Irrig Sci (2007) 26:35–48
DOI 10.1007/s00271-007-0070-3

ORIGINAL PAPER

Cotton yields under different furrow irrigation management techniques in the Southeastern Anatolia Project (GAP) area, Turkey

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Received: 10 February 2006 / Accepted: 23 January 2007 / Published online: 14 February 2007

Abstract The continuous flow furrow irrigation (COFFI), surge flow furrow irrigation (SUFFI), cutback flow furrow irrigation (CUFFI), variable alternate flow furrow irrigation (VAFFI), and tail water reuse system furrow (TWRSF) techniques with the same inflow rate of 0.072 m^3 min^{-1} were compared in relation to the cotton yield and water use efficiency at a 3-year field study conducted on cotton (*Gossypium* spp.) in the Southeastern Anatolia Project (GAP) area of Turkey. Yields revealed significant statistical differences between the furrow management techniques ($P < 0.05$). The maximum yield was obtained from the COFFI treatment (2,630 and 2,920 kg ha^{-1}) in the first 2 years, and from SUFFI and CUFFI treatments (3,690 and 3,780 kg ha^{-1}, respectively) in the last year. There were significant yield reductions, which varied from 10 to 35% in TWRSF and from 11 to 19% in VAFFI treatments although 43 and 28% more water was applied to the TWRSF than to CUFFI and SUFFI treatments, respectively. The average total water use efficiencies (WUE_{ET}) varied from 4.14 (VAFFI) to 2.59 (COFFI). The corresponding values were 0.37 and 0.36 kg ha^{-1} m^{-3} for CUFFI and SUFFI, respectively. The average irrigation water use efficiency (WUE_{IR}) for CUFFI and SUFFI treatments were 0.30 and 0.23 kg ha^{-1} m^{-3}, respectively.

Communicated by T. Trooien.

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Introduction

Cotton (*Gossypium* spp.) is a major crop grown throughout many arid regions of the world. Since large quantities of irrigation water are needed to produce cotton in these regions, achieving maximum crop productivity per unit of applied water has become critical as costs for water and constraints on water availability increase (Hunsaker et al. 1998). Cotton is also the most important crop in the irrigated area of the Southeastern Anatolia Project (GAP) area covering about 85% of the cropped land in the region. The Turkish seed-cotton production averaged 697,000 tons from 697,000 ha, of which 46% was from 300,000 ha in the GAP area (Ozudogru 2004). The GAP project is an integrated project, and while bringing various services to the area, irrigation is one of its principle aims. GAP covers an area of 74,000 km^2 at the lower reaches of Euphrates and Tigris rivers. Following the completion of the project, 1.65 million hectares of land will be irrigated and 27 billion kWh of energy will be obtained annually (Tekinel et al. 1992).

Irrigated areas have been expanding in the region with the introduction of the water in 1995. In general, surface irrigation methods, especially the furrow, are widely used for cotton production in this region (Karaata 1984; Cetin 1992) with constant flow rates. This method causes large amounts of water losses by excess runoff and deep percolation from the irrigated fields. Moreover, farmers in the GAP region have a tendency to over irrigate, resulting in drainage and salinity problems caused by high water losses and low irrigation efficiencies (Kanber et al. 2001). Efficient irrigation is essential in the GAP region to control the rising groundwater table and environmental deterioration from salinization–alkalization and soil erosion, which contributes to ground water pollution (Cullu et al. 2000; Ozer and Demirel 2004). At the same time, inadequate surface irrigation management in more arid parts of the region induces the shortage of water due to the increasing farm water losses, and decreases, the productivity (Karaata 1984; Kanber et al. 1996, 2001). Therefore, water shortage has become a major limiting factor in crop production.

Earlier studies have shown that agricultural water-use efficiency (WUE) in this area is relatively low (Karaata 1984; Kanber et al. 1996, 2001), hence severely requiring a sustainable WUE program to improve the existing irrigation systems and management practices, despite the economic and social drawbacks. One way to improve the efficiency is to develop the furrow irrigation management techniques to reduce water use. Accordingly, numerous field studies were conducted in order to save the excess use of water in irrigation with various researchers developing several approaches to improve the efficiency and uniformity of furrow irrigation systems with the ‘‘cutback flow’’ (Garton 1966; Humpherys 1978), and the ‘‘runoff recovery system’’ methods (Stringham and Hamad 1975; Johnson 1990). The intermittent application of water, i.e., the surge irrigation method, during the advance phase (Stringham and Keller 1979; Walker and Skogerboe 1987; Humpherys 1989a, b; Jalali-Farahani et al. 1993a, b), and the ‘‘variable/fixed alternate furrow irrigation’’ (Stewart et al. 1981; Musick and Dusek 1982) are the other significant methods which are widely used for attaining a high level of irrigation efficiency. Furthermore, cutback irrigation, the tailwater recovery system and cablegation (Kemper et al. 1981) are ways used to cope with the runoff problem.

Alternate-furrow irrigation techniques, with combinations of narrow and wide-spaced furrow irrigation are used for many row crops for promoting irrigation efficiency and preventing loss water (Stewart et al. 1981; Musick and Dusek 1982; Graterol et al. 1993; Sepaskhah and Kamgar-Haghighi 1997; Kang et al. 2000). However, the results obtained from some crops, such as sorghum (New 1971), dry bean (Samadi and Sepaskhah 1984), and sugarbeet (Sepaskhah and Kamgar-Haghighi 1997), revealed some yield reductions in the alternate furrow irrigation with less water use compared to every-furrow irrigation. Graterol et al. (1993) reported that soybean yields were similar in the two irrigation treatments although less water was applied to the alternate than to every-furrow irrigation treatment. Stone and Nofziger (1993) stated that wide-spaced furrow irrigation could often produce acceptable cotton yields with less water than every-furrow irrigation. Goldhamer and Peterson (1984) compared a linear-move sprinkler machine and 380 m long alternate furrow irrigation system on a sandy loam soil. They found slightly lower cotton yields for the alternate furrow system while infiltration of water was similar for both.

Surge irrigation has been reported to increase the advance rate, reducing total water required for an irrigation application, increasing efficiency, and decreasing in infiltration in soils with a high intake rate (Izuno and Podmore 1986; Goldhammer et al. 1987a, b; McCornick et al. 1988). Similarly, the studies carried out by Onder (1994) and Kanber et al. (2001) on cotton grown in clayey soils revealed that surge flow irrigation with level furrows was successfully managed with decreases in the total water applications, water intake, and deep percolation below the root zone (120 cm), except for tail water runoff losses as compared to continuous flow. However, the cotton yields were the same in both applications, while WUE in the surge was slightly lower than the continuous flow furrow. Fulton et al. (1991) compared a subsurface drip irrigation system, an upgraded furrow system, and a surge irrigation system with traditional furrows on a clay loam soil with 12% higher cotton yields in the drip compared to the furrow. There were no differences in yield between the furrow systems even though the surge furrow had 6% less water than the traditional furrow. Musick et al. (1987) showed that the surge furrow irrigation reduced both seasonal water use and grain yields of corn by 6% and had no effect on the seasonal WUE for grain production on the graded furrow systems. Another similar study was carried out by Wang et al. (2005) in the Yellow River Basin of China. Both authors stated that surge irrigation with sediment laden water played an important role in forming a sealing layer on the soil surface, which decreased surface roughness and speeded up the water flow advance to the end of the field with higher irrigation efficiencies and lower irrigation water requirements.

The possibilities of improving irrigation methods, conserving water, and reducing downstream contamination have led to the development of several operational techniques to recycle and recover the runoff water. Stringham and Hamad (1975) designed a reuse system where water was collected in a sump and then pumped back to the head end of the field to irrigate additional furrows. Reddy and Clyma (1983) minimized cost to find optimum values of design variables. Later, Rayej and Wallender (1987) added an evaporation pond to runoff recovery to optimize a combined system again by minimizing the cost for an assumed uniform soil. Similarly, Wallender and Rayej (1989) optimized a combined runoff recovery-evaporation pond system for maximum profit on nonuniform soils under cotton production. Hanson and Ayars (2002) reported that using the tailwater return system in the Panoche Water and Drainage District eliminated surface runoff and reduced the drainage flow significantly, in turn increasing the irrigation efficiencies of cotton, tomato and alfalfa crops.

Cutback irrigation involves a decrease in the rate of inflow to the open-ended (graded) furrows during irrigation to reduce the runoff and improve the application efficiency (James 1988). Balcin (2004) compared the cutback numbers in irrigation in a bean field in the transition zone from Central Anatolia to the Black Sea region of Turkey, stating that increasing the cutback numbers in turn increased the seed yield by 8–20%, and decreased the runoff by 33–77% together with the total water applied, by 10–24%, compared to the furrow without cutbacks. Moreover, reductions of deep percolation and soil losses in the cutback irrigation furrows are 65 and 85%, respectively, which are less than those in the furrow without cutback, whereas, in contrast, Kanber et al. (1996) found that the cutback furrow irrigation decreased both water losses and yield in irrigated cotton. The optimum management of a cutback furrow irrigation system, with spatially variable infiltration, based on an average intake function was analyzed by Bautista and Wallender (1993) disregarding the final water distribution, predicting the total infiltration with an average function. Furthermore, they determined the cutback time with the least impact on the application efficiency and uniformity.

Many studies carried out in different parts of the world, are either concerned with the comparison at two different furrow management techniques or the different variations of a single management technique. This paper aims to determine the effects of the furrow management techniques on water loss and the efficient use of water. Moreover, to determine the relationships between the yield and irrigation water applications along with WUE for cotton irrigated by different furrow irrigation management techniques such as the variable alternate-furrow, surge, cutback furrow, runoff recovery system, and continuous furrow in the Harran Plain, located in the GPA Area.

Materials and methods

The experiment was conducted for 3 years, from 1993 to 1995, at the Koruklu Research Center of the Harran University located in the Harran Plain-Sanliurfa (latitude: 36°42′N; longitude: 38°58′E; and altitude: 410 m.s.l.). A semi-arid climate prevails in the Harran region with warm winters and hot and dry summers. The maximum temperature is 46.8 and the average temperature is 17.1°C and the average annual rainfall is 365.2 mm. The relative humidity is about 62% in the winter months and decreases to 36% during summer period. The total free water surface evaporation losses is 1,849 mm for beginning of March to end of November (KHSAE 2003). The average annual rainfall and total free water surface evaporation for the period between 1993 and 1995 were 457 and 1,584 mm, respectively, with only 15 and 43 mm of rainfall in 1993 and 1995, respectively, during irrigation periods. The maximum average summer time temperatures were about 43.7°C.

The field experiment was conducted on the dominant soils of the Harran Plain-the Harran soil series (*Vertic Calcisol; VerticXerochrept*, Dinc et al. 1991). The profile is uniformly clayey with angular to subangular subsoil structure from a depth of 85 to 135 cm. Soil properties related to irrigation such as available soil water capacity, total salts Electrical Conductivity (EC), bulk density, and texture were obtained from systematically sampled soils from 30 cm layers at the 120 cm profile in several plots of the experimental fields. The clay profile contains 15–20% calcium carbonate, increasing with depth. The average available soil moisture capacity is 14% by volume for a profile water available capacity of 168 mm per 1.2 m (Table 1).

The experiment was conducted on a 160 m long field with 0.7 m spaced furrows as recommended by Karaata (1984). Furrow slopes, as recommended by Merriam and Keller (1978) were 0.13% at the beginning of the irrigation season and reached an average of 0.16% at the end of the irrigation season varying from 0.094 to 0.209% depending on treatments and irrigation events during the irrigation period.

Cotton (*c.v. Sayar*) was planted to furrow ridges (constructed before the first irrigation with no further

Table 1 Soil characteristics

	Soil depth, cm			
	0–30	30–60	60–90	90–120
Organic matter, %	1.7	1.3	–	–
Mineral matter, %	98.3	98.7	100.0	100.0
Sand, %	8.9	8.6	8.8	8.7
Silt, %	29.5	25.4	24.3	23.2
Clay, %	61.6	66.1	67.0	68.1
Soil texture	C	C	C	C
EC, dS m^{-1}	0.253	0.149	0.201	0.185
pH (in paste)	7.45	7.46	7.40	7.40
Bulk density, g cm^{-3}	1.32	1.37	1.31	1.45
M.C. at FC (%, ww^{-1})	34.9	34.7	35.4	35.8
M.C. at PWP (%, ww^{-1})	21.5	21.2	21.5	21.5
A.W.C (mm)	53.1	55.5	54.6	62.2

cultivation) on three consecutive dates (May 24, 1993—143rd day of the year; April 28, 1994—117th day of the year, and April 27, 1995—116th day of the year) following the preplant irrigation (average 20 mm) in mid-April. Stands were thinned to approximately ten plants per square meter. The crop was fertilized with nitrogen (160 kg ha^{-1}) and phosphorus (60 kg ha^{-1}) at planting as recommended by Yasar (1987).

The irrigation water had an average Sodium Absorption Ratio (SAR) of 1.15 and EC of 0.294 dS m^{-1}, with no restrictions on use, where the EC was much lower than the salinity threshold (5.1 dS m^{-1}) of cotton given by Ayers and Westcot (1989). As for the water quality impacts on soil permeability, the combination of the SAR and EC also posed little or no restrictions on use (Grattan 2002).

Treatments of the continuous flow furrow irrigation (COFFI, also the freely drained open-end furrows), surge flow furrow irrigation (SUFFI) with a cycle ratio (CR) of 0.5 and an on-time (T_{on}) of 40 min, cutback flow furrow irrigation (CUFFI), variable alternate flow furrow irrigation (VAFFI), and runoff recovery system furrow or the tail water reuse system furrow (TWRSF) were studied in this experiment. An inflow rate of 0.072 m^3 min^{-1}, predetermined according to the technique developed by Merriam et al. (1980) was used in all treatments. In the CUFFI treatment, the inflow rate was decreased to 50% after the advance phase and the open-end furrows were used similar to the continuous furrow treatment in the VAFFI treatment. The irrigation water was applied as a variable in every-other-furrow treatment, i.e., one of the two neighboring furrows was alternately irrigated during consecutive irrigation. In the TWRSF treatment, after the advance phase the tail water runoff was collected in a sump placed at the end of the furrow and then pumped back to the head end of the plots for reuse. The amount of water pumped from the sump as well as its temperature and silt content together with salinity was periodically measured during irrigation.

Five adjacent V-shaped furrows for COFFI, SUFFI, CUFFI, and TWRSF and six for VAFFI were used in the plots. The advance, tail runoff, deep percolation, soil losses, soil water and yield data were collected from one of the five and two of the six furrows of the plot identically managed for all treatments. The stations along the furrows were located at 20 m intervals for monitoring the water advance and recession (Walker 1989). The experimental design was a randomized complete block design with three replications. The blocks consisted of different furrow management techniques, which were randomly distributed and placed side by side in the field.

Irrigation was repeated at 10–14 days intervals, when the available soil water content was depleted to 20–30% in the 1.2 m profile. Based on the soil moisture content, the soil moisture deficit (SMD) was determined by a neutron scattering method 1–2 days before irrigation at the head, middle, and end of the furrows. Additional soil water data were taken between some irrigation applications, at planting and harvest. Data were collected at 0.3 m increments to a soil depth of 1.2 m. The water content of the profile was raised to the field capacity at the end of the furrow length during irrigation.

Water curls made by barrels were used to obtain constant water flow rates to the plots. The barrels had three gates; two were placed on the upper part for water flow into and out of the barrel, the third one was located on the lower part and connected to a valve controlling the flow of the irrigation water to the plot. Inflow rates higher than required were used to create a constant hydraulic head in the barrel. The system was installed at the upper end of each plot and water was applied through gated plastic pipes connected to the third gate of the water curl. The holes of the pipes were adjusted by gate plugs to obtain the constantly checked flow rate used in the experiment. Surge valves (Waterman Company-Hp 500 model, Boca Raton, FL, USA) connected to the third gate of the barrel supplied the water in the surge flow treatments. The system was automatically operated via a computer that was powered by a solar panel placed on the valve.

The inflow to the furrows was ceased when the total outflow duration was equivalent to the intake opportunity time estimated by the typical infiltration functions for each application, i.e., the time required to replenish the actual depleted soil water (Criddle et al. 1956; Merriam et al. 1980). The total irrigation time for all irrigation events in the furrow management techniques was estimated by the summation of the advance time (T_{adv}) and the net infiltration time at the lower end of the furrows (T_{i}).

Runoff was measured through use of Parshall flumes placed at the ends of the furrows; these data were used to create the tailwater hydrographs with respect to time. The total tailwater runoff losses for each treatment were determined from the tailwater hydrographs by using a perpendicular trapezoidal approach (Ray et al. 1975; Walker and Skogerboe 1987).

Water samples were collected from the Parshall flume (at 5–10-min intervals during runoff) with one-liter bottles, when the wetting front reached the end of the furrow, to measure the silt and total salt contents of the out flow water in the TWRSF treatment.

Infiltration tests were conducted using the blocked furrow method for obtaining cumulative infiltration depths before irrigations, at the head, middle, and end of the furrow (Walker and Skogerboe 1987). The time-based Kostiakov model with average results of the tests was used to obtain a typical infiltration function of the field (Eq. 1).

$$Z = aT^b, \tag{1}$$

where Z is the typical infiltration depth (mm); T the total irrigation time (min) (irrigation duration); a and b are the infiltration coefficients.

Coefficient a was adjusted by the average actual and typical infiltrated depths using the method given by Walker and Skogerboe (1987) (Eqs. 2, 3). To obtain typical infiltrated water depths along the furrow length, the net infiltration time at each station was calculated from the difference between the recession and advance times (Merriam et al. 1980). The typical infiltration depth at each station was calculated by substituting the corresponding net infiltration time into the typical infiltration function (Walker and Skogerboe 1987; Walker 1989). The water inflow volume, tail water runoff and furrow areas were used for determining the actual infiltrated water depth. The average typical and adjusted infiltration depths along the furrow were estimated by using a perpendicular trapezoidal approach (Walker and Skogerboe 1987; Walker 1989).

$$a_{\mathrm{adj}} = a\left(\frac{Z_{\mathrm{ac}}}{Z_{\mathrm{typ}}}\right), \tag{2}$$

$$Z_{\mathrm{ac}} = \frac{V_{\mathrm{in}} - V_{\mathrm{out}}}{A}, \tag{3}$$

where a_{adj} is the adjusted a value, Z_{ac} and Z_{typ} the average actual and typical infiltration depths along the furrows, respectively, in mm; V_{in} the water inflow volume (l), V_{out} the water runoff volume (l); and A is the furrow area (m^2).

Evapotranspiration values for all treatments were calculated using the formula given below (Eq. 4).

$$\mathrm{ET} = \mathrm{Rainfall} + \mathrm{Total\ irrigation} + S_{\mathrm{g}} - D_{\mathrm{p}} - R_{\mathrm{f}} \pm \Delta W, \tag{4}$$

where ET is evapotranspiration (mm); ΔW is the change in soil water content (final minus initial), which was calculated by subtracting the total soil water content in the 1.2 m soil profile determined during the calculated period in mm; S_{g} is the capillary contribution from the ground water table to the crop root zone (mm); D_{p} the deep percolation from the root zone (mm); and R_{f} is the surface runoff water losses (mm). Moreover, the water table was lower than 15 m and the S_{g} was nearly zero during the experiment (Karaata 1984). Deep percolation at each station and for each treatment was estimated from the difference between the infiltrated depth for the infiltration opportunity time estimated by the adjusted infiltration function and the required depth (Walker 1989). The average D_{p}-value along the furrow was calculated by using a perpendicular trapezoidal approach (Walker 1989).

The Christiansen uniformity coefficient was used to evaluate the infiltrated water distribution along the furrow. The Christiansen uniformity coefficient of infiltrated water in the soil profile is defined as follows:

$$\mathrm{CU}_s = 100\left(1 - \frac{\sum_{i=1}^{N}|D_i|}{N \times \overline{Z}}\right), \tag{5}$$

$$D_i = \left|Z_i - \overline{Z}\right|, \tag{6}$$

where Z_i is the infiltrated water depth at the observation point i (or each station) (mm). The infiltrated depth at each station was calculated by substituting the corresponding infiltration opportunity time into the adjusted infiltration function. N is the number of stations. $\overline{Z}$ is the average depth of infiltrated water (mm).

Two water-use efficiencies were estimated (Howell et al. 1990): The total water-use efficiency ($\mathrm{WUE_{ET}}$), which is the yield produced per m^3 of the total water used, and the irrigation water-use efficiency ($\mathrm{WUE_{IR}}$), which is the yield produced per m^3 of the irrigation water.

$$\mathrm{WUE_{ET}} = \frac{\mathrm{Yield}}{\mathrm{ET}}, \quad (7)$$

$$\mathrm{WUE_{IR}} = \frac{\mathrm{Yield}}{\mathrm{IR}}. \quad (8)$$

Cotton was harvested twice by hand. The first harvest was conducted when 60% of all the bolls on plants, opened on October 8, 1993 (280 DOY), September 23, 1994 (265 DOY) and September 25–28, 1995 (267–270 DOY). The second harvest, when the remaining bolls opened, was done on November 4, 1993 (307 DOY), November 1, 1994 (304 DOY), and October 23, 1995 (295 DOY).

Results and discussion

Cotton yield and water use efficiencies

The seed cotton yield, irrigation water amount, evapotranspiration and WUE for treatments are shown in Table 2. The cotton yield ranged from an average of 2,890 kg ha^{-1} for COFFI, CUFFI, and SUFFI treatments together, to an average of 2,330 kg ha^{-1} for the TWRSF treatment. The yields in TWRSF and VAFFI treatments were on the average 17 and 19%, less than those in COFFI, SUFFI, and CUFFI treatments, respectively. The different furrow management techniques significantly affected cotton yield consistently over the years with statistically significant differences between yields in the treatments at the 0.05 level. The highest yields were obtained from the COFFI treatment with 2,630 and 2,920 kg ha^{-1} in 1993 and 1994, and from the CUFFI treatment with 3,780 kg ha^{-1} in 1995, respectively. The lowest yields were in VAFFI with 2,130 kg ha^{-1} in 1993 and 1,890 kg ha^{-1} in TWRSF treatment in 1994, and 2,750 kg ha^{-1} in VAFFI treatment in 1995. The yield from the SUFFI was close to the yield of CUFFI and both of them were in the same statistical group in 1995. This result indicated that the furrow management techniques were more effective on the cotton yield than the amount of the irrigation water used.

The average seed cotton yield in the GAP area varies from 1,212 to 1,413 kg ha^{-1} (Ozudogru 2004), whereas our yields were significantly higher than the average yields for the area. However, the yields of this experiment were the same or slightly lower than those from the previous experiments using surface and pressurized irrigation methods in the Harran Plain (Cetin and Bilgel 2002; Kanber et al. 2001, 1996). In central Arizona, Hunsaker et al. (1998) reported a maximum lint yield of 1,515 and 1,378 kg ha^{-1} obtained by high frequency surface irrigation. Howell et al. (1984) reported an average lint yield of 1,583 kg ha^{-1} using narrow row cotton with a full irrigation regime and 1,423 kg ha^{-1} for a limited irrigation regime in the San Joaquin valley of California. Similar results on cotton yield and suitable irrigation methods or irrigation programs at similar regions were obtained by numerous scientists (Phene et al. 1984; Oron 1984; Fereres et al. 1985; Patmakumari and Sinavapan 1985; Meiri et al. 1992).

Earlier studies conducted in the Harran region on seasonal water used by cotton revealed variation from 551 mm in the VAFFI to 1,480 mm in the COFFI treatments. Water use was the highest in the COFFI treatment in all trial years except in 1993 with an average of 1,153 mm (SD = 311). The minimum value was calculated in the VAFFI treatment with an average of 580 mm (SD = 41). Generally, in treatments like the COFFI, water use was high due to the high water applications in irrigation and was also higher than the TWRSF treatments even at similar amounts of water applications. The lower ET in the TWRSF treatment was due to higher runoff losses bound to the decreasing infiltration capacity of the soil. A previous study carried out at the location of this paper by Cetin and Bilgel (2002), revealed that the amount of irrigation water used by furrow irrigation was found to vary between 626 and 1,872 mm. Kanber et al. (2001) reported that the water use by cotton at the same area under surface irrigation conditions was 1,670 mm. Howell et al. (1984) reported that the measured evapotranspiration of narrow row cotton under a full irrigation regime was 778 mm, 594 mm under a limited irrigation regime, and 441 mm under a regime with no post-plant irrigation. Tennakoon and Milroy (2003) found that the estimated mean cotton seasonal ET was 735 mm for 25 farms and over 200 fields in Australia.

Water use efficiencies based on evapotranspiration ($\mathrm{WUE_{ET}}$) and the applied irrigation water amounts ($\mathrm{WUE_{IR}}$) were affected by different furrow management techniques for cotton. There were statistically significant differences between treatments at the 0.01 level. The highest value was calculated in the SUFFI treatment with 0.53 kg ha^{-1} m^{-3}. In the first two trial years, the maximum WUE values were obtained in the VAFFI treatment with less water use and applied irrigation water. In general, WUE increased with decreasing water use. WUE for VAFFI, CUFFI and SUFFI treatments were high and comparably favorable with the previous findings (Howell et al. 1984; Kanber et al. 1996, 2001; Hunsaker et al. 1998; Cetin and Bilgel 2002; Tennakoon and Milroy 2003). WUE based on the ET were higher than the irrigation WUE

Table 2 Seed cotton yield, irrigation water amount (IR), evapotranspiration (ET), and water use efficiencies (WUE) for different furrow management techniques

Years	Treatments	Yield kg ha^{-1}	IR mm	ET[d] mm	WUE_{IR} kg ha^{-1} m^{-3}	WUE_{ET} kg ha^{-1} m^{-3}
1993	VAFFI	2,130 b	673	626	0.32 a	0.34 a
	CUFFI	2,280 b	798	707	0.29 a	0.32 ab
	SUFFI	2,240 b	1,151	935	0.19 b	0.24 b
	TWRSF[a]					
	COFFI	2,630 a	1,183	862	0.22 b	0.30 b
	ASTDEV[b]	65.91			0.0089	0.0098
	LSD[c]	228.1			0.469	0.516
1994	VAFFI	2,280 b	838	551	0.27 a	0.42 a
	CUFFI	2,610 ab	1,157	984	0.23 a	0.27 bc
	SUFFI	2,740 ab	1,278	899	0.21 a	0.30 ab
	TWRSF	1,890 b	1,750	860	0.11 b	0.22 bc
	COFFI	2,920 a	1,709	1,480	0.17 b	0.19 c
	ASTDEV	163.13			0.016	0.024
	LSD	532.0			0.774	1.141
1995	VAFFI	2,750 b	811	562	0.34 ab	0.49 a
	CUFFI	3,780 a	967	729	0.39 a	0.52 a
	SUFFI	3,690 a	1,296	701	0.29 bc	0.53 a
	TWRSF	2,770 b	1,685	868	0.16 c	0.32 b
	COFFI	3,090 b	1,578	1,117	0.19 c	0.28 b
	ASTDEV	181.48			0.017	0.0258
	LSD	591.83			0.804	1.225

Values followed by the same letters are not significantly different at the 0.01 level (LSD test)

[a] TWRSF treatment was carried out for the last two trial years

[b] ASTDEV is the average standard deviation

[c] Differences in yield and WUEs are significant at $p < 0.05$ and $p < 0.01$ levels, respectively

[d] Rainfall received in the all growing seasons of cotton were 157 mm in 1993, 105 mm in 1994, and 44 mm in 1995 years

values. Differences between the two values can be explained by the inefficient consumption of the applied irrigation water, runoff losses and deep percolation in some treatments. Comparison of the WUE suggests that VAFFI, SUFFI, and CUFFI treatments achieved a more efficient utilization of the water in yield production.

Water application

The irrigation interval, number of irrigations and irrigation water applied during irrigation seasons in the different furrow management techniques are shown in Table 3. The first irrigation events were applied about 50 days after planting between mid-June and the first week of July. Thus, irrigation season lengths varied from 58 to 76 days. The gross irrigation amount for the total season was influenced by years, the furrow irrigation systems and their interaction. Less water was applied in 1993 than in other years and less water was applied to the variable alternate furrow irrigation system in each year. The average seasonal water applications in the treatments varied from 1,490 mm for COFFI to 774 mm in variable alternate continuous flow furrow irrigation (VAFFI). There were statistically significant differences between the amount of irrigation water for the management techniques at 0.01 levels (ASTDEV = 62.36, LSD = 295.01). The applications in the treatments of COFFI and TWRSF were higher than those in the others. The surge, cutoff and VAFFIs were successfully managed to reduce the cumulative application by 17, 35, and 48%, respectively, as compared to continuous flow furrows. These reductions were associated with the reduced water intake and wetting of the deep soil profile. The highest water conservation was obtained in the VAFFI. This was obtained by applying a limited amount of water since only half of the areas of plots were irrigated.

The actual amounts of fresh water from the resources used in the TWRSF plots were 1,289 and 1,230 mm for the last two trial years. A total of 461 and 455 mm additional irrigation water for 1994 and 1995, respectively, was covered by the runoff recovery system. Thus, the water saved in this management technique was 25 and 22% compared to COFFI. The water application depths per irrigation varied from 138 to 262 mm for COFFI, 129 to 265 mm for the SUFFI, 81 to 192 mm for the CUFFI, 63 to 152 mm for the VAFFI, and 172 to 269 mm for the TWRSF treatments. In July and August, when water use was high, irrigations in treatments were

Table 3 Date of irrigation applications, total irrigation water amount (mm) for cotton grown under different furrow management techniques during 1993–1995

Year	Irrigation No	Irrigation date[a]	Furrow managements[b]				
			COFFI	SUFFI	CUFFI	VAFFI	TWRSF[c]
1993	1	9/7 (189)	184	140	158	125	–
	2	20/7 (200)	181	179	100	117	–
	3	1/8 (212)	214	149	139	96	–
	4	13/8 (224)	229	213	106	115	–
	5	25/8 (236)	192	265	150	117	–
	6	5/9 (247)	183	206	145	104	–
	TOTAL		1,183a	1,151a	798b	673b	–
	AVE		197	192	133	112	–
	STDEV		20	46	24	11	–
	%		1.00	0.97	0.67	0.57	–
1994	1	22/6 (172)	232	174	167	104	225
	2	4/7 (184)	261	214	162	143	256
	3	18/7 (198)	277	189	168	133	255
	4	1/8 (212)	260	168	192	148	249
	5	15/8 (226)	156	165	165	73	250
	6	25/8 (236)	262	212	151	117	252
	7	6/9 (248)	262	156	151	121	263
	TOTAL		1,709a	1,278ab	1,157b	838c	1,750a
	AVE		244	183	165	120	250
	STDEV		41	23	14	26	12
	%		1.00	0.75	0.68	0.49	0.75
1995	1	16/6 (166)	138	129	81	63	172
	2	26/6 (176)	172	154	91	88	225
	3	10/7 (190)	259	217	133	122	240
	4	19/7 (199)	223	190	143	120	269
	5	31/7 (211)	324	209	188	151	257
	6	10/8 (221)	232	208	160	152	260
	7	21/8 (232)	230	189	171	116	262
	TOTAL		1,578a	1,296ab	967b	811b	1,685a
	AVE		225	185	138	116	241
	STDEV		60	32	40	32	34
	%		1.00	0.82	0.61	0.51	0.78

In 1995, 150 mm irrigation water was applied to all plots for germination and emergence

[a] Figures in the brackets show the irrigation dates as DOY

[b] Irrigation water amounts applied per event for the all types of furrows are calculated using inflow rate, total irrigation time and area irrigated per furrow. They do not include rainfall

[c] 461 and 455 mm of total applied water in 1994 and 1995 are taken from run off recovery system. Percentages show the fresh water taken from water resource as to COFFI treatment

generally more frequent. The differences observed in amounts of the irrigation water were attributed to the different approaches used in the irrigation treatments. As explained by Walker and Skogerboe (1987), Walker (1989), Kanber et al. (1993), Onder (1994), and Kanber et al. (2001) the total irrigation time and the amount of the applied water could have been affected by a change in infiltration functions and irrigation phases in the treatments.

Irrigation management

Water advance

Over 3 years, the advance time was different for all the furrow management techniques at all monitored sites. The average water advance times over the years are shown in Fig. 1. During the advance phases, the same approaches were used in COFFI, CUFFI, and TWRSF treatments. For this reason, the advance curve for COFFI in Fig. 1 was developed using the average data taken from the treatments mentioned above. Water in the VAFFI treatment reached the mid-point along the length of the furrow about 11 and 22 min later and the end of the full furrow length about 56 and 90 min later as compared to the COFFI and SUFFI management systems, respectively. Water reached the end of the furrow with high velocity by surging where in the SUFFI treatment the advance velocity was 28 and 68% higher than those in COFFI and VAFFI plots, respectively. Thus, the water used during the advance phases was the difference in the treatments, and the highest amount of water was used in the VAFFI treatment with 60–70% of the total applied water for irrigation. The lowest amount of water used for the advance phase was calculated in the SUFFI treatment as 45% of the total applied water.

Infiltrated water

The average infiltrated water in treatments for all irrigation seasons was calculated from adjusted infiltration functions (USDA-SCS 1983). Table 4 shows the values of the typical and adjusted infiltration

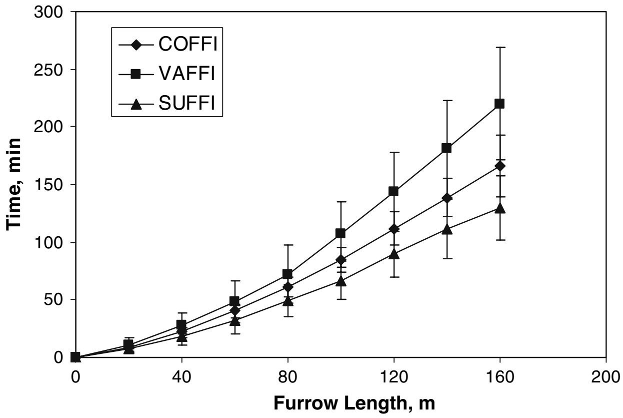

Fig. 1 Water advance per length of run in the different furrow management techniques. The advance curve for COFFI was obtained using results taken from COFFI, TWRSF, and CUFFI treatments in which same procedures were applied during the advance phases

coefficients of "*a*" and "*b*" in the Kostiakov function along the irrigation seasons. The typical values of both coefficient varied by irrigation from year-to-year. These variations may develop by properties of soil surface conditions, which change during irrigations due to the formation of cracks and crusts (surface sealing layer). The variations in the adjusted coefficients of "*a*" are due mostly to its typical values, furrow management techniques, and partly to the amount of irrigation water applied. The average typical "*a*" varied from 2.13 (SD = 0.43) in 1993 to 0.87 (SD = 0.13) in 1995. The average maximum and minimum adjusted values of "*a*" were obtained in the VAFFI treatment with 1.94 (SD = 1.15) in 1993 and TWRSF treatments with 0.48 (SD = 0.11) in 1995 in the trial years, respectively. As the values in Table 4 indicate, the infiltration coefficients (the typical and adjusted "*a*" values) were higher at the first two or three irrigations, when the soil surface was kept in a loose condition by primary tillage, indicating relatively high soil infiltration rates, and then decrease toward the end of the irrigation season showing decreased soil infiltration rates in all treatments. The reductions in the average infiltration coefficients were greater in the SUFFI (12–42%) and TWRSF (33–56%) treatments compared to the COFFI treatment. The reduction of infiltration coefficients in these treatments might have been caused by the formation of the sealing layer on the soil surface from the sediment laden water in the TWRSF

Table 4 Typical and adjusted "a" coefficients in Kostiakow infiltration function for irrigations and trial years

Year	Irrigation No	Typical values		Adjusted values of Coefficient of a				
		a	b	COFFI	SUFFI	CUFFI	VAFFI	TWRSF
1993	1	2.31	0.41	2.11	2.51	2.26	3.07	–
	2	2.4	0.58	2.21	1.94	2.09	3.36	–
	3	1.29	0.57	2.31	2.13	1.99	2.23	–
	4	2.03	0.49	2.2	1.66	1.31	0.96	–
	5	2.36	0.55	1.34	0.83	2.04	1.51	–
	6	2.38	0.46	0.87	0.66	1.14	0.5	–
	Ave	2.13	0.51	1.84	1.62	1.81	1.94	–
	STDEV	0.43	0.07	0.59	0.74	0.46	1.15	–
	%			1.00	0.88	0.98	1.05	–
1994	1	1.31	0.59	1.49	0.86	1.11	1.45	0.89
	2	1.16	0.58	1.47	0.87	1.1	1.41	0.87
	3	0.9	0.57	1.56	0.43	0.97	1.42	0.78
	4	1.53	0.46	0.76	0.41	0.99	1.36	0.86
	5	1.5	0.47	1.54	0.5	0.54	0.72	0.49
	6	1.54	0.47	0.88	0.83	0.43	0.68	0.38
	7	1.53	0.48	0.75	0.84	0.49	0.64	0.67
	Ave	1.35	0.52	1.16	0.68	0.80	0.83	0.51
	STDEV	0.25	0.06	0.40	0.22	0.30	0.10	0.15
	%			1.00	0.58	0.69	0.62	0.44
1995	1	0.72	0.66	1.06	0.26	0.51	0.36	0.58
	2	0.89	0.64	0.39	0.33	0.55	0.43	0.57
	3	1.1	0.51	0.43	0.59	0.54	0.94	0.48
	4	0.77	0.61	0.49	0.3	0.52	1.11	0.52
	5	0.77	0.61	0.77	0.3	0.52	0.63	0.56
	6	0.85	0.54	0.67	0.48	0.59	0.73	0.39
	7	0.96	0.58	0.59	0.36	0.45	0.52	0.28
	Ave	0.87	0.59	0.63	0.37	0.53	0.67	0.48
	STDEV	0.13	0.05	0.23	0.12	0.04	0.27	0.11
	%			1.00	0.59	0.83	1.07	0.77

and surge effects in the SUFFI treatments as stated by Wang et al. (2005) and Humpherys (1989a).

The average infiltrated water and soil moisture deficiency values at every station along the furrow showed the type of the irrigation level. Figure 2 illustrated that some of the furrows of the SUFFI and TWRSF were full, whereas some had less water than the SMD level, while irrigations were over for COFFI and CUFFI treatments, and furrows were full for the VAFFI. The infiltrated water depths indicated that SUFFI and TWRSF decreased to a different extent with the length-of-run. The observed results in the mentioned treatments may be due to the lower infiltration rate caused by surging and using tail water with high silt contents (Humpherys 1989a, b; Johnson 1990) or insufficient infiltration equations for some irrigation events.

The infiltrated amounts of water were affected by the different management of furrows, years and irrigation events in the same treatments. Generally, in the first irrigation more water was infiltrated than in other applications. The differences in the results of water intake for the treatments were statistically significant at a level of 0.01 (ASTDEV = 6.36; LSD = 20.68).

The cumulative water storages in the treatments are shown in Fig. 3. The highest cumulative intake of 1,139 mm was recorded for the COFFI, whereas this was 794, 790, 469, and 801 mm for SUFFI, CUFFI, VAFFI, and TWRSF, respectively. The reductions in the cumulative water storage were about 30% for SUFFI and TWRSF, 41% for CUFFI and 59% for VAFFI compared to COFFI. The effect of surge flow on reducing water intake is lower than that of the cutoff flow technique. This reduction in the CUFFI treatment might be caused by the decreasing wetted furrow perimeter after the inflow cutoff as stated by Hart et al. (1981).

Tail water losses

The cumulative average tailwater runoff for treatments is shown in Fig. 4. The effects of furrow management techniques on tailwater runoff losses are statistically different at the 0.05 significance level (ASDEV = 7.59). The highest losses were observed in SUFFI and TWRSF treatments with 505 (SD = 56) and 460 mm (SD = 44), respectively. The average total tailwater was 351 mm or 24% of the water applied for COFFI; 346 mm or 42% for the VAFFI and 237 mm or 23% for the CUFFI treatments; while the ratios of the runoff losses to applied water were 39 and 27% (36% of the fresh water) for the SUFFI and TWRSF, respectively.

The surge flow and re-use runoff recovery systems increased tail water losses by 44 and 30%, respectively, compared to furrow irrigation by continuous flow. By decreasing the inflow rate in the CUFFI treatment, the average total tail water losses decreased 32% as compared to the COFFI. The increased volume of the tailwater runoff in the SUFFI and TWRSF treatments may be attributed to the decreasing soil infiltration capacity during irrigation due to the surge effect that occurred at on and off-times, as stated by Walker and Skogerboe (1987) as well as a sealing layer that may have formed on the soil surface by the sediments in the tail water of the TWRSF causing trapping, settling, and sealing in the irrigated field as noted by Wang et al. (2005). On the other hand, as indicated by Onder (1994), Goldhammer et al. (1987a), and Kanber et al. (2001) the runoff losses in all treatments increased toward the end of the irrigation season.

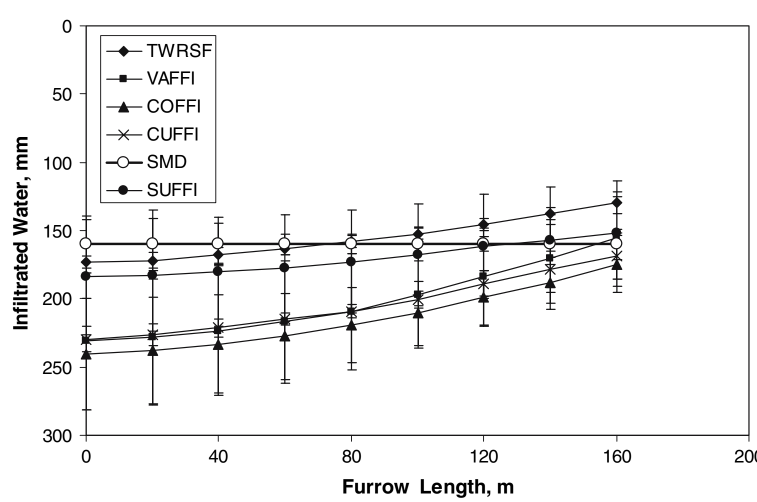

Fig. 2 Variation of average infiltrated water along the furrow for different furrow management techniques. The average infiltrated water data for all irrigation seasons after soil moisture deficit values at every station along the furrow showed that irrigations were over for COFFI and CUFFI treatments, full for VAFFI considering only one irrigated furrow and under for SUFFI and TWRSF treatments

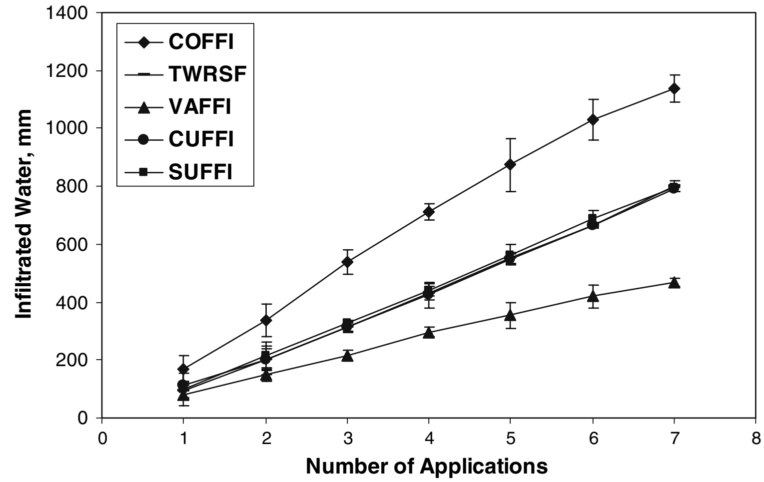

Fig. 3 Average cumulative water storage in the different treatment applications

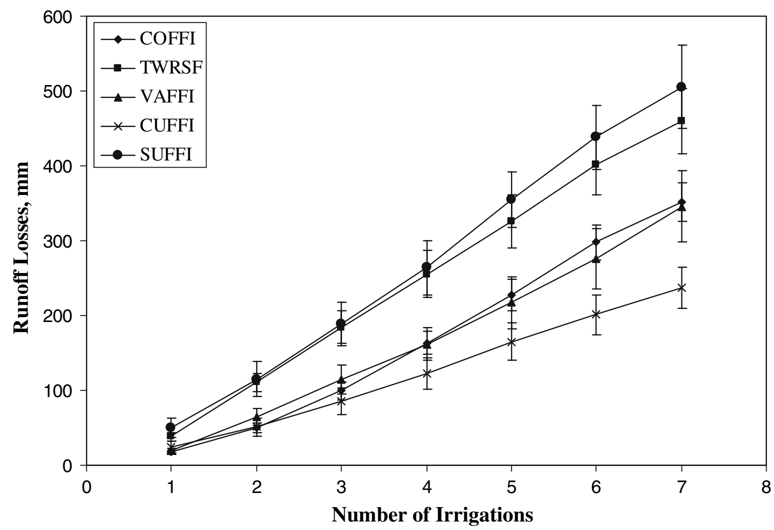

Fig. 4 Average runoff losses measured in the different furrow management techniques. In SUFFI and TWRSF treatments, maximum losses were measured compared to CUFFI

Deep percolation losses

The average SMD before applications was almost 160 mm (SD = 13.28) for all seasonal irrigations. The amounts of deep percolation losses in the management techniques were found to be statistically different at the 0.01 significance level (ASTDEV = 4.97). The average cumulative deep percolation was 106 mm or 7% of the applied water in the COFFI treatment and 45 mm or 4% in the CUFFI treatment, while the minimum deep percolation losses were obtained in the SUFFI and TWRSF treatments with 17 and 13 mm or 1% of irrigation water, respectively (Fig. 5). Actually, the average 49 mm percolation was measured from the irrigated furrow of the variable alternate furrow management technique (VAFFI). However, this amount was considered to be the consequence of the side percolation from the irrigated furrow to the non-irrigated neighboring furrow, which remained at the root depth of this treatment. This shows that, the deep percolation losses might not occur in the treatments of VAFFI, as determined by Sepaskhah and Kamgar-Haghighi (1997) in sugar beet. The reduced deep percolation losses in the SUFFI and TWRSF treatments could be associated with a decreasing infiltration rate, insufficient water application and short total irrigation time.

Irrigation uniformity

For the evaluation of the infiltrated water distribution along the furrow, the Christiansen Uniformity Coefficients (CUC) were calculated for all treatments and (Fig. 6) were found at acceptable levels. The maximum value was calculated in the SUFFI treatment at 0.94, while the minimum value of 0.90 was found in the VAFFI treatment. Thus, this reveals, that the surge flow furrow has the advantage of achieving a more

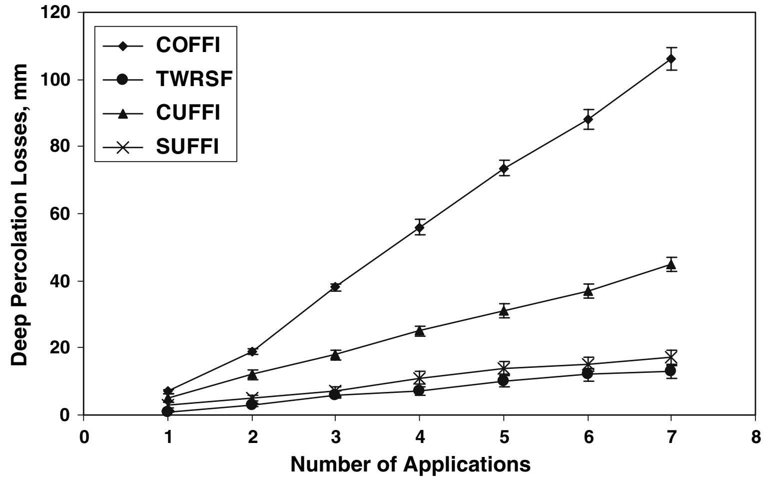

Fig. 5 Cumulative average deep percolation losses measured in different furrow management techniques. In VAFFI treatment (not shown here), an average of 49 mm percolation losses was measured, however, this amount was not considered as deep percolation loss because it was a lateral movement within the soil profile in root depth

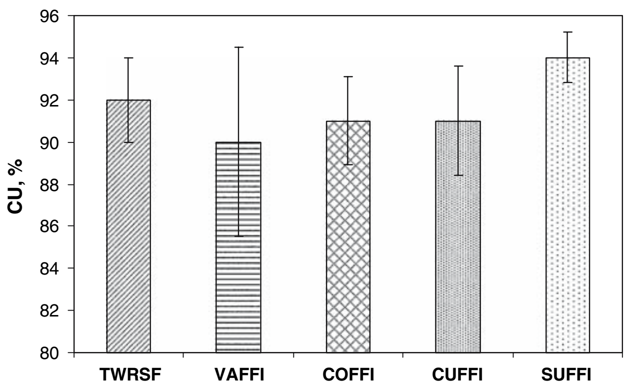

Fig. 6 Christiansen Coefficients for different furrow management techniques. In calculations, all infiltrated water data after irrigations along the furrow were used. There were no statistical differences between treatments (ASTDEV = 1.41, LSD = 4.763)

uniform irrigation, by speeding up the irrigation water advance and reducing deep percolation, as earlier indicated by Humpherys (1989a, b).

Conclusions

The results revealed that the cotton yield was significantly affected by the different furrow management techniques in the semi-arid Southeastern Anatolian Region. The yields from treatments were statistically significant at difference levels of $P < 0.05$. The COFFI, SUFFI, and CUFFI treatments produced statistically similar yield in the trial years. There were significant yield reductions in the treatments, which were slightly greater for the TWRSF treatment (10% in 1994 and 35% in 1995) than for the VAFFI treatment (19% in 1993 and 11% in 1995). The average maximum cotton yield was 2,890 kg ha^{-1} for the COFFI, SUFFI, and CUFFI treatments, while the minimum average yields were 2,330 kg ha^{-1} in the TWRSF and 2,390 kg ha^{-1} for the VAFFI. The average yields of the TWRSF and VAFFI treatments were 17 and 19% less than those of the COFFI, SUFFI, and CUFFI treatments, respectively. These results demonstrated that the furrow management techniques have been more effective on the cotton yield than the amount of the irrigation water.

The maximum amount of irrigation water was applied to the COFFI (1,183–1,709 mm), and TWRSF (1,685–1,750 mm) and the minimum amount was applied in the VAFFI (673–838 mm) treatments. Significant water savings were determined in the SUFFI, CUFFI, and VAFFI treatments, indicating that the applied treatments successfully managed to reduce the cumulative application by 17, 35, and 48%, respectively, as compared to the continuous flow furrows (COFFI).

The irrigation water losses, by runoff and deep percolation, were found to be different in the various furrow management techniques studied. The average maximum runoff losses were measured in the SUFFI (505 mm), and TWRSF (460 mm) treatments, while the minimum value was determined in the CUFFI (237 mm) treatment. The runoff losses decreased by 32% by the application of the cutoff furrow management technique compared to the COFFI. The runoff losses of the surge flow treatments increased by 44 and 30% when compared to the COFFI treatments. On the contrary, deep percolation losses, were decreased by 84 and 88%, by the surge flow and tail water runoff recovery systems, respectively, compared to the COFFI treatment. Additionally, by applying the cutoff flow techniques, a high reduction of 58% in deep percolation losses, as compared to the continuous flow furrow treatment, was obtained.

Based on this study, the cutoff flow furrow irrigation and SUFFI management techniques appear to be promising alternatives for decreasing water losses in the Harran Plain. Results demonstrated that either high cotton yields or significant water savings can be obtained compared to the conventionally widely used continuous flow furrow management in the area. However, additional information is needed to establish the best management practices in the field such as the optimal combination of the cutoff amount, time, and suitable inflow rates, and their relationship with the surge flow technique. Furthermore, the surge flow approach can be employed with the cutoff flow technique in the area. In the advance phase, water could be applied to furrows by surge flow, whereas in the storage phase, the cutoff flow management may be used.

This study indicated that the proper furrow irrigation management techniques could result in higher yields, and lower use of water leading to significant water conservation. This, in turn, would lead to increased profit and could lead to reduced environmental pollution.

Acknowledgments The authors acknowledge the Southeast Anatolia Project Authority in Ankara for the financial support to the project. Furthermore, we thank Prof. Selim Kapur from Soil Science Department, University of Çukurova, Turkey for his help in preparing the manuscript.

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