridity and man-made desertification. To reduce the disproportion between water demand and supply improved water management is required, particularly aimed at water saving and conservation in irrigated agriculture. One main issue is demand management by reducing the farm irrigation water demand by improved crop irrigation management since the modernization and rehabilitation of the conveyance and distribution systems are presently out of the scope in Uzbekistan. Under this perspective, the improvement of furrow irrigation systems, which are used on 98% of the irrigated lands, is a main issue. 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. Irrigation management alternatives included several furrow inflow rates (1.2–2.4 l/(s furrow)) and furrow lengths (130 and 400 m); comparing every-furrow irrigation with 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 rate of 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

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irrigation. Large water saving also resulted from reducing the irrigation cut-off times in every-furrow irrigation, corresponding 150–200 mm through the irrigation season. Also, improving the multi-tier reuse method when adjusting the cut-off times in agreement with the inflow rates produced high irrigation performances and water savings larger than 300 mm for the season. The field research provided information for alternative approaches to be further considered, such as surge-flow irrigation aiming at reducing advance times and tail-end runoff.

Keywords: Alternate furrow irrigation; Application efficiency; Cut-off times; Distribution uniformity; Irrigation water management; Multi-tier irrigation; Uzbekistan; Water saving

1. Introduction

The Aral Sea basin is widely known as a water scarce region where problems due to man made desertification add to aridity and drought. Understanding the concepts of aridity and desertification is required to identify proper measures and practices that help to cope with these water scarcity regimes, including irrigation water saving practices (Pereira et al., 2002a). A typical Aral Sea syndrome has been identified by the international scientific community to represent the cases, where desertification is caused by large-scale projects involving deliberated reshaping of the natural environment (Downing and Lüdeke, 2002). Solving the problem of water scarcity in the area faces problems of very different nature and includes several issues in water and salts management at various temporal and space scales (Dukhovny and Sokolov, 1998). Issues for solving the problems are of very different nature and preferably should be such that minimize the impacts of both aridity and desertification. This includes the control of irrigation demand through improved farm irrigation performance (Horst, 1989).

Studies aiming at water savings and salinity control to combat desertification are being developed through a EU funded cooperative research project, which applies to the Fergana Valley (Fig. 1), Syr Darya River basin, and concerns three main locations: Fergana in Uzbekistan, Osh in Kyrgyzstan, and Khojent in Tajikistan. 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). An improved crop irrigation management is supposed to contribute to fight against desertification (IPED, 1996) and to the sustainable use of water in irrigated agriculture, including the management of salinity (Djurabekov and Laktaev, 1983).

The Fergana Valley is an ancient irrigated oasis, with relatively high farming standards, and long and good traditions of irrigation and water management. Surface irrigation is prevalent there. The farm irrigation systems are generally through earthen ditches, with low technology regulation and control, and complex water distribution systems. Several improved technologies were implemented in the past, including for cotton irrigation (Laktaev, 1978; Djurabekov and Laktaev, 1983; Horst, 1989), but the change in the land structures and privatization created new challenges to adopt modern surface irrigation. It is

Fig. 1. The Aral Sea basin and location of the Fergana Valley.

therefore required to assess the present irrigation conditions and the potential for water savings by improving the farm irrigation systems and irrigation scheduling but controlling salinity at such a level that yields may not be affected. The combined management of irrigation and drainage, which complexity in arid zones is well known (Djurabekov and Laktaev, 1983; Bucks et al., 1990; Dukhovny et al., 2002), is another challenge in this research.

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.

2. Material and methods

2.1. Field experiments

Field studies were performed in the farm ‘‘Azizbek-1’’ in central Fergana Valley (Fig. 1) 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. Surge flow (Pavlov and Horst, 1995) was not considered in the present experiments, which were designed to identify improvements that could easily and promptly be implemented by the farmers without requiring investments in equipment. Thus, precision land levelling is not considered in this study despite the importance it could have to achieve higher performances and water saving (Pereira et al., 2002b). The irrigation scheduling in this field study 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[a]	Furrow irrigation management	Drainage conditions
A	1	130	0.0025	2.4	Compacted	Irrigation every furrow	Normal
	2	130	0.0025	1.8	Compacted		
	3	130	0.0025	1.2	Compacted		
	4	130	0.0025	1.8	*n*/compacted		
B	5	400	0.0020	2.4	Compacted	Irrigation every furrow	Normal
	6	400	0.0020	1.8	Compacted		
	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 furrows	Normal
	10	400	0.0020	1.8	Compacted		
D	11	400	0.0026	1.8	Compacted	Irrigation every furrow	Improved drainage
	12	400	0.0026	1.8	*n*/compacted		

[a] Compaction by tractor wheels.

Irrigation with short furrows (treatment A) may be improved when using the so-called multi-tier irrigation (Fig. 2). With this field layout, the outflow 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, in an amount whose should correspond to the difference between the volumes supplied and flowing out of the first furrows' tier. This supply is conveyed through a furrow called ''shokh-aryk'', which runs parallel to the irrigated furrows. 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.

Soils in the area were studied to characterize selected soil hydraulic properties. Soil characteristics referring to seven 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 $-1/3$ 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.

2.2. 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.

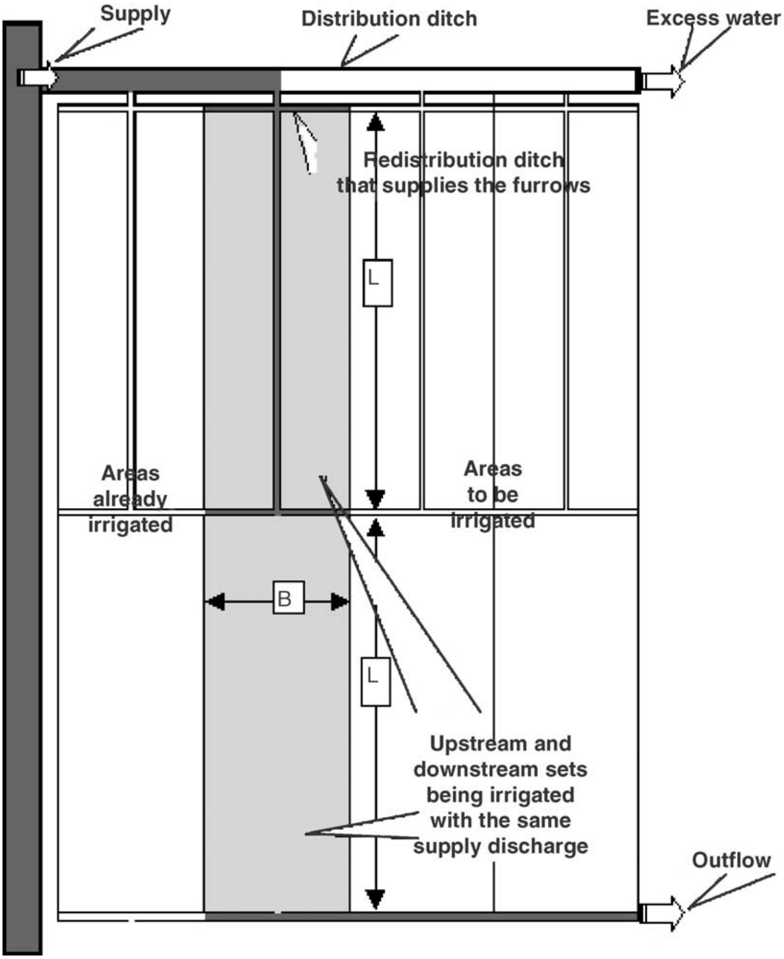

Fig. 2. Schematic representation of multi-tier irrigation to reuse runoff in successive furrow sets.

Table 2
Soil physical and hydraulic properties

Genetic horizon (cm)	Layer thickness (cm)	Bulk density (g/cm^3)	Porosity (%)	Field capacity		Wilting point		Available soil water	
				$m^3 m^{-3}$	mm	$m^3 m^{-3}$	mm	$m^3 m^{-3}$	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

Deviations from actual to target field elevations were measured using a square grid 20 m × 20 m in a field with 400 m × 250 m. The standard deviation of field elevation differences $\mathrm{S.D._p}$ (m) was computed as:

$$\mathrm{S.D._p} = \left[\sum_{i=1}^{N} \frac{(h_i - h_{\mathrm{t}i})^2}{(N-1)}\right]^{0.5} \tag{1}$$

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

Along with $\mathrm{S.D._p}$, the relative non-uniformity indicator Δ_y (%), adopted by Li and Calejo (1998), was also used:

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

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

Discharges into and in 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. 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 min until the flow became stable. After the stabilization, measurement intervals increased up to 20–30 min; in case of abrupt changes of the flow rate in the upstream water supply ditch, measurements were taken more frequently until the supply flow rate was stabilized.

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

$$Q_{\mathrm{avg}} = \frac{\sum_{i=1}^{N} A_{\mathrm{q}i}}{t_{\mathrm{ap}}} \tag{3}$$

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

$$A_{\mathrm{q}i} = 30(Q_i + Q_{i-1})(t_i - t_{i-1}) \tag{4}$$

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} the measured furrow flow rates (l/s) at those times t_i and t_{i-1}; N the number of flow rate measurements; 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 coefficient of variation and by the sum of the squares of the deviations of the current inflow measurements to the average rate Q_{avg}:

$$\mathrm{SSD_q} = \sum_{i=1}^{N} (Q_i - Q_{\mathrm{avg}})^2 \tag{5}$$

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:

$$n = \frac{AR^{2/3}S_o^{1/2}}{Q_{inf}} \tag{6}$$

where Q_{inf} is the inflow rate to the furrow (m^3/s); A the cross-sectional area of the furrow flow (m^2); R the hydraulic radius (m); 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:

$$Z = k\tau^{\alpha} + f_0\tau \tag{7}$$

where Z is the cumulative infiltration per unit length of furrow (m^3/m); τ the intake opportunity time (min); α and k the empirical parameters; f_0 is the 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. The need for using both advance and recession observations when searching the infiltration parameters (Calejo et al., 1998) was confirmed in this study. The roughness parameters (n), obtained with Eq. (6) from observed furrow discharges and furrow shape parameters, were kept constant during the search procedure.

The initial values for the infiltration parameters f_0, α and k were determined using the "two-point" method proposed by Elliott and Walker (1982). The estimation procedure starts with the definition of the final infiltration rate f_0 from the inflow–outflow hydrograph for each of the studied irrigation treatments. The methodology described by Walker and Skogerboe (1987) was adopted.

Soil water content measurements were performed in each furrow irrigation field at three locations at distances of 0.25L, 0.5L and 0.75L 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 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}).

2.3. 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 E_a is a management performance indicator (Pereira and Trout, 1999; Pereira et al., 2002b). They are described by the following relationships:

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

$$\mathrm{DU} = \frac{Z_{\mathrm{lq}}}{Z_{\mathrm{avg}}} \times 100 \tag{9}$$

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 the average water depth (mm) applied to the irrigated area; Z_{lq} the average low quarter depth of water infiltrated in the field (mm); 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:

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

where k, α and f_0 are the infiltration parameters characterizing each irrigation; $(t_r)_i$ and $(t_a)_i$ are the, respectively, 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:

$$D = \frac{q_{\mathrm{avf}} \times 60 \times t_{\mathrm{co}}}{L \times s} \tag{11}$$

where q_{avf} is the average furrow inflow rate (l/s) during an irrigation event, t_{co} the cut-off 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:

$$V_{\mathrm{out}} = \frac{q_{\mathrm{out}} \times 60 \times t_{\mathrm{out}}}{L \times s} \tag{12}$$

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

3. Results and discussion

3.1. Furrow characteristics and inflow rates

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 slopes standard deviation was S.D. = 0.00030 m/m and the coefficient of variation was CV = 0.14, i.e. the variations of the longitudinal slope are generally small along the furrows. The average slope across the field was $S_{across} = 0.00065$ m/m, 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.

Typical furrow cross sections before and after irrigation and the adjusted parabola are shown in Fig. 3. Comparing the cross sections before and after irrigation, 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 (2.4 l/s) 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. 4, where small variations in the inflow rates are shown, as well as the respective impacts on outflows. This example also shows that the outflow volume may be a significant fraction of the total inflow.

The effect of inflow rates on furrow erosion is significant in Fergana soils. The small and medium inflow rates tested (1.2 and 1.8 l/s) were generally non-erosive, but the largest one

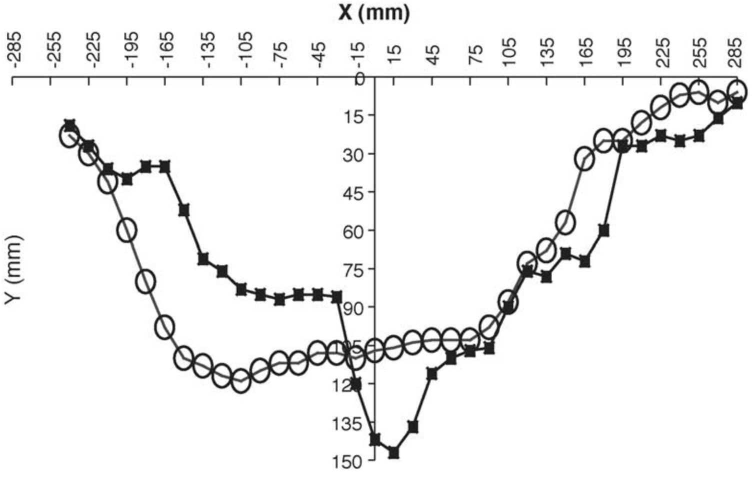

Fig. 3. Typical furrow cross sections before (■) and after irrigation (○) (furrow no. 9, treatment C, inflow rate 2.4 l/s, observations by 11 and 15 July 2001, respectively).

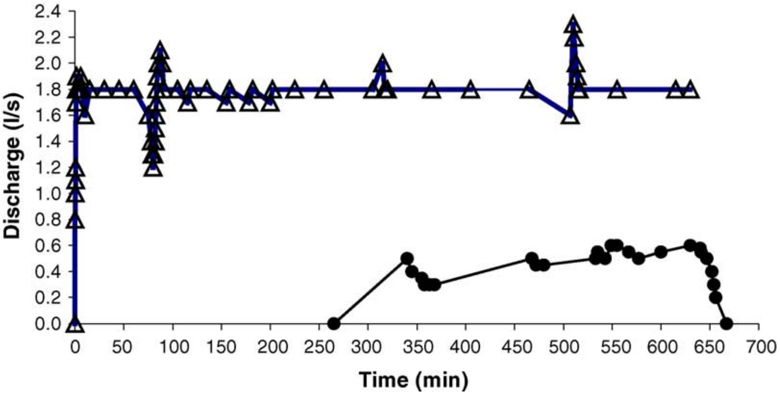

Fig. 4. Typical inflow (△) and outflow (●) hydrographs (furrow 12, treatment D, 1.8 l/s, third irrigation).

(2.4 l/s) has shown to be erosive in the furrows upstream sections, particularly for the first irrigation as shown in Fig. 3.

3.2. Hydraulics roughness and infiltration

The hydraulics roughness parameter 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 $n = 0.018\ \mathrm{m}^{-1/3}\ \mathrm{s}$ and varied 0.020–0.017 $\mathrm{m}^{-1/3}$ s from the first to the third irrigation events for the long furrows (400 m).

The estimated final infiltration rate, f_0, 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_0 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.

The average final infiltration rate f_0 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

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

	Statistical indicators (n ($\mathrm{m}^{-1/3}$ 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

Table 4
Estimated infiltration parameters and respective statistical indicators

	Statistical indicators	f_0 (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

referred relative to changes in furrow cross-sections in Fig. 3, which becomes more stable only after the second irrigation. The parameters k and α did not show 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. 5). The infiltration parameters relative to these families were later used with SIRMOD to evaluate the irrigation systems performance and to design improved solutions. It may be observed (Fig. 5) 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.

3.3. Actual irrigation performances

Typical advance and recession curves measured and simulated with SIRMOD model are presented in Fig. 6. Results show that the SIRMOD model adequately describes advance and recession when the parameters search technique referred in Section 2.2 are applied. The example shows that the advance time is very long and that the recession curve is about linear, with relatively small differences between the upstream and the downstream sections (50 min for a 400 m furrow in case of Fig. 6). This produces relatively important differences in the infiltration opportunity time between upstream and downstream

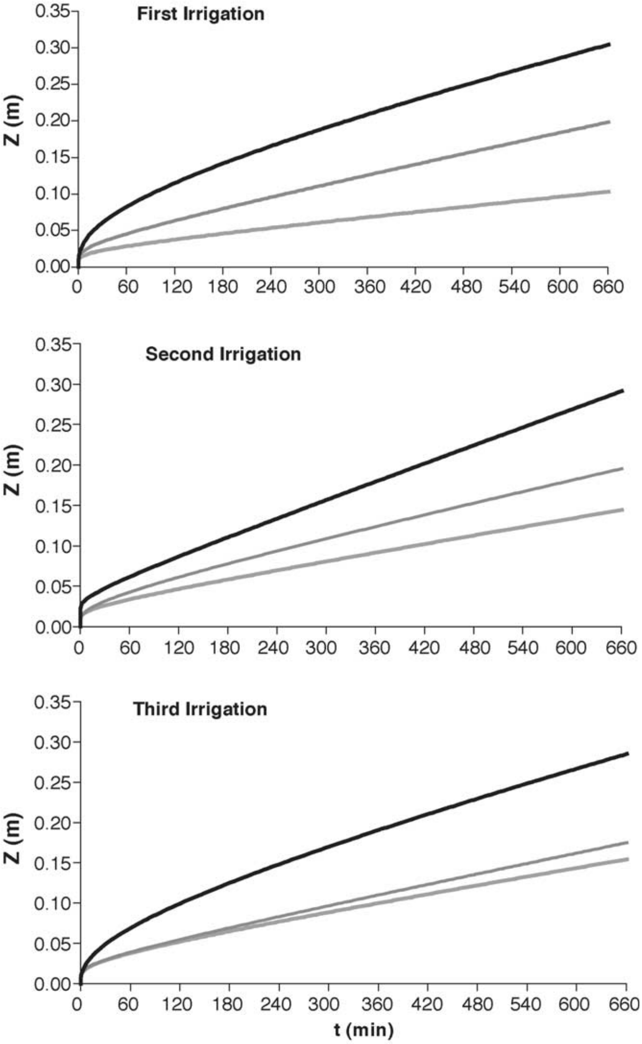

Fig. 5. Average cumulative infiltration curves relative to high (▬), medium (—) and low (▬) soil infiltration families relative to three irrigations events (treatments B, C, and D).

(225 min in case of Fig. 6), which become larger when the cut-off time is shorter. This may be a cause for the farmers to adopt larger t_{co} and therefore to over-irrigate.

The results of the first and the third cotton irrigations were used to analyze the observed irrigation performances. The first irrigation was performed 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 are shown in Table 5. Results show that DU is generally high to very high, with only furrows 6 and 12 having DU $<$ 83%. This is related to slope and infiltration conditions, which originate very long advance times. Irrigation depths D are generally much above the

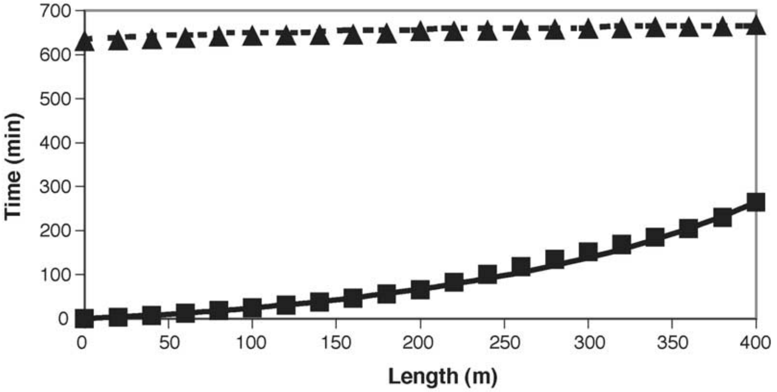

Fig. 6. Observed advance (■) and recession (▲) vs. simulated advance (▬) and recession (- - -) curves (furrow 12, treatment D, inflow rate 1.8 l/s, third irrigation).

required Z_{req}. This also relates to the large advance times (e.g. Fig. 6) and the excessive times for cut-off. In fact, to avoid crop water stress farmers use a very long duration of irrigation, which results in over irrigation.

Soil water observations at time of irrigation allowed to estimate the soil water depletion fraction p used by the farmer when scheduling irrigations: p ranged from 0.43 to 0.56, generally much smaller than the commonly recommended soil water depletion fraction for no stress for cotton, $p = 0.65$ (Allen et al., 1998). Thus, an irrigation schedule without allowing 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 average soil moisture deficit (SMD) at time of irrigation were smaller than those aimed when water saving irrigation is practiced. As a consequence of the adopted irrigation scheduling, the depth of water added to root zone storage observed 3 or 4 days after irrigation is generally small, thus favouring low application efficiencies. These conditions indicate a large potential to increase the application efficiency if the irrigation intervals are enlarged.

Despite D was excessive, the low quarter depth infiltrated was in some cases smaller than the target Z_{req}. This is explained through the uneven infiltrated depths (e.g. Fig. 7) resulting from the above referred differences in infiltration opportunity times at the furrows up- and downstream ends, although DU was high.

The tail-end runoff (e.g. Fig. 4) is not very high for most cases, particularly for alternate furrow irrigation, but the runoff time (t_{out}) is often quite long due to excessive t_{co}. 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 the inflow rates utilized, it may be concluded that high inflow rates are not appropriate, even 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%). However, this discharge is erosive as analyzed before. When $q_{in} = 1.8$ l/s, the

Table 5
Characteristics and performances of the first irrigation event

Treatment	Long furrows ($L = 400$ m)							Multi-tier ($3 \times L = 130$ m)		
	Target inflow rates							Average inflow rates		
	2.4 l/s		1.8 l/s				1.2 l/s	1.80 l/s	1.29 l/s	0.96 l/s
	B	C	B	C	D		B	A		
Furrow number	5	9	6	10	11	12	7	1	2	3
q_{in} (l/(s furrow))	2.35	2.34	1.74	1.78	1.79	1.79	1.17	2.30[a] 1.67	1.75[a] 1.09	1.17[a] 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	70.24	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

[a] Inflow rates during advance and after advance is completed.

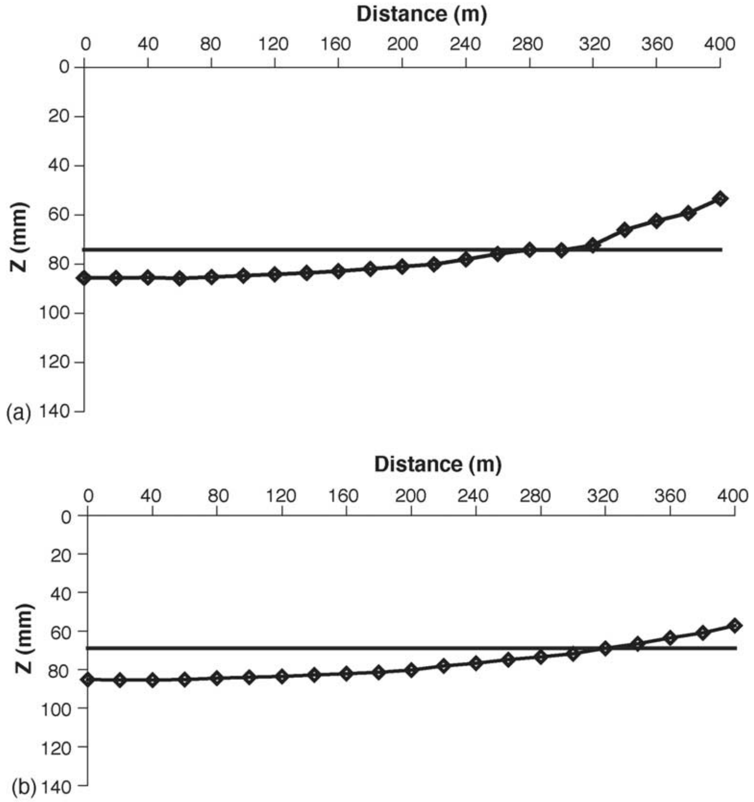

Fig. 7. Infiltration profiles of furrow 10, treatment C, inflow rate 1.8 l/s: (a) first irrigation and (b) third irrigation.

best E_a and DU were also obtained for the same treatment C with $E_a = 80.8\%$ and DU = 83.6% (Fig. 7). This results 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%). Thus, when every furrow irrigation is adopted, the inflow rate $q_{in} = 1.2$ l/s is a valid alternative.

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 performed the SMD ranged between 69.0 mm for treatment C and 78.9 mm for treatment B. The respective evaluation results are presented in Table 6. These results show that DU generally improved relatively to the first irrigation event, with only one case having DU < 85%. These higher DU values were mainly due to the fact that the furrow bed surfaces were smoothed after the preceding irrigations, thus favouring smaller advance times, which positively influenced DU.

The irrigation depths D were generally much above those required because the t_{co} times were generally larger than for the first irrigation while the Z_{req} were not larger. This is only explained, as for the first irrigation, by the common farmers practice aimed at avoiding crop

Table 6
Characteristics and performances of the third irrigation event

Treatment	Long furrows ($L = 400$ m)							Multi-tier ($3 \times L = 130$ 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
	B	C	B	C	D		B	A		
Furrow number	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[a] 1.94	1.79 1.02	1.19 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

[a] Inflow rates during advance and after advance is completed.

water stress, thus preferring to over irrigate to better control risks relative to water deficiencies. Consequently, the low 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, mainly when high inflow rates were used and over irrigation was practiced. 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 applied. For long furrows with q_{in} = 2.4 l/s, the best E_a and DU were again obtained for 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 treatment C, with E_a = 80.8% and DU = 84.5%. Probably, this inflow rate is the most appropriate for alternate furrow irrigation. For the smallest q_{in} = 1.2 l/s, the best E_a and DU combination corresponded again to treatment B, with long furrows and irrigation in every furrow (E_a = 54.5% and DU = 78.9%), but these performances are worst than those obtained for treatment C with q_{in} = 1.8 l/s.

3.4. Simulating improved irrigation management

Water saving may be achieved when irrigation performances such as the distribution uniformity (DU) and the application efficiency (E_a) are improved. DU and E_a 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, the time of cut-off and the longitudinal slope of the furrows. In addition, E_a depends on the soil water deficit at time of irrigation (Pereira, 1999; Pereira and Trout, 1999). 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). However, since this study aims at field assessment of water saving potential adopting easy accessible technologies related to furrow irrigation, and distribution uniformities assessed are good, precision land levelling was not considered. Therefore, the factors by which a farmer may manage a system in order to improve the distribution uniformity and the application efficiency may be expressed by simplified functional relationships (Pereira and Trout, 1999) such as:

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

and

$$E_{\mathrm{a}} = f(q_{\mathrm{in}}, t_{\mathrm{co}}, \mathrm{SMD}) \tag{14}$$

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 referred to q_{in} = 1.2 l/s during advance and q_{in} = 0.75 l/s after the advance is completed. Results also show that other relevant factors leading to improve the performances are, first, to reduce the time 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, which is already under implementation (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 6) decreasing t_{co} but keeping all other variables constant. Simulation results in Table 7 show that adopting smaller cut-off 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 the case of every-furrow irrigation.

Treatment C—irrigation of alternate furrows—responds to changes in t_{co} by decreasing the infiltrated depth below target. This peculiar response to a decrease in t_{co} is related to the fact that soil water storage is much larger than in the case of every-furrow irrigation. Comparing results from treatment C with those relative to B and D (Table 6), the applied depths for C were already about half of those relative to every furrow irrigation. A similar but less drastic reduction of the applied depth was also observed for the first irrigation (Table 5). Therefore, water savings due to the use alternate furrow irrigation instead of every furrow irrigation represent about 200–00 mm/year. Nevertheless, further improvements leading to reduce the advance time and to make infiltration more uniform such as surge-flow need to be considered.

In multi-tier irrigation, t_{co} may be reduced to about one third of the current value 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 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 these cotton irrigations, the water savings could vary from 300 to 700 mm/year when an appropriate management of the three furrow tiers could be implemented. 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 after 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’’ distributor ditch (Fig. 2) and needs a quite 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 seasonal potential water saving of 150–200 mm if cut-off times are better adjusted.

Further water savings are expected from adopting surge-flow irrigation as already observed in past (Pavlov and Horst, 1995). As discussed above, adopting more appropriate cut-off times needs to be combined with more adequate irrigation timings. This requires better approaches to irrigation scheduling, which are already under consideration through the installation of an irrigation scheduling simulation model operating in GIS (Fortes et al., 2005). In addition, a DSS tool (Gonçalves and Pereira, 1999) to better support the search for improved management and irrigation practices focusing on both the farm income and water saving is also being prepared to operate with GIS, and to combine irrigation system and scheduling decisions.

Table 7
Simulated performances of the third irrigation when the cut-off time is improved

Treatments	Long furrows ($L = 400$ m)							Multi-tier ($3 \times L = 130$ 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
	B	C[a]	B	C[a]	D	B	A			
Furrow number	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[b] 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

[a] Field, not simulated results.

[b] Inflow rates during advance and after advance is completed.

4. Conclusions

Field evaluations performed in farmer managed fields have shown that the distribution uniformities are generally high, indicating appropriate system performance, 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, short intervals between irrigations, and excess water application related to large cut-off times. Both the irrigation timings and duration reflect the farmers' preference to over-irrigate to avoid crop water stress.

The best performances for long furrows were observed for alternate furrow irrigation, with seasonal potential for water savings relative to every-furrow irrigation of about 200–300 mm/year. 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. An alternative practice to be considered for long furrows is a reduction in the irrigation cut-off times when every-furrow irrigation is used. For the conditions observed, reducing t_{co} by about one third led to about 70 mm water savings when q_{in} = 1.8 l/(s furrow) was applied, and near 90 mm when q_{in} = 2.4 l/(s furrow). The seasonal potential water savings are then 150–200 mm/year. The best performances were obtained for q_{in} = 1.8 l/(s furrow), while q_{in} = 2.4 l/(s furrow) show to be an erosive discharge and therefore to be avoided.

The multi-tier irrigation, where three tiers of furrows 130 m long operate successively to reuse the upstream runoff, shows to perform well when the inflow discharges and the cut-off times are well adapted. The seasonal potential water saving observed exceed 300 mm/year. However, this irrigation method requires intensive management by the farmers, which may be a cause for difficulties in its proper adoption in practice.

Further developments aiming at water saving include the adoption of improved irrigation scheduling, the extensive use of farm irrigation models, improvements in canal management and the collaboration with farmers to enhance the transfer of research findings.

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