THE INFLUENCE OF DIFFERENT DRIP IRRIGATION LAYOUT DESIGNS ON SUGAR BEET YIELD AND THEIR CONTRIBUTION TO ENVIRONMENTAL SUSTAINABILITY

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ABSTRACT

Drip irrigation may constitute a method for sustainable management of water resources and can contribute to environmental protection and sustainability. However, there is still limited information on the application of drip irrigation to row field crops in Mediterranean environments, especially with respect to its appropriate lateral layout, a parameter that affects initial system installation cost as well as water use efficiency. Surface drip irrigation (SDI) field experiments with sugar beets (*Beta vulgaris* L.) were conducted in central Greece over a 3-year period to determine the effects of different layout designs (4 treatments with 6 replications) on root yield, sucrose accumulation characteristics (percent sugar content of roots (POL), raw sugar yield), water productivity index (WPI), and to study the contribution of different layout designs to environmental protection and sustainability. The treatments used consist of combinations of drip-pipes with varying lateral distances of every-other-furrow (e-o-f) (1.00 m) and every-three-furrows (e-t-f) (1.50 m), and between the dripper spacing (0.50 m and 0.75 m).

The mean root yield results in the e-o-f treatments were 108.46, 111.46 and 105.11 $t{\cdot}ha^{-1}$, and in the e-t-f treatments were 106.17, 113.59 and 103.84 $t{\cdot}ha^{-1}$ for each year, respectively. The root sugar contents varied from 11.68% to 13.00% in e-o-f and from 11.46% to 13.41% in e-t-f. The WPI results were 19.74, 19.44 and 17.97 $kg{\cdot}m^{-3}$ in e-o-f, and 19.32, 19.81 and 17.75 $kg{\cdot}m^{-3}$ in e-t-f, respectively. Differences in root yield, POL, raw sugar yield and WPI between the 3 harvest periods were not statistically significant ($p<0.05$). Therefore, in agricultural Mediterranean areas with aquic soil moisture regimes, the suggested layout design of e-t-f (1.5 m x 0.75 m) instead of the common farmers' layout of e-o-f (1.0 m x 0.50 m) can be applied without statistically significant differences in root yield, POL, raw sugar yield or WPI, and with considerable plastic material reduction (-33.3% polyethylene), which corresponds to an initial cost reduction of -37.2%. Moreover, using this method, important installation labour savings, as well as cost reductions for transportation and storage facilities, are realized.

KEYWORDS: Sugar beet yield, drip irrigation layouts, time domain reflectometry (TDR), water productivity index (WPI), aquic soil moisture regime, plastic material reduction.

INTRODUCTION

World sugar beet production amounts to about 234 10^6 t and covers an area of 6 10^6 ha; the mean root yield ha^{-1} is 39.7 t [1]. The European Union, United States, and Russia are the world's three largest sugar beet producers. Beet sugar accounts for 30% of the world's sugar production [2]. According to FAOSTAT (2009) [3], the mean root yield in EU (27) for the years 1998-2000 was 53.20 $t{\cdot}ha^{-1}$ and for 2004-2006 was 59.62 $t{\cdot}ha^{-1}$. According to FAO/AGL [4], the root yield obtained during a growth period of 160–200 days, with a sugar content (POL) of 15%, is considered to be commercially quite satisfactory.

Research on sugar beet irrigation by the sprinkler method is very extensive [4-7, 8, 9], as is research on furrow [10-14] and flood [12, 13] irrigation. Hang and Miller (1986) [5] determined the effect of lack of water on the percent sugar content, the weight of roots and the dry matter yield of beets grown in sandy loam and sandy soil. The authors concluded that using an arrangement of limited irrigation by the sprinkler method led to an increase in percent sugar content and alleviation of dry matter. Sepaskhah and Kamgar-Haghighi (1997) [11] studied the irrigation of sugar beets in furrows, using two systems of irrigation (irrigation every other furrow (e-o-f) and irrigation in each furrow (e-f)) with different frequencies of irrigation.

E-o-f irrigation with a frequency of 10 days used a smaller amount of water than e-f irrigation, but resulted in a reduction of yield. However, more frequent (every 6 days) e-o-f irrigation achieved a similar yield as e-f irrigation every 10 days and economized, on average, 23% in irrigation water.

In sugar beet field experiments conducted in 1996-1997 in southeastern Wyoming, Sharmasarkar et al. (2001) [12] compared surface drip irrigation (SDI) with furrow irrigation; their study included measurement of the rate of soil moisture depletion. The results showed that yield, defined as the percent of sugar content, was 3-28% higher for drip irrigation than for furrow irrigation when the water depletion did not exceed 20%. In the same work, a comparative estimate was made of water losses due to deep infiltration between irrigation with furrows and drip irrigation. It appeared that when using SDI, water loss was decreased because of the higher frequency of irrigation, the deep infiltration of water below the level of the root system, and the smaller quantities of water used in each application [12]. With respect to the effect of soil moisture depletion in water losses due to deep infiltration using SDI, similar conclusions were reached by Dioudis et al. [15]. In their work concerning the economical analysis of the use of drip irrigation in sugar beet production, Sharmasarkar et al. (2001) [14] reported that root weight and sugar content were higher with the use of SDI than with furrow irrigation. Togneti et al. (2003) [8], in an experimental field study of sugar beets in southern Italy, found that crop performances, yields and physiological responses of sugar beets that were drip-irrigated with 75% of estimated ET mostly matched those of sugar beets that were irrigated by low-pressure sprinklers with 100% of estimated ET, which resulted in 25% savings in water volume. Moreover, these authors found that SDI, even when applied to every-other-furrow, appeared to be more consistently advantageous than low-pressure sprinkler irrigation for sugar beet performance in semi-arid environments [8].

The majority of these studies used the evaporation pan method to calculate crop water requirements. This method is used in many parts of the world [7, 16-23]; in England, it is used for irrigation scheduling of approximately 45% of the irrigated areas of the country (outdoor cultivation, not in greenhouses) [21]. According to this method, the water needs of sugar beets in Thessaly plain [24], where the experiments were conducted, vary between 600 and 700 $mm \cdot year^{-1}$.

Irrigation water for field crop production will become increasingly limited at Mediterranean latitudes due to climate and land-use changes [25]. It is evident that scarce water resources frequently limit crop production in semi-arid lands. Decreases in and scarcity of water resources resulting from many environmental effects and sources, and especially from agricultural irrigation consumption, are major environmental issues worldwide [22, 23]. Moreover, Goodland (1995) [26] of the World Bank has suggested that, in order to sustain the environment in the future, it will be more important to improve the efficiency of all technological processes, including farming and irrigation, than simply to increase the total amount of natural resources used [26]. Properly used, drip irrigation, in conjunction with soil moisture monitoring, may constitute a method for improving root yield and water use efficiency for sustainable management of water resources, and can contribute to environmental protection and sustainability. However, there are still no definite results or information on its application for sugar beet crops in Mediterranean environments.

Sugar beet irrigation by the trickle method (drip irrigation) is currently being carried out at an experimental level and no definite results have yet been reported [8, 12-14, 16-18, 27, 28]. Both surface and subsurface drip irrigations are currently under investigation [8, 14, 16, 17, 27-29]. If sugar beet crops can be shown to be well-adapted to drip irrigation systems, farmers with these irrigation systems already established may consider using sugar beet plants in crop rotations in their fields.

The present study was conducted in order to determine the effects of various drip irrigation system layout designs utilizing varying distances between pipes (every-other-furrow and every-three-furrows) and drippers (0.50 m and 0.75 m spacing), on:

1. The sugar beet root yield and sucrose accumulation characteristics (percent sugar content of roots (POL) and raw sugar yield).
2. The water productivity index (WPI).
3. The system's contribution to environmental protection and sustainability by means of water use saving and efficiency (high WPIs), the amount of reduction in the use of plastic materials, which are long-life cycle polluters of the environment, cost reduction in materials used in drip irrigation system installation (which can help with SDI proliferation) and capability for sugar beet crop rotation.

MATERIALS AND METHODS

The experiments were conducted in representative fields of Karditsa Prefecture in central Greece in the agricultural areas of Lefki, Mataranga and Elia during the years from 1998 to 2000. Soil properties were analyzed according to standard procedures [30]. The saturated hydraulic conductivity, Ks, was measured at 15 and 45 cm soil depths using a Guelph permeameter.

Sugar beet (*Beta vulgaris* L., var. Rizor) grains were sown with a seed drill in early April of each year, at a row spacing of 0.50 m and in-row spacing of 0.12 m. The final experimental area was chosen at the time when the sugar beet plants had already been established, to include an area with a reasonable percent germination and with minimum void spaces in the field. Field plots were fertilized with 140 kg $N \cdot ha^{-1}$, 100 kg $P \cdot ha^{-1}$, and 80 kg $K \cdot ha^{-1}$, which was distributed prior to seedbed preparation.

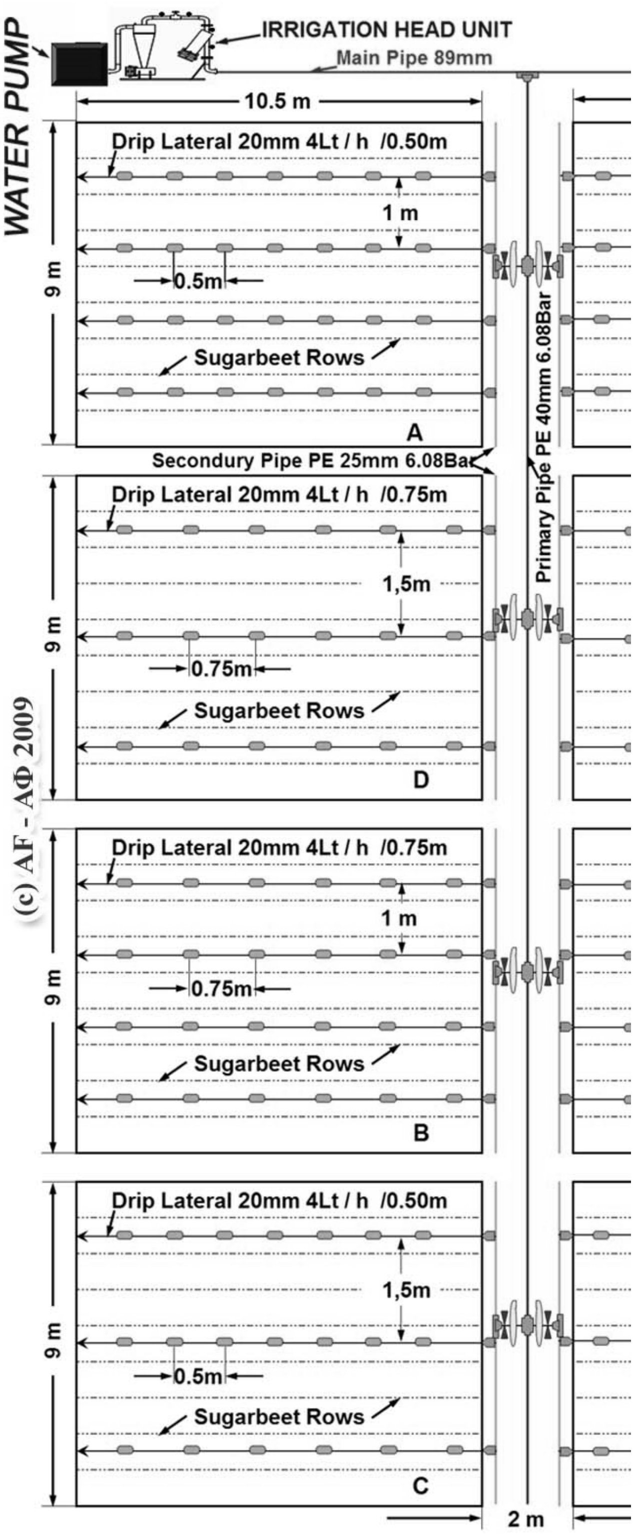

FIGURE 1 - Details of the layout design and of the drip irrigation system.

Weeding was carried out by hand four times during the growing season of the beets each year.

The experimental field had a completely randomized block design (CRBD) layout consisting of four treatments each for six replicates (the unit area of replication was 378.0 m^2). The four treatments (A-D), were combinations of drip lateral pipes with varying distances of every-other-furrow (1.00 m) or of every-three-furrows (1.50 m), and also with varying inline dripper distances (0.50 m and 0.75 m), (Fig. 1), i.e., a) 1.00 m x 0.50 m b) 1.00 m x 0.75 m c) 1.50 m x 0.50 m and d) 1.50 m x 0.75 m, with a total number of 24 experimental plots.

Each experimental plot was 9 m in width (across the crop rows) and 10.5 m in length (lengthwise of the crop rows) (Fig. 1). The irrigation network consisted of a head unit with a hydrocyclone, a screen filter and various accessories, a main water delivery polyethylene (PE) pipe of external diameter Φ = 89 mm, primary pipes (PE, Φ = 40 mm/ 6.08 bar), secondary pipes (PE, Φ = 25 mm/6.08 bar), drip laterals (PE, Φ = 20 mm/6.08 bar), and pressure regulators (Fig. 1). The drip laterals were 20 mm external diameter polyethylene pipes with inline drippers. Before being used in the field experiments, the drippers were tested in the laboratory, as well as in the field, to ensure proper function. Drippers had a discharge rate of 4 $L \cdot h^{-1}$, at 122 kPa pressure after testing according to I.S.O. standards [31]. Soil moisture was measured by applying the TDR (time domain reflectometry) method. The TDR method is a non-radioactive method based on the direct measurement of the dielectric constant of soil and its conversion to water volume content [32-35] that has proven to be quick and reliable, irrespective of soil type, except in extreme cases of soils [32, 33, 23, 36]. For the application of the TDR method, a TDR measuring instrument (model MP-917 from ESI-Environmental Sensors, INC, Canada) and soil moisture TDR probes were used (Fig. 2).

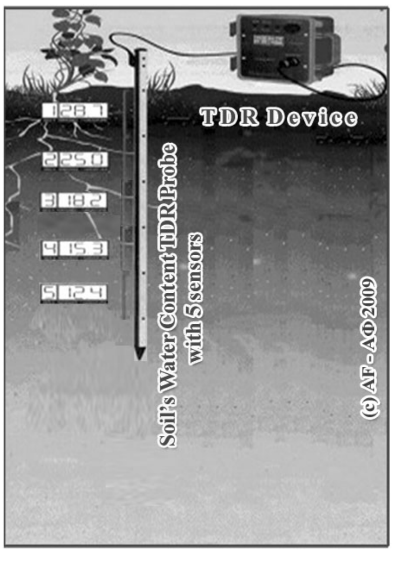

FIGURE 2 - The TDR measuring instrument and soil water content TDR probe with five sensors.

Each probe had five sensors, placed at 0–15, 15–30, 30–45, 45–60 and 60–75 cm depths (Fig. 2). Fifteen soil moisture TDR probes were installed in each treatment of the first replication.

In treatments A and B (Fig. 3), which had drip lateral pipe distances of 1.0 m (every-other-furrow), two groups of three TDR probes each (2x3) were installed adjacent to drip lateral pipes, two groups of three TDR probes each (2x3) were installed adjacent to sugar beet rows, and one group of three TDR probes (1x3) was installed between the rows (Fig. 3a). In treatments C and D (Fig. 3), which had drip lateral pipe distances of 1.5 m (every-three-furrows), two groups of three TDR probes each (2x3) were installed adjacent to drip lateral pipes, and three groups of three TDR probes each (3x3) were installed adjacent to sugar beet rows (Fig. 3b).

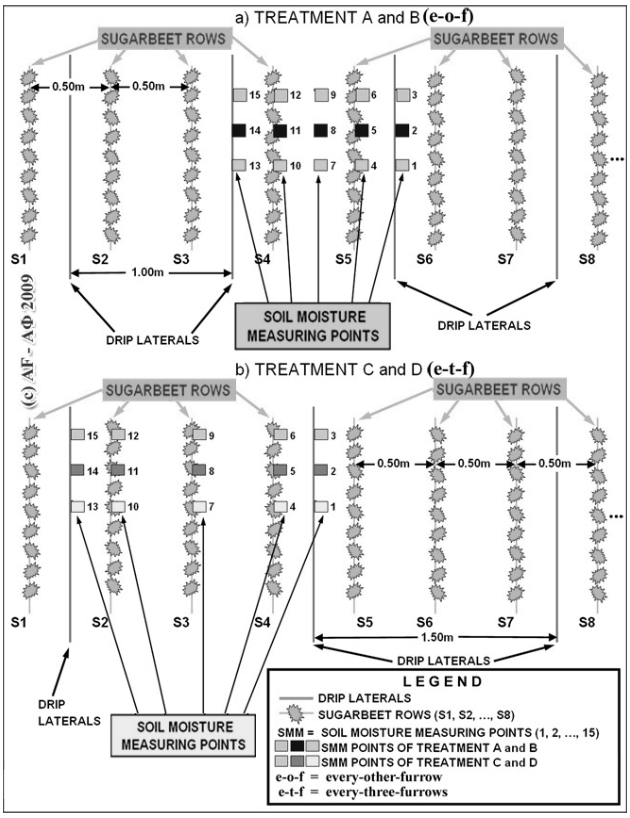

FIGURE 3 a) Layout of the inline dripper lateral pipes of the plots of every-other-furrow (A and B). b) Layout of plots of every-three-furrows (C and D). Both layouts include the soil moisture measuring (SMM) points.

The above groups of soil moisture TDR probes were used in 1998. In 1999 and 2000, five soil moisture TDR probes, instead of fifteen, were installed in each treatment. The reason for tripling the number of soil moisture probes in 1998 was to acquire experience in using the TDR method, which was then being used for the first time in Greece. The TDR measuring instrument was calibrated to the soils at Lefki, Mataranga and Elia experimental sites over a wide range of soil water content each year.

The Class 'A' evaporation pan method uses a 1.21 m (4 ft) diameter circular pan filled with water. The daily rate of evaporation from the pan is determined from the change in water level (adjusted for rainfall) [17, 37, 38, 23]. The crop evapotranspiration method, which is estimated using a Class 'A' evaporation pan that is corrected by the monthly evaporation pan coefficient (Kp) and by the crop stage coefficient (Kc), has been used successfully by many researchers [4, 7, 17-20, 23, 27, 33, 36-41].

In the present study, the following equation was used for calculation of the crop evapotranspiration:

$$ETc = Epan \cdot Kp \cdot Kc \qquad (1)$$

where:

ETc = crop evapotranspiration (mm·day^{-1}),

Epan = pan evaporation (mm·day^{-1}),

Kp = pan coefficient and

Kc = crop stage coefficient.

Meteorological data were obtained from the meteorological station nearest to each experimental field (Palama, Kallifoni, Karditsomagoula), and the rainfalls for each year (1998, 1999 and 2000) were measured using a rain gauge that was installed in each experimental field. The effective rainfall for the experimental site conditions for each year was calculated according to USDA-SCS [42].

The net irrigation requirement (NIR) [42, 43, 23], that is the irrigation water delivered to the experimental field and available for the sugar beet crop to be used, was calculated using equation (2):

$$NIR = ETc - Pe \qquad (2)$$

where:

NIR = net irrigation requirement (mm·month^{-1}),

ETc = evapotranspiration (mm·month^{-1}) and

Pe = effective rainfall (mm·month^{-1}).

Drip system materials cost was calculated for each treatment as the sum cost of all the installation materials of the irrigation network for each corresponding treatment, without taking into account the cost of the head unit. Cost differences between treatments were then calculated on a percent basis.

The crops were harvested each year by hand, and the percent sugar content of roots (POL) and the raw sugar yield were determined for each plot using a measuring procedure that used a Venema balance and a BETALYSER analysis system. The data obtained were statistically processed by means of analysis of variance (ANOVA) using the MINITAB statistical package. The Zero Hypothesis (H_0) was that the yield variances were equal under all the e-o-f (A, B) and e-t-f (C, D) treatments of drip irrigation.

RESULTS AND DISCUSSION

Each year, sugar beet crop growth experiments were conducted in the same geographical area in Karditsa Prefecture, but in different fields, due to the need for crop rotation. Therefore, the irrigation water characteristics of the experiments (Table 1) and the soil physical characteristics (Table 2) differed from year to year. With respect to safe irrigation, the most important parameter is the irrigation

TABLE 1 - Irrigation water characteristics of the experiments.

Irrigation water characteristics	Unit	Year 1998	Year 1999	Year 2000
		Value		
pH	pH units	7.30	6.90	7.20
(1)EC	$\mu S\ cm^{-1}$ at 25 °C	472.00	574.00	490.00
(2)SAR	-	0.30	0.33	0.34
NH_4^+	$mg\ L^{-1}$	0.00	0.00	0.00
K^+	$mg\ L^{-1}$	2.80	4.70	3.90
Na^+	$mg\ L^{-1}$	10.70	11.80	12.70
Ca^{++}	$mg\ L^{-1}$	86.30	84.20	90.40
Mg^{++}	$mg\ L^{-1}$	6.90	7.30	9.70
Cl^-	$mg\ L^{-1}$	8.00	12.00	14.00
NO_2^-	$mg\ L^{-1}$	0.90	0.80	0.90
NO_3^-	$mg\ L^{-1}$	15.30	11.50	14.70
SO_4^{--}	$mg\ L^{-1}$	6.93	7.10	6.70
HCO_3^-	$mg\ L^{-1}$	250.10	220.30	230.70

(1)EC = Electrical Conductivity, (2)SAR = Sodium Adsorption Ratio

water quality [44, 22, 23, 36]. The comprehensive irrigation water analysis (Table 2) indicated its suitability for irrigation use, according to previously published results [44-48, 22, 23, 30].

The experiments were conducted in different fields during the three years of experimentation because a four-year crop rotation is necessary in the cultivation of sugar beets, in order to prevent certain crop diseases and enemies including *Cercospora Leaf Spot* (pathogen: *Cercospora beticola*), *Rhizomania* (pathogen: *beet necrotic yellow vein virus*), nematodes (sugar beet cyst, *Heterodera schachti;* root knot, *Meloidogyne arenaria, M. incognita, M. javanica, M. hapla* and *M. chitwood;* false root knot, *Nacobbus dorsalis*) and aphids. In the case of the appearance of *beet necrotic yellow vein virus*, either a 4-6 year crop rotation is imposed or sugar beet cultivation is excluded from the region for several years [27, 49-51].

Figures 4a, 4b and 4c present climatic data regarding air temperature and rainfall for the study irrigation periods in 1998, 1999 and 2000. These are compared with the corresponding means of a 25-year period for the region of study. The mean daily temperatures of air in °C (mean of 10-day period) for each year were obtained from the meteorological station nearest each experimental field (Palama, Kallifoni, Karditsomagoula). The rainfalls for years 1998, 1999 and 2000 were measured using a rain gauge installed in the experimental fields. The mean daily temperatures of air in °C (mean of 10-day period) and the rainfall for the 25-year period were obtained as means recorded at the meteorological station nearest each experimental field (Palama, Kallifoni, Karditsomagoula) [27]. The climate of the experimental sites is Mediterranean temperate [22], with an average cultivation period temperature of 26.4 ºC in 1998, 26.8 ºC in 1999, 26.3 ºC in 2000, and a cultivation period rainfall amount of 29.8 mm in 1998, 75.3 mm in 1999 and 39.4 mm in 2000 (Table 3). As shown in Figs. 4a, 4b and 4c, the periods 1998, 1999 and 2000 were more droughty and warmer than an average year.

According to USDA-Soil Survey Staff [52], soil texture was characterized as clay (in the field used in 1998), as loam (in the field used in 1999) and as a clay loam (in

TABLE 2 - Soil characteristics for the experiments conducted in 1998-2000.

Soil characteristics	Unit	1998	1999	2000
Bulk density	$g{\cdot}cm^{-3}$	1.29	1.45	1.30
Mechanical analysis	% Clay	58.00	21.17	36.45
	% Silt	20.06	36.72	39.33
	% Sand	21.94	42.11	24.22
Texture class	Class	Clay	Loam	Clay Loam
Field capacity	(3)% wt	37.90	18.34	29.00
	(4)% vol	49.00	26.60	37.70
(1)PWP	(3)% wt	21.00	10.07	15.90
	(4)% vol	27.00	14.60	20.70
Available water	$cm{\cdot}cm^{-1}$	0.22	0.12	0.17
(2)Ks (at 15cm depth)	$cm{\cdot}sec^{-1}$	$2.60{\cdot}10^{-4}$	$3.63{\cdot}10^{-4}$	$5.80{\cdot}10^{-5}$
(2)Ks (at 45cm depth)	$cm{\cdot}sec^{-1}$	$2.80{\cdot}10^{-6}$	$3.63{\cdot}10^{-4}$	$8.72{\cdot}10^{-5}$

(1) PWP = Permanent wilting point. (2) Ks = Saturated hydraulic conductivity. (3) % wt = % on dry soil weight basis. (4) % vol = % on volume basis.

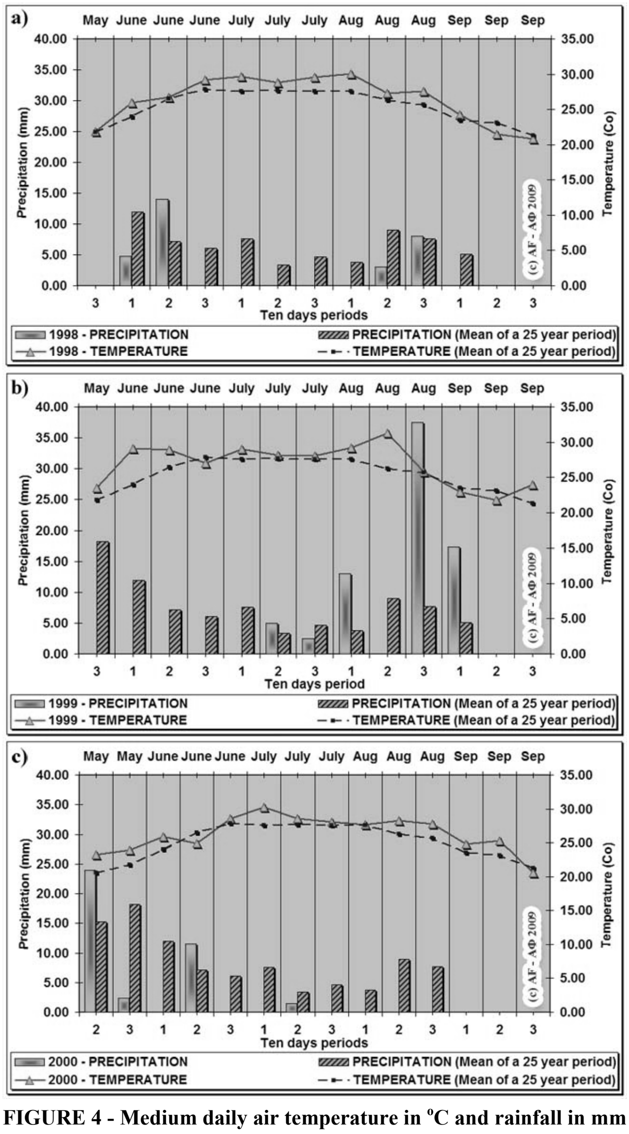

FIGURE 4 - Medium daily air temperature in °C and rainfall in mm (means of 10-day periods during the farming periods for the years: a) 1998, b) 1999 c) 2000, and for the 25-year period) in Leyki, Mataraga and Hlia of Karditsa Prefecture.

the field used in 2000) (Table 2); its profile was uniform. Based on the results of the soil map of Karditsa Prefecture, the soils of the experimental fields are characterized as Aquic according to Soil Taxonomy [52]. Soils with aquic (L. *aqua*, water) conditions (regime) are those that currently undergo continuous or periodic saturation and reduction. The presence of these conditions is indicated by redoximorphic features [53].

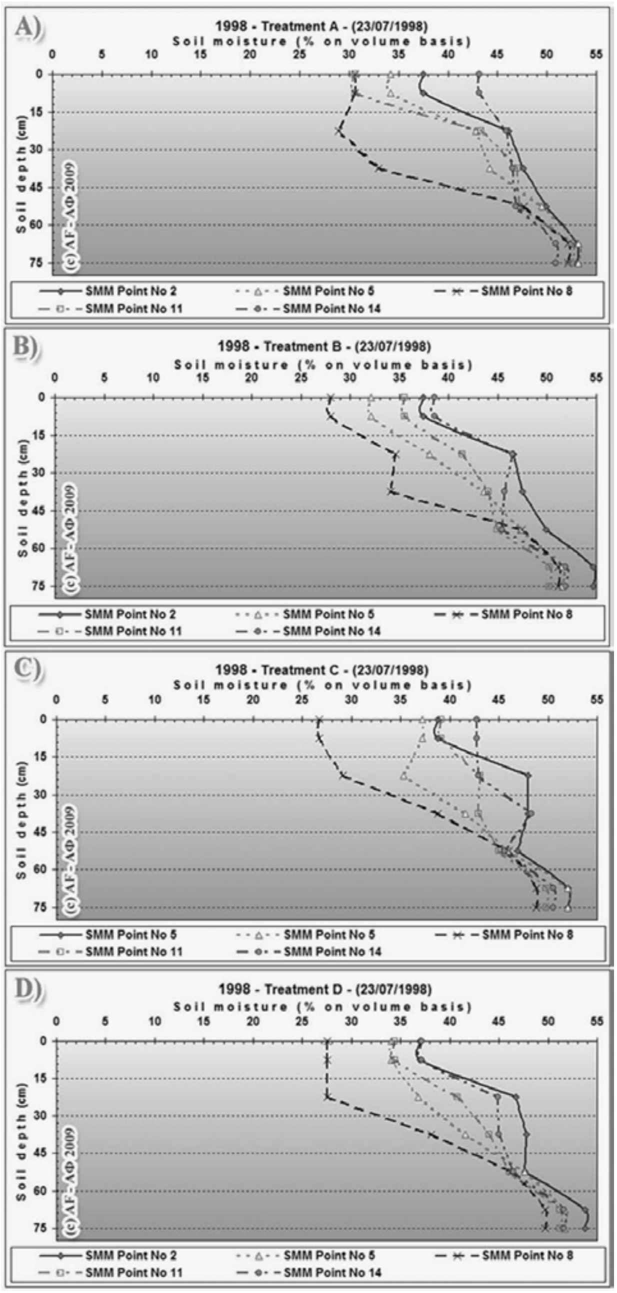

FIGURE 5 - Representative soil moisture distribution profiles for treatments A, B, C and D for the experimental plots of 1998.

Saturated hydraulic conductivity (Ks) of soils averaged 0.06042 cm·min^{-1} at 15 cm soil depth but 0.00906 cm·min^{-1} at 45 cm soil depth; according to Kutilek and Nielsen [54], these are considered to be high values. Water table depth of the different fields was measured at 1.04 m in 1998, 1.20 m in 1999, and 1.24 m in 2000. From the soil moisture content measurements obtained using the TDR method, soil moisture distribution profiles were constructed for various dates of each year of the experiment. Representative soil moisture distribution profiles for experimental field treatments A, B, C and D for years 1998, 1999 and 2000 are presented in Figs. 5, 6 and 7. As shown in these figures, an obvious increase in soil moisture content (volumetric water content) in the deeper soil layers occurred. The extended shape of the soil moisture curves in the deeper soil layers suggests the possibility that water contribution from the ground water table occurred [55, 56].

The procedure used to calculate the irrigation amount for each month of the cultivation period over the years 1998-2000 is presented in Table 3.

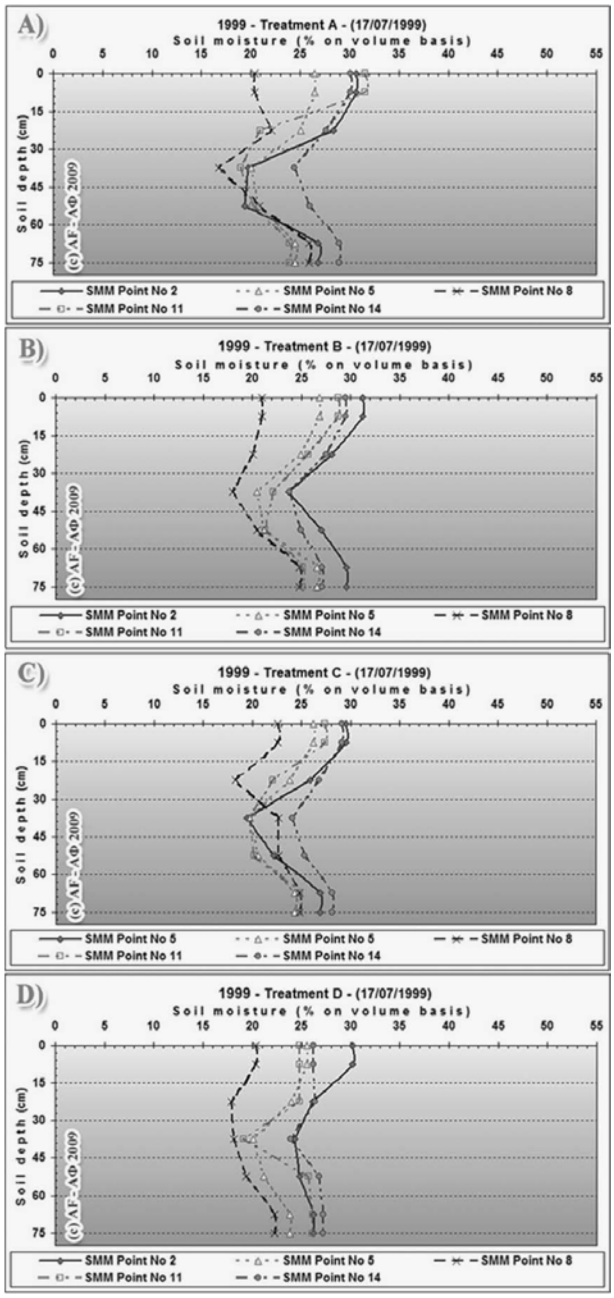

FIGURE 6 - Representative soil moisture distribution profiles for treatments A, B, C and D for the experimental plots of 1999.

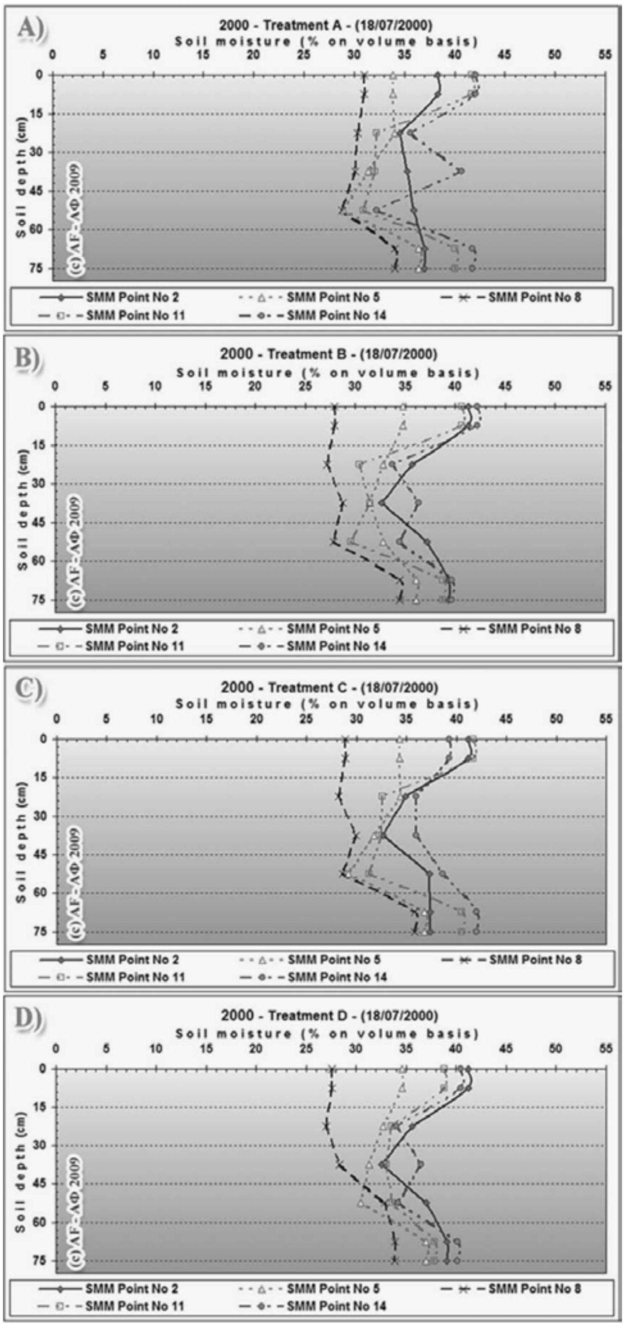

FIGURE 7 - Representative soil moisture distribution profiles for treatments A, B, C and D for the experimental plots of 2000.

From the TDR sensor measurements (the average of the total soil moisture content measurements at five different depths), the depletion of available soil moisture (ASMD) was calculated and evaluated in relation to each drip irrigation treatment. Doorenbos and Kassam [17] reported that soil water depletion (WD) up to 60% of available soil water has a non-statistically significant effect on sugar beet yield. Table 4 shows the mean maximum and mean average values of ASMD over the three years of experimentation, and for each drip irrigation treatment layout design.

It can be seen that the mean maximum values of ASMD at SMM point 8 (see Fig. 3) were similar for all treatments.

The calculated values of ASMD (mean maximum values), derived from the soil moisture content TDR sensor measurements for each drip irrigation treatment layout design of each year, and the mean average depletion values of SMM points 2, 5, 8, 11 and 14 for the three years of each drip irrigation treatment (Table 4) were consistent with the peak water depletion limit (60%) previously recommended [17].

Figure 8 presents the effective rainfall (calculated according to USDA-SCS [42]), the daily evapotranspiration (calculated using Class 'A' evaporation pan [18, 27, 38, 22] and corrected using the monthly evaporation pan coefficient *Kp* [18, 38, 22]), and the crop stage coefficient *Kc* [18, 27, 38] for the experimental site conditions for the years 1998, 1999 and 2000.

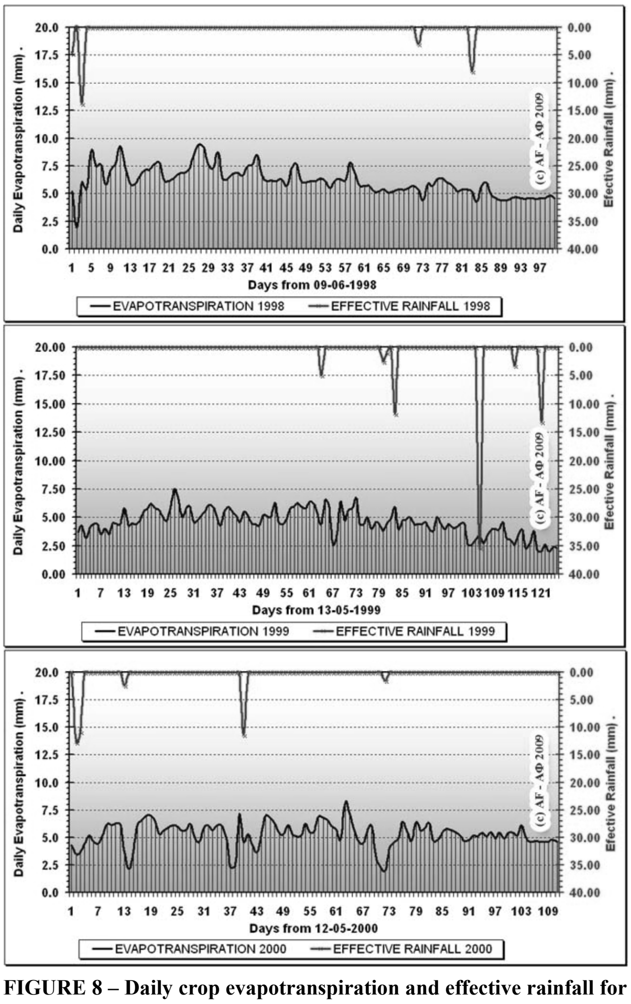

FIGURE 8 – Daily crop evapotranspiration and effective rainfall for the experimental field conditions for 1998, 1999 and 2000.

The crop evapotranspiration method has been used successfully by many researchers [4, 7, 17-20, 23, 27, 33, 37-41]. The crops' daily evapotranspiration varied widely; it was between 1.9 mm and 9.3 mm (period mean 6.40 mm) in 1998, between 2.0 mm and 7.5 mm (period mean 4.58 mm) in 1999, and between 2.0 mm and 8.2 mm (period mean 5.28 mm) in 2000. The daily evapotranspiration values compare well with *ETc* values in the relevant literature [7, 16, 19, 20, 24, 27-29]. Also, Maldonado *et al.* [7] showed that in a temperate Mediterranean climate, the pan evaporation method provided a good estimate of crop evapotranspiration for irrigation scheduling in sugar beets. There were no significant statistical differences between values obtained using the pan evaporation and those obtained using the Penman-Monteith equation. Overall, the pan evaporation method estimated adequately the crop evapotranspiration for sugar beet irrigation scheduling [7].

TABLE 3 - Calculation of the Net Irrigation Requirements.

Year	Month	Epan Epan=pan evaporation ($mm \cdot month^{-1}$)	ETr ETr = reference evapotranspiration ETr = Epan Kp ($mm \cdot month^{-1}$)	Kc Kc = crop stage coefficient (-)	ETc ETc = crop evapotranspiration ETc = ETr Kc ($mm \cdot month^{-1}$)	P P = Rainfall ($mm \cdot month^{-1}$)	Pe Pe = Effective rainfall ($mm \cdot month^{-1}$)	Crop NIR water needs NIR = net irrigation requirement NIR = ETc - Pe ($mm \cdot month^{-1}$)	Irrigation amount (mm)
1998	June	169.40	127.30	1.15	146.40	18.75	18.19	128.21	121.30
	July	251.10	188.80	1.15	216.90	0.00	0.00	216.90	223.30
	Aug	202.70	152.50	1.15	175.20	11.00	10.81	164.39	151.90
	Sep.	13.50	10.20	1.15	11.70	0.00	0.00	11.70	24.00
Total (mm)		636.70	478.80	1.15	550.20	29.75	28.99	521.21	520.50
1999	May	96.30	72.40	1.15	83.50	0.00	0.00	83.50	63.00
	June	186.00	139.80	1.15	161.00	0.00	0.00	161.00	163.10
	July	186.30	140.00	1.15	161.20	7.50	7.41	153.79	166.20
	Aug	149.10	111.70	1.15	128.10	50.50	46.42	81.68	75.80
	Sep	44.60	33.40	1.15	38.30	17.30	16.82	21.48	34.60
Total (mm)		662.30	497.30	1.15	572.10	75.30	70.65	501.45	502.70
2000	May	118.90	89.20	1.15	102.80	26.40	25.28	77.52	43.30
	June	188.10	141.60	1.15	162.70	11.50	11.29	151.41	178.20
	July	193.60	145.40	1.15	166.90	1.50	1.50	165.40	160.00
	Aug	179.10	134.10	1.15	154.00	0.00	0.00	154.00	165.50
Total (mm)		679.70	510.30	1.15	586.40	39.40	38.07	548.33	547.00

TABLE 4 - Mean maximum values of SMM point 8 and mean average values of SMM points 2, 5, 8, 11 and 14 of available soil moisture depletion (ASMD).

Treatment	Available Soil Moisture Depletion (%)							
	(3)Mean maximum values (%) at point 8				(3)Mean average values (%) at points 2, 5, 8, 11 and 14			
	1998	1999	2000	1998-2000	1998	1999	2000	1998-2000
(1)e-o-f - A	47.91	44.83	40.35	44.36	21.95	21.40	17.27	20.21
(1)e-o-f - B	45.27	47.67	50.01	47.65	24.91	15.10	20.09	20.03
(2)e-t-f - C	50.55	46.50	43.65	46.90	25.42	22.57	16.61	21.53
(2)e-t-f - D	50.82	58.17	50.65	53.21	27.20	23.20	18.66	23.02

(1)e-o-f = every-other-furrow. (2)e-t-f = every-three-furrows. (1)A = 1.00m x 0.50m, (1)B = 1.00m x 0.75m, (2)C = 1.50m x 0.50m, (2)D = 1.50m x 0.75m.
(3) Mean of five soil depths (0–15 cm, 15–30 cm, 30–45 cm, 45–60 cm and 60–75 cm).

TABLE 5 - Data and averages of the experimental and farmers' irrigation amounts, including the mean root yields from the experiment, farmers', Greece and EU (27) and WPIs from the experiment and farmers'.

Data Description	Year 1998	1999	2000	Average
Experimental irrigation amount (mm)	520.50	502.70	547.00	523.40
(1)Farmers' irrigation amount (mm)	481.23	412.49	481.23	458.32
Effective Rainfall (mm)	28.99	70.65	38.07	45.90
Experimental mean root yield ($t\ ha^{-1}$)	107.31	112.52	104.47	108.36
(2)Farmers' mean root yield ($t\ ha^{-1}$)	62.50	63.40	61.80	62.57
(3)Greece - mean root yield ($t\ ha^{-1}$)	60.50	55.20	62.90	59.53
(3)EU (27) - mean root yield ($t\ ha^{-1}$)	50.10	54.10	55.40	53.20
Experimental WPI(4) ($kg\ m^{-3}$)	19.53	19.63	17.86	19.03
Farmers' WPI (4) ($kg\ m^{-3}$)	12.25	13.12	11.90	12.42

(1) Farmers' irrigation amount (mm) refers to irrigation with hose reel. (2) Farmers' mean root yield ($t\ ha^{-1}$) refers to the study area (Karditsa's Prefecture), regardless of the irrigation method. (3) Source: (FAOSTAT, 2009) [3]. (4) WPI = Water Productivity Index ($kg\ m^{-3}$).

To avoid crop water stress, rainfall and irrigation must be sufficient to meet the crop's *ETc* requirement [42, 43, 23]. For any period of time during the growing season, the net irrigation requirement (NIR) is the amount of necessary water that is not effectively provided by rainfall. NIR denotes irrigation water that is delivered to the field and that is available for the crops to be used [43]. Therefore, the rule followed in our experiments was to supply a sufficient irrigation amount (NIR) to the field to meet the crop's *ETc* requirement, and avoid crop water stress (Table 3). Additionally, in avoiding crop water stress, soil moisture content monitored with TDR sensors and the calculation of ASMD in relation to each drip irrigation treatment helped to keep the maximum depletion (ASMD) below the recommended peak depletion value (60%) [17]. In the experimental drip-irrigated field, the irrigation system capacity was such that water could be added at greater than peak use rates, and the TDR soil moisture sensor readings never exceeded the corresponding ASMD peak depletion value. Also, plants never showed any sign of wilting. It should be noted that the small differences between the crop's NIR water needs and actual irrigation amount (Table 3) are due to irrigation interval, which did not correspond exactly to the last day of each month. The experiment's NIR and the corresponding total irrigation amount of each year varied from 502.7 mm to 547.0 mm (Table 5).

Yield results showed that the mean maximum sugar beet yield obtained in the experiments was about 108.1 t·ha^{-1}, while the corresponding mean maximum sugar beet yield of local farmers' fields varied from 61.8–63.4 t·ha^{-1}. The farmers' mean root yield refers to the entire study area (Karditsa Prefecture), regardless of the irrigation method (in the study area during the three-year period 1998-2000, approximately 87% of farmers irrigated with hose reel, 8% with drip irrigation and 5% with other methods [27]).

In 1998, the mean harvested sugar beet yield obtained experimentally was 107.3 t·ha^{-1}; whereas in 1999, it was 112.5 t·ha^{-1}, and in 2000, it was 104.5 t·ha^{-1}. The mean harvested sugar beet yield for each year of the experiment is considerably higher than the corresponding annual (1998-2000) mean yield of Greece (59.53 t ha^{-1}) [3] (Table 5).

Furthermore, a survey of the yield data for the last 3 years (2006-2008) in Greece shows that the production means over that period were 61.3, 62.9 and 65.4 t·ha^{-1} per year, respectively, and that the mean over the three-year period was 63.2 t·ha^{-1} (FAOSTAT, 2009) [3]. Therefore, the mean yield of the experimental fields (108.1 t·ha^{-1}) is also significantly higher than the average yield (63.2 t·ha^{-1}) over the last three-year period (2006-2008) in Greece. The mean root yield results (100% ET) in the e-o-f treatments (A, B) in 1998, 1999 and 2000 were 108.46, 111.46 and 105.11 t·ha^{-1} per year, respectively. The e-t-f treatments (C, D) in 1998, 1999 and 2000 yielded 106.17, 113.59 and 103.84 t·ha^{-1} per year, respectively.

TABLE 6 - Literature's sugarbeet yield and WPI comparison with various irrigation methods.

Year	Irrigation Method	Irrigation (system, spacing, etc)	Yield (t·ha^{-1})	WPI (kg·m^{-3})	Literature reference
1986	springler irrigation	springler irrigation	40.0 to 60.0	6.0 to 9.0	[17]
1991	furrow irrigation (6 days i.)	e-f (0.6m spacing)	42.90	19.1	[11]
1991	furrow irrigation (6 days i.)	e-o-f (1.2m spacing)	27.50	22.8	[11]
1992	furrow irrigation (6 days i.)	e-f (0.6m spacing)	41.20	38.5	[11]
1992	furrow irrigation (6 days i.)	e-o-f (1.2m spacing)	41.80	52.1	[11]
1995	springler irrigation	springler irrigation	62.52	9.29	[13]
1996	springler irrigation	springler irrigation	63.75	10.68	[13]
1996	SDI, 20% WD	SDI e-f (0.76m x 0.55m dripper spacing)	67.76	10.60	[12]
1996	SDI, 35% WD	SDI e-f (0.76m x 0.55m dripper spacing)	64.06	9.90	[12]
1996	SDI, 50% WD	SDI e-f (0.76m x 0.55m dripper spacing)	62.91	9.60	[12]
1996	flood irrigation, 65% WD	flood irrigation	58.49	5.30	[12]
1997	SDI, 20% WD	SDI e-f (0.76m x 0.55m dripper spacing)	44.45	17.70	[12]
1997	flood irrigation, 65% WD	flood irrigation	43.27	3.80	[12]
1999	SDI, 80% ET	SDI e-o-f (1m x 1m dripper spacing	54.58	14.75	[28]
1999	SDI, 100% ET	SDI e-o-f (1m x 1m dripper spacing	60.31	13.58	[28]
1999	subsurface DI, 80% ET	subsurface DI e-o-f (1 m x 1m dripper spacing	66.69	18.02	[28]
1999	subsurface DI, 100% ET	subsurface DI e-o-f (1 m x 1m dripper spacing	68.87	15.51	[28]
99-00 and 00-01	rain fed	rain fed (control dry)	40.20 (pooled data)	-	[8]
99-00 and 00-01	SDI , 50% ET	SDI e-f (0.9 m) and e-o-f (1.8 m) at 0.60 m dripper spacing	63.10 (pooled data)	12.36	[8]
2001	furrow irrigation	furrow	50.50	-	[14]
2001	SDI	SDI at 0.55 m dripper spacing	56.00	13.69	[14]
2002-2003	springler irrigation, (ET=pan evaporation)	fixed sprinkler irrigation	134.36	21.91	[7]
2002-2003	springler irrigation, (ET=Penman-Monteith)	fixed sprinkler irrigation	132.08	17.53	[7]
2003	springler irrigation	sprinkler irrigation e-f (0.55 m)	93.5 and 99.4	14.20 and 12.50	[9]
2004	springler irrigation	sprinkler irrigation e-f (0.55 m)	64.8 and 68.7	10.40 and 9.70	[9]

SDI = surface drip irrigation, DI = drip irrigation, WD = water depletion, e-f = every-furrow, e-o-f = every-other-furrow, ET = evapotranspiration.

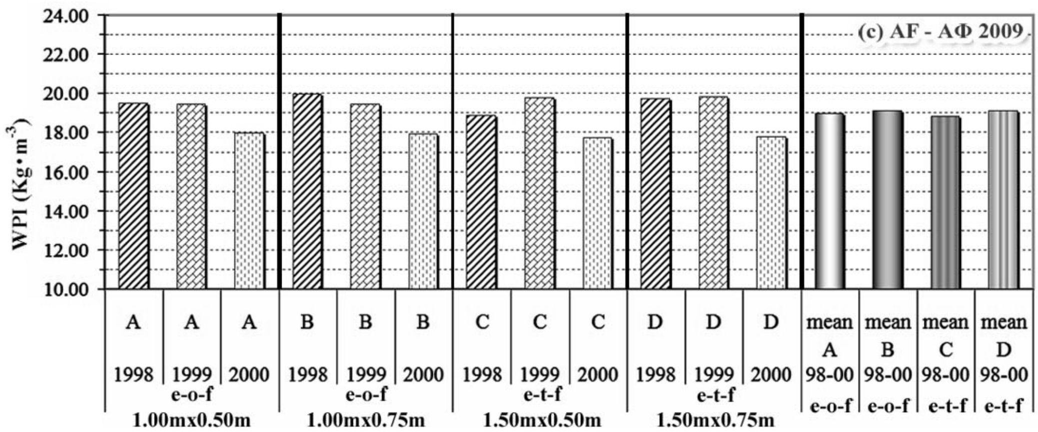

FIGURE 9 - WPIs for treatments A, B, C and D and mean WPIs for the years 1998, 1999 and 2000.

The harvested sugar beet yields following the four experimental treatments using surface drip irrigation (SDI) compared well with those reported in the relevant literature (Table 6) with various irrigation methods, systems and spacing (every furrow, every other furrow, etc).

The root sugar content of the crops varied from 11.68% to 13.00% in e-o-f treatments (A, B) and between 11.46-13.41% in the e-t-f treatments (C, D); these values compare favourably with values reported in the relevant literature [7-9, 11-14, 17, 28, 29]. The raw sugar yield results varied from 12.68 $t \cdot ha^{-1}$ to 13.76 $t \cdot ha^{-1}$ in e-o-f treatments (A, B), and from 12.14 $t \cdot ha^{-1}$ to 14.39 $t \cdot ha^{-1}$ in e-t-f treatments (C, D). These also compare well with the relevant literature data [7-9, 11-14, 17, 28, 29].

The mean WPI results were 19.74, 19.44 and 17.97 $kg \cdot m^{-3}$ in e-o-f treatments (A, B), as well as 19.32, 19.81 and 17.75 $kg \cdot m^{-3}$ in the e-t-f treatments (C, D), respectively, for each year. Figure 9 depicts the WPIs of all the treatments for each year. The mean WPIs corresponding to the four treatments (e-o-f (A and B) and e-t-f (C and D)) were found to be 19.97, 19.12, 18.80 and 19.11 $kg \cdot m^{-3}$ in 1998, 1999 and 2000, respectively. These data compared well with WPIs reported in the relevant literature (Table 6) with various irrigation methods, systems and spacing (every furrow, every other furrow, etc). The experimental WPIs (100% ET) were high with regard to those reported in many relevant studies (see Table 6), and defined the high water use efficiency, the good irrigation management, and the good cultivation practices employed in the experimental cultivation. The highest WPIs were observed in 1999; these were assisted by the highest effective rainfall amount of the 3-year period.

According to the statistical test ANOVA, the observed differences in root yield, sugar beet content, raw sugar yield and water productivity indices between all the treatments, i.e., every-other-furrow (A = 1.00 m x 0.50 m and B = 1.00 m x 0.75 m) and every-three-furrows (C = 1.50 m

TABLE 7 - The effects of various layout designs (treatments) on sugar beet mean root yield, mean percent sugar (POL), mean raw sugar yield and WPI.

Year	Treatment Distance between drip lateral pipes (m) x distance between built–in drippers (m)	Replicates	Mean root yield ($tn\ ha^{-1}$)	Mean percent of roots sugar content (%)	Mean raw sugar yield ($tn\ ha^{-1}$)	WPI[4] ($kg\ m^{-3}$)
1998	[1] e-o-f - 1.00 x 0.50	6	107.08	11.558	12.381	19.49
	[1] e-o-f - 1.00 x 0.75	6	109.83	11.810	12.974	19.99
	[2] e-t-f - 1.50 x 0.50	6	103.83	11.459	11.879	18.90
	[2] e-t-f - 1.50 x 0.75	6	108.50	11.460	12.408	19.75
	p-value		0.558	0.192	0.198	0.339
1999	[1] e-o-f - 1.00 x 0.50	6	111.50	12.371	13.833	19.45
	[1] e-o-f - 1.00 x 0.75	6	111.42	12.300	13.693	19.43
	[2] e-t-f - 1.50 x 0.50	6	113.50	12.646	14.378	19.80
	[2] e-t-f - 1.50 x 0.75	6	113.67	12.630	14.394	19.83
	p-value		0.851	0.397	0.515	0.883
2000	[1] e-o-f - 1.00 x 0.50	6	105.22	12.942	13.585	17.98
	[1] e-o-f - 1.00 x 0.75	6	105.00	13.067	13.727	17.95
	[2] e-t-f - 1.50 x 0.50	6	103.67	13.408	13.849	17.72
	[2] e-t-f - 1.50 x 0.75	6	104.00	13.404	13.903	17.78
	p-value		0.987	0.354	0.961	0.708
1998-2000	α=0.05		NSS [3]	NSS [3]	NSS [3]	NSS [3]

(1) e-o-f = every-other-furrow. (2) e-t-f = every-three-furrows. (3) NSS = not statistically significant. (4) WPI = Water Productivity Index ($Kg\ m^{-3}$).

x 0.50 m and D = 1.50 m x 0.75m) were statistically significant (Table 7) at the level of $p<0.05$.

Based on the statistical analyses (statistically significant at level $p<0.05$) of the root yield, sugar content percent of roots, raw sugar yield and WPIs (Table 7), of the environmental advantages of the four treatment drip irrigation layout designs, and of comparisons with neighbouring farmers' yields and results of work of other researchers, it was concluded that for sugar beet irrigation in agricultural Mediterranean areas with *Aquic* soil moisture regime, the wider drip irrigation layout design of every-three-furrows (1.50 m x 0.75 m) is the most advantageous method, which should be applied instead of the more common layout of every-other-furrow (1.00 m x 0.50 m), (mean $p = 0.885$).

From the environmental point of view, groundwater contamination from agricultural pesticides [57], as well as nutrient contamination, is a major environmental issue in Greece and Europe, in areas that undergo intensively irrigated agricultural production [22, 23, 48, 57-60]. Heavy rains, irrigation methods and flooding also affect the amount of nitrate that reaches both ground and surface water [23, 48, 58-60]. Excess water from irrigation (especially from sprinkler and hose reel applications) can leach nutrients from the soil and can carry these nutrients and pesticides into groundwater supplies through percolation. Also, surface water receives sediment and nutrient runoff originating from agricultural irrigation applications. Erosion is increased by excess water and unneeded irrigation. Additionally, the lack of politically inspired penalties for wasting water is reflected in the scarcity of this source [58].

Filintas et al. (2009) state that "*advances in electronics and computers generated new techniques to maximize the farmer's profit and to protect the environment*" [57]. Irrigation management using new techniques, such as high precision TDR measurements of soil moisture, depletion (ASMD) calculations with computer software and daily soil moisture and ASMD diagram development reduces the amount of water applied to the sugar beet crop and also reduces excess water use, while maintaining a soil moisture that is ideal for intensive crop production and that results in high crop yield. In this way, the above mentioned proper irrigation management contributes to: (a) the farmer's profit to be maximized, (b) the saving of the irrigation water, and (c) the protection and sustainability of the environment and natural resources.

The application of the suggested drip irrigation layout design of e-t-f (1.50 m x 0.75 m) also has additional and important environmental and agronomical advantages that contribute to environmental protection and sustainability. These include:

- Improved irrigation water management (soil moisture high precision TDR measurements, depletion (ASMD) calculations and daily soil moisture and ASMD diagram development, ideal soil moisture maintenance, high WPIs with improved water use efficiency, negligible losses due to deep infiltration, water saving);
- Reduction of plastic materials (which represent long-life cycle, polluting elements of the environment), calculated at -33.3% for polyethylene;
- Considerable purchase cost reduction (calculated at -37.2%) of drip irrigation installation materials compared to other methods;
- Important installation labor savings;
- Transportation and storage facilities cost reduction.

CONCLUSIONS

The mean sugar beet yield obtained in the experiments conducted was 108.1 t ha$^{-1,}$ while the corresponding mean sugar beet yield of local farmers' fields varied by about 61.8–63.4 t ha^{-1}. The mean root yield results in the e-o-f treatments (A, B) were 108.46, 111.46 and 105.11 t·ha^{-1}, and in the e-t-f treatments (C, D) were 106.17, 113.59 and 103.84 t·ha^{-1}, respectively, for each year (1998-2000). The root sugar content results varied between 11.68-13.00% in e-o-f treatments (A, B) and 11.46-13.41% in e-t-f treatments (C, D). The raw sugar yield results varied from 12.68 t·ha^{-1} to 13.76 t·ha^{-1} in e-o-f treatments (A, B), and from 12.14 t·ha^{-1} to 14.39 t·ha^{-1} in e-t-f treatments (C, D). The 3-year mean WPIs for the four treatments (e-o-f (A and B) and e-t-f (C and D)) were found to be 19.97, 19.12, 18.80 and 19.11 kg·m^{-3}, respectively. The harvested sugar beet yields obtained using the four treatments compare well with those reported in the relevant literature [7-9, 11-14, 17, 28, 29], as do the root sugar content, raw sugar yield and WPI results.

Based on statistical analyses (statistically significant, at level $p<0.05$) of the root yield, sugar content percent of roots, raw sugar yield and WPI results and also on the environmental advantages of the four treatment drip irrigation layout designs and on comparisons with neighbouring farmers' yields and the results of similar work of other researchers, we concluded that for sugar beet irrigation in agricultural Mediterranean areas with *Aquic* soil moisture regime, the wider drip irrigation layout design of every-three-furrows (1.50 m x 0.75 m) is the best solution and should be applied instead of the common farmers' layout of every-other-furrow (1.00 m x 0.50 m).

Deductively, from the environmental point of view, the application of the suggested drip irrigation layout design has additional and important environmental and agronomical advantages that contribute to protection of the environment and to sustainability, including: (a) improved irrigation water management (soil moisture high precision TDR measurements and depletion (ASMD) calculations, ideal soil moisture maintenance, improved water use efficiency with high WPIs, negligible losses due to deep infiltration, water saving); (b) plastic material reduction (calculated at -33.3% for polyethylene); (c) considerable purchase cost reduction (calculated experimental result was -37.2%) of drip irrigation installation materials; (d) important installation labor savings; (e) transportation and storage facilities cost reduction; (f) reduced groundwater contamination due to reductions in amounts of nutrients and pesticides leaching to ground water through percolation; (g) reduced sediment and nutrient runoff to surface water sources; and (h) decreased soil erosion through the elimination of excess irrigation water and unneeded irrigation, based on soil moisture high precision TDR measurements and depletion (ASMD) calculations.

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