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Deficit Irrigation Analysis of Red Pepper (*Capsicum annum* L.) Using the Mathematical Optimisation Method

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Abstract: The objectives of this study were to analyse deficit irrigation with the mathematical optimisation method using the water-yield relationship and cost functions of red pepper, and to determine alternative deficit irrigation water levels. For this purpose, the effect of 5 different irrigation levels (I_1, I_2, I_3, I_4, and I_5) on dry yield (DY) was determined using a line source sprinkler irrigation system in Kahramanmaraş, Turkey in 1999 and 2000. The average water amounts applied with I_1 (non-water stress treatment) and I_5 (water stress treatment) for the 2 years were 913 and 296 mm, and I_2, I_3, and I_4 varied between these extremes. The quadratic production and cost functions were established between the average irrigation water and DY, and between water and total costs, respectively. Maximum irrigation water (W_m), economically optimum level of irrigation water for land-limiting (W_l) and water-limiting (W_w), and equivalent deficit level for land-limiting (W_{el}) and water-limiting (W_{ew}) for red pepper yield were calculated as 1026, 815, 752, 603, and 551 mm, respectively. The most economical irrigation levels, in terms of both net income from per unit of land and water, were 815 mm and 752 mm, respectively. At W_{ew} level, field irrigation was 1.86 times greater than at the W_m level, without reducing net farm income. The findings of this study suggested that water resources should be distributed over the entire farm, rather than concentrated to maximise yields on particular parts of the farm.

Key Words: Line source sprinkler, deficit irrigation, *Capsicum*, strategic water levels

Matematik Optimizasyon Yöntemini Kullanarak Kırmızı Biberin Kısıntılı Sulama Analizi

Özet: Bu çalışmanın amacı, kırmızı biberde su-verim ile maliyet ilişkilerini kullanarak kısıntılı sulama analizi yapmak ve alternatif kısıntılı sulama düzeylerini belirlemektir. Bu analizde matematiksel optimizasyon yöntemi kullanılmıştır. Bu amaçla, Kahramanmaraş İlinde çizgi kaynaklı yağmurlama sulama sistemi kullanarak 1999 ve 2000 yılları yetiştirme mevsiminde 5 farklı sulama düzeyinin (I_1= tam sulama; I_2, I_3, I_4 ve I_5= kısıntılı sulama) kırmızı kuru biber verimine olan etkisi belirlenmiştir. I_1 sulama konusuna ortalama 913 mm, I_5 sulama konusuna ortalama 296 mm ve diğer sulama konularına ise bu iki değer arasında sulama suyu uygulanmıştır. Kuru kırmızı biber verimi ile sulama suyu arasında ikinci dereceden ve maliyet arasında ise doğrusal bir fonksiyon bulunmuştur. Hesaplanan en yüksek sulama suyu (W_m) 1026 mm'dir. Kısıtlı arazi (W_l) ve sulama suyu (W_w) koşullarında ekonomik optimum sulama suyu düzeyleri 815 ve 752 mm; kısıntılı arazi (W_{el}) ve sulama suyu (W_{ew}) koşullarında denk gelir sulama suyu düzeyleri ise 603 ve 551 mm olarak hesaplanmıştır. Birim alandan ve sudan elde edilen en ekonomik su seviyeleri sırasıyla 815 mm ve 752 mm olarak bulunmuştur. Net geliri azaltmadan, W_{ew} seviyesinde sulanan alan miktarı, W_m düzeyinde sulanan alan miktarının 1.86 katıdır. Bu çalışma, sulama suyunu, birim alandan en yüksek verimi elde etmek için uygulamak yerine, birim su miktarından en fazla gelir sağlayacak şekilde tüm alana yaymak daha fazla net gelir sağlayacağını göstermiştir.

Anahtar Sözcükler: Çizgi kaynaklı yağmurlama, kısıntılı sulama, *Capsicum*, en yüksek, ekonomik optimum, denk gelir sulama düzeyleri

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Introduction

Water is becoming scarce, not only in arid and drought-prone areas, but also in regions where rainfall is abundant (Pereira et al., 2002). In some locations, the available water supply is inadequate to produce the maximum yield on irrigable land. In other regions, the water available for irrigation is already regulated and requires deficit irrigation. For many surface water projects, the annual supply of irrigation water is limited by reservoir capacity and annual reservoir inflow. These examples highlight the need for deficit irrigation management on a seasonal basis (Martin et al., 1989). Deficit irrigation is a strategy that allows a crop to sustain some degree of water deficit in order to reduce costs and potentially increase income. It can lead to increased net income where water costs are high or where water supplies are limited (English and Raja, 1996).

Deficit irrigation is widespread in the southern Ogallalla region, the Columbia Basin, and other areas of the U.S., the Indian subcontinent, parts of Africa, and other regions of the world where water is in short supply (English et al., 1990). Çevik et al. (1996) concluded that 14% of irrigation water would be saved with a 3% reduction in pepper yield under Harran Plain conditions. Kırnak et al. (2002) reported that a subsurface drip system for bell pepper irrigation could be a better choice compared to a surface drip irrigation system under deficit irrigation in the Harran Plain. Dorji et al. (2005) compared traditional drip system irrigation to deficit irrigation (DI) and partial rootzone drying (PRD) drip system irrigation for hot pepper irrigation and found that water savings with DI and PRD were about 50% of traditional drip irrigation. Antony and Singandhupe (2004) reported that total capsicum yield was less at lower levels of irrigation. Kang et al. (2001) conducted a hot pepper study applying water through alternate drip irrigation on partial roots (ADIP), fixed drip irrigation on partial roots (FDIP), and drip irrigation on whole roots (EDIP), and concluded that ADIP maintained high yield, with as much as a 40% reduction in irrigation compared to EDIP and FDIP; moreover, the highest water-use efficiency occurred with ADIP. Costa and Gianquinto (2002) reported that continuous water stress significantly reduced total fresh weight of fruit and that the highest marketable yield was obtained with irrigation of 120% ET (Evapotranspiration), lowest at 40% ET, and marketable yield was the same at 60%, 80%, and 100% ET. Jaimez et al. (2000) revealed that a water deficit during the period between flowering and fruit development reduced final fruit production.

Red pepper is commonly grown in drought-prone areas of Turkey where climactic conditions are hot and water sources are scarce. In these circumstances, deficit irrigation will probably contribute to the economical use of water sources if significant reduction does not occur in crop yields.

Many field studies of DI have been conducted. Such field studies are needed for economic analysis of DI and to increase net income and water-use efficiency (Stewart et al., 1974; English, 1990).

The objectives of this study were to analyse the effect of DI on red pepper dry yield (DY), to determine alternative DI water levels, and to maximise net income using the crop yield–water relationship and production costs under conditions of Kahramanmaraş, Turkey.

Materials and Methods

The research was conducted at an experimental field at Kahramanmaraş Sütçü İmam University Agricultural Facility (lat 37° 32′ 08″ N, long 36° 54′ 59″ E; altitude 700 m above sea level) during the 1999 and 2000 growing seasons. The local red hot pepper variety (*Capsicum annum* L.) of “Kahramanmaraş” was used because it is widely used in Turkish cuisine.

The soil in the area was classified as Inceptisol, heavy textured, and homogeneously structured. Soil profile at depths of 0-30 cm and 30-60 cm was clay loam and clay. Field capacity (FC) on a mass basis, wilting point (WP) on a mass basis, bulk density, salinity, and pH at soil layer depths of 0-30 cm and 30-60 cm were 26.0% and 33.6%, 16.4% and 26.2%, 1.4 and 1.8 g cm^{-3}, 0.06% and 0.07%, and 7.90 and 8.03, respectively. Irrigation water used in the area was classified as C_2S_1 with an electrical conductivity of 0.46 dS m^{-1}.

The local climate was semi-arid. During the growing season, the average temperature and relative humidity were 17.1 °C and 59%. Total rainfall for 1999 and 2000 was 442.7 and 680.3 mm, respectively. Total rainfall between day of year (DOY) 120-148 in 1999 and DOY 100-250 in 2000 was 20 and 38 mm, respectively.

Fertiliser (50 kg N ha^{-1} and 50 kg P_2O_5 ha^{-1}) was applied based on soil analysis and incorporated into soil during tillage and seedbed preparation. Seeds were sowed into the top 3 cm of soil on DOY 120 in 1999 and DOY 100 in 2000. The inter-plant and inter-row spacing were 30 and 70 cm, respectively. At the time of first irrigation, an additional 115 kg N ha^{-1} was applied. Weeds were controlled by manual methods.

The experiment was uniformly irrigated for 2-3 h every 3 days using a hand-move sprinkler irrigation system (12 x 12 m) in order to provide optimum soil moisture for homogeneous emergence and stand establishment until DOY 192 in 1999 and DOY 187 in 2000. By these dates (prior to the early flowering stage), the irrigation water applied to the experimental plots reached depths of 258 and 316 mm in 1999 and 2000, respectively. The plot was thinned to one plant per 30 cm in each row. The number of pepper plants per hectare was about 47,619. After these dates, irrigation with a line source sprinkler irrigation system began and continued until the first week of September. Sprinkler heads with nozzle sizes of 4.5 x 4.8 mm and with an application rate of 6.57 mm h^{-1} were located 6.0 m apart on the line source. The system was operated at a pressure of 300 kPa to obtain a linearly decreasing water distribution from the line source sprinkler irrigation system to the wetted perimeter. The experimental area (30 m long and 29.4 m wide) was irrigated every week by the line source sprinkler system (Hanks et al., 1980). As seen in Figure 1, 5 irrigation treatments were arranged at both sides of the line source sprinkler system. Treatments were replicated 3 times. Irrigation treatments were denoted as I_1, I_2, I_3, I_4, and I_5. I_1 represents full irrigation and the others were deficit irrigation treatments. The size of each treatment plot was 10 x 2.8 m. The plant rows adjacent to the line source and perimeter were not included in treatments I_1 and I_5. Plant rows were parallel to the line source.

Prior to an irrigation, available soil water content for all the treatments was measured in the third plant row at 0-30 cm and 30-60 cm soil depths using the gravimetric sampling method (Jury et al., 1991). The total depth of water applied to treatment I_1 was sufficient to bring the measured gravimetric soil water content to FC level in the 60 cm soil profile. The depth of water applied to treatment I_1 was calculated for 0-30 cm and 30-60 cm depths using the equation given by Kanber (1997) and then summed to determine total water depth.

$$d = \frac{(\theta_{fc} - \theta_w) Z \rho_b}{10} \qquad (1)$$

where d is the depth of water to apply to treatment I_1 (mm), θ_{fc} is soil water content on a mass basis at the field capacity (%), θ_w is the soil water content on a mass basis (%), Z is the rooting depth (cm), and ρ_b is the bulk density of soil (g cm^{-3}).

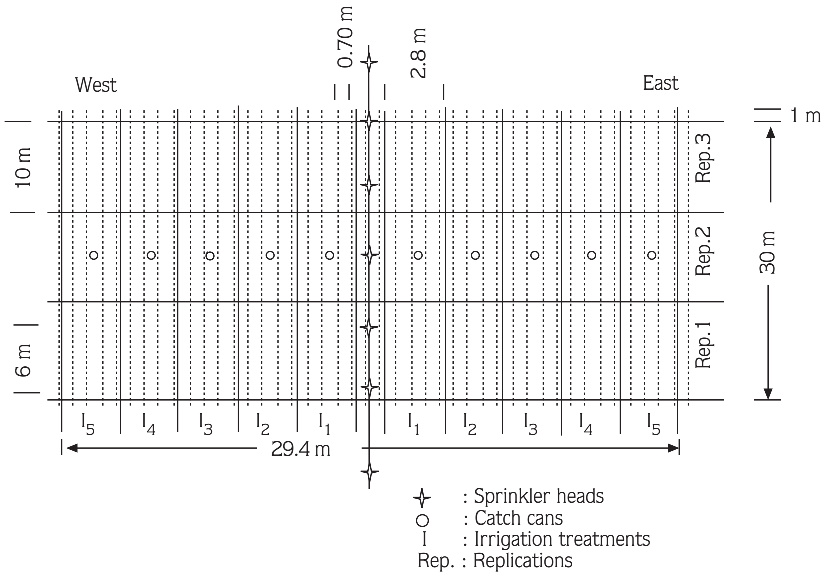

Figure 1. Experimental layout of the line source sprinkler irrigation system.

Irrigation water was intermittently applied by the sprinkler line source irrigation system so that runoff from the treatment plots would not occur. The depth of applied water decreases linearly away from the line source when using the line source sprinkler system (Hanks et al., 1980). The depth of water applied in each treatment was measured using a catch can located above the canopy at the centre of each plot on both sides of the line source sprinkler system (Figure 1). The area of each catch can was 78.85 cm^2. To determine the duration of sprinkler operation, the depth-time relationship was used.

Red peppers were harvested from an area of 28 m^2 on DOY 221, DOY 256, and DOY 288 in 1999 and on DOY 208, DOY 244, and DOY 278 in 2000. The total mass from each treatment was weighed. Fresh pepper sub-samples of 1 kg were taken randomly from the production of each treatment and dried in an oven at 65 ºC until reaching constant weight to determine DY.

Line source statistical principles (analysis of variance) given by Hanks et al. (1980) were used for DY. The parameter was analysed using LSD multiple range tests.

Procedure of deficit irrigation analysis

Deficit irrigation of dry red pepper was analysed with the method given below by English (1990). The method required a quadratic production function, which was determined using regression analysis between irrigation water applied to irrigation treatments and their red pepper DY. Its general form was given as:

$$y(w) = a_1 + b_1w + c_1w^2 \quad (2)$$

where y(w) is yield per unit of land expressed as a function of w (kg ha^{-1}); w is irrigation water applied to irrigation treatments (mm); and a_1, b_1, and c_1 are coefficients of the dry pepper quadratic production function.

The dry red pepper cost function was established using regression analysis between irrigation water applied to irrigation treatments and their total production costs as follows:

$$c(w) = a_2 + b_2w \quad (3)$$

where c(w) is production cost per unit of land in \$ ha^{-1}, expressed as a function of w; a_2 and b_2 are coefficients of dry red pepper cost function. The cost function is the straight line, with an intercept, a_2, that represents non-irrigated treatment costs and slope b_2, which represents an increase in variable costs with per unit of irrigation water increase.

Variable and fixed costs for dry red pepper grown in Kahramanmaraş were determined for full irrigation conditions (I_1). Costs of red pepper harvesting, drying, transportation, and circulation capital interest for I_2, I_3, I_4, and I_5 irrigation treatments were proportional to the red pepper DY. Other variable costs for the other treatments were proportional to the quantity of applied irrigation water. For irrigation treatments, total production costs were the sum of the fixed and variable costs.

Net income obtained from dry pepper determined from per unit of land under irrigation was calculated as follows:

$$i_l(w) = P_c y(w) - c(w) \quad (4)$$

where $i_l(w)$ is net income per unit of land under irrigation (\$ ha^{-1}), $P_c y(w)$ is income per unit of land (\$ ha^{-1}), and P_c is crop price of dry pepper (\$ kg^{-1}).

The level of water use that will maximise red pepper DY W_m (mm) can be determined by taking the derivative of the production function (Eq. 2):

$$\frac{\partial y(w)}{\partial w} = 0 \quad (5)$$

$$Wm = \frac{-b_1}{2c_1} \quad (6)$$

Net income per unit of land will be maximised when the level of applied water reaches W_l (mm), at which point the slope of the cost line equals the slope of the income line. When land is limiting, the equation for optimum water use W_l (mm) is written as follows:

$$P_c \frac{\partial y(w)}{\partial w} = \frac{\partial c(w)}{\partial w} \quad (7)$$

$$W_l = \frac{b_2 - P_c b_1}{2P_c c_1} \tag{8}$$

When water is limiting, the equation for optimum water use W_w (mm) is written as follows:

$$W_l \left[P_c \frac{\partial y(w)}{\partial w} - \frac{\partial c(w)}{\partial w} \right] = P_c y(w) - c(w) \tag{9}$$

$$W_w = \left(\frac{P_c a_1 - a_2}{P_c c_1} \right)^{0.5} \tag{10}$$

If applied water is sufficiently reduced, a point will be reached at which the vertical difference between the cost and income lines will again equal the difference at W_m. That point is illustrated as the equivalent deficit level by W_{el} (mm) for the land-limiting case and W_{ew} (mm) for the water-limiting case. The range of applied water between either of those points and W_m might be referred to as the range of profitable deficits, since the net income associated with any deficit within that range will result in greater net income than would be realised with full irrigation. The 2 water use levels (W_{el} and W_{ew}) were determined by substituting W_m into Eq. 4 and then the net income under full irrigation is determined:

$$i_l(W_m) = P_c y(W_m) - c(W_m) \tag{11}$$

This net income may then be substituted for the left-hand side of Eq. 4:

$$i_l(W_m) = P_c y(w) - c(w) \tag{12}$$

When Eq.11 is set equal to Eq. 12, the following equations are written:

$$P_c y(W_m) - c(W_m) = P_c y(w) - c(w) \tag{13}$$

$$P_c c_1 w^2 + (P_c b_1 - b_2)w + \left(\frac{P_c b_1^2}{4c_1} - \frac{b_1 b_2}{2c_1} \right) = 0 \tag{14}$$

Equivalent deficit level for the land-limiting case W_{el} (mm) is derived from the positive root of Eq. 14:

$$W_{el} = \frac{-(P_c b_1 - b_2) + \left((P_c b_1 - b_2)^2 - 4P_c c_1 \left(\frac{P_c b_1^2}{4c_1} - \frac{b_1 b_2}{2c_1} \right) \right)^{0.5}}{2P_c c_1} \tag{15}$$

The irrigated field (A) may also be a function of water use. If water supply is limited, the farm manager may put so many fields under irrigation that the water supply is exhausted. The irrigated area will be:

$$A = \frac{W_T}{w} \tag{16}$$

where A is total field of the crop to be irrigated (ha), W_T is total available water supply (m^3), and w is water applied per unit of field (m^3 ha^{-1}). On the other hand, if land is the limiting resource, it is reasonable to expect the farm to put all available land into production:

$$I_f(w) = A\ i_l(w) \tag{17}$$

where I_f (w) is net farm income from all irrigated fields (\$) and $i_l(w)$ is net income per unit of field under irrigation (\$ ha^{-1}).

The equivalent income level of irrigation when water is limiting W_{ew} (mm) can be derived from Eqs. 16 and 17:

$$I_f\,(W_m) = \frac{W_T}{W_m}\, i_l\,(W_w) \tag{18}$$

$$I_f\,(W_m) = \frac{W_T}{w}\, i_l\,(w) \tag{19}$$

$$\frac{W_T}{W_m}\, i_l\,(W_m) = \frac{W_T}{w}\, i_l\,(w) \tag{20}$$

$$P_c c_1 w^2 + \left(\frac{P_c b_1^2}{2b_1} + \frac{2P_c c_1 a_1}{2b_1} - \frac{2c_1 a_2}{2b_1} \right) w - (a_2 - P_c a_1) = 0 \tag{21}$$

The positive root of Eq. 21 will be W_{ew} (mm):

$$W_{el} = \frac{-\left(\frac{P_c b_1^2 + 4P_c a_1 c_1 - 4a_2 c_1}{2b_1}\right) + \left(\left(\frac{P_c b_1^2 + 4P_c a_1 c_1 - 4a_2 c_1}{2b_1}\right)^2 - 4P_c c_1 (P_c a_1 - a_2)\right)^{0.5}}{2P_c c_1} \qquad (22)$$

In order to evaluate the efficiency of calculated irrigation water (CIW, mm) denoted as W_m, W_l, W_w, W_{el}, and W_{ew} water levels (W_l), water deficit (WD, %), calculated yield determined from production function using CIW (CY, kg ha^{-1}), calculated yield reduction (CYR, %), net income to water (NIW, \$ m^{-3}), net income increase at land-limiting (NIILL, %), net income increase at water-limiting NIIWL, calculated yield (CY, kg ha^{-1}) from production function, irrigated land (IL, ha), total production (TP, kg), and production increase (PI, %) were calculated using the following equations:

$$WD = \frac{(CIW_{W_m} - CIW) \times 100}{CIW_{W_m}} \qquad (23)$$

$$CYR = \frac{(CY_{W_m} - CY) \times 100}{CY_{W_m}} \qquad (24)$$

$$NIW = \frac{i_l\,(w)}{CIW} \qquad (25)$$

$$NIILL = \frac{\left(i_l\,(w)_{W_l} - i_l\,(w)_{W_m}\right)}{i_l\,(w)_{W_m}} \qquad (26)$$

$$NIIWL = \frac{\left(NIW_{W_w} - NIW_{W_m}\right)}{NIW_{W_m}} \qquad (27)$$

$$IL = \frac{CIW}{CIW_{W_m}} \qquad (28)$$

$$TP = IL \times CY \qquad (29)$$

$$PI = \frac{\left(TP - TP_{W_m}\right)}{TP_{W_m}} \qquad (30)$$

Results and Discussion

Table 1 shows total depth of the irrigation water applied by the different treatments by the line source sprinkler system. The number of irrigations was 9 in the 1999 growing season and 10 in the 2000 growing season. Each sprinkler irrigation event for I_1 treatment operated until ponding on the soil surface, and these application periods ranged between 3 and 4 h. A depth of water consumed weekly by red pepper was applied to the I_1 treatment of full irrigation. The other deficit irrigation treatments, I_2, I_3, I_4, and I_5, received less water than I_1 treatment and their water deficit levels were 13%, 32%, 60%, and 68%, respectively. The mean total depth of irrigation applied to treatments I_1 through I_5 ranged from 913 to 296 mm.

Analysis of variance showed that there were no differences between the pepper DYs obtained from the 1999 and 2000 growing seasons ($P < 0.05$). Average DYs for the irrigation treatments are given in Table 1. Irrigation treatments constituted 4 different groups of pepper DY. The highest DYs were obtained from treatments I_1 and I_2 (in order) and took place in the same statistical group. The lowest DYs were obtained from treatments I_4 and I_5 (in order), thought they were in different statistical groups. As a result, DY of pepper decreased as total water applied decreased. Red pepper DY reductions in treatments I_1, I_2, I_4, and I_5 were 18%, 24%, 47%, and 79%, respectively. Hence, DY may be the best indicator of the response of pepper plants to irrigation (Bernstein and Francois, 1973).

As seen in Figure 2, the quadratic production function was derived from the average total amount of applied water (mm) and DY (kg ha^{-1}). In the water production function, a_1, b_1 and c_1 were equal to -487.6, 3.49, and -0.0017, respectively.

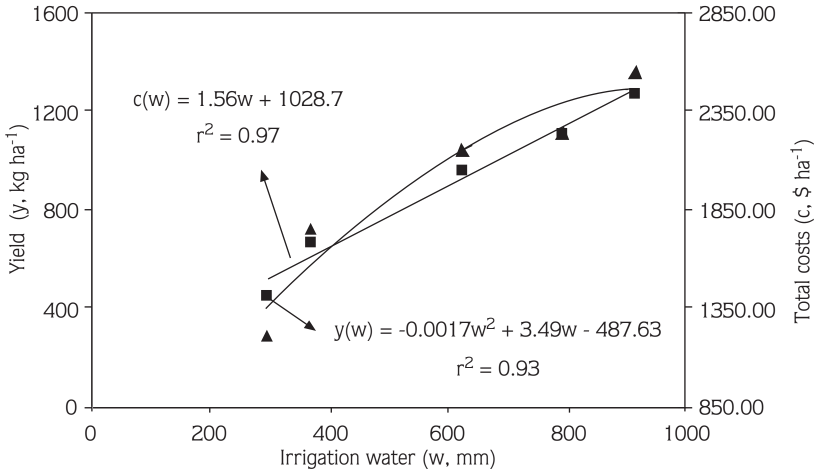

Figure 2. Water-yield and costs relationship of dry red pepper.

Total variable costs and total costs (total production costs) of dry red pepper, depending on the applied irrigation water, changed between 882 and 1923 $ ha^{-1}, and 1402 and 2443 $ ha^{-1}, respectively (Tables 1 and 2). Total fixed costs, not changing with the production, were 520 $ ha^{-1}. Variable and fixed costs were 79% and 21% of the total production costs. In dry red pepper production, the cost of renting a field was the highest value among both variable and fixed costs in Kahramanmaraş, accounting for 18%. This cost was followed by the cost of harvesting (16%), water and irrigation cost (14%), and the cost of hoeing (13%). Other costs were found to be less than 10%. Total cost was the highest with treatment I_1, which used the most irrigation water, and decreased with irrigation water declination. Total production cost changed depending on the quantity of irrigation water applied.

The dry red pepper linear cost function was established from applied irrigation and total costs, and was c(w) = 1.56w + 1028.7 (Figure 2). In this equation, production costs increased by about $156.00 with every 100 mm increase in irrigation water. However, in Turkey, the cost function may change from region to region because dry red pepper costs vary depending on input prices, production techniques, farmers' attitudes, and other variables.

Maximum irrigation water (W_m), economic optimum level of irrigation water for land-limiting (W_l) and water-limiting (W_w), and equivalent deficit level for land-limiting (W_{el}) and water-limiting (W_{ew}) were determined for red pepper DY (Table 3). W_m, W_l, W_w, W_{el}, and W_{ew} were calculated as 1026, 815, 752, 603, and 551 mm, respectively. As seen in Table 3, strategic irrigation water levels from maximum to economic optimum and equivalent deficit irrigation levels decreased.

The calculated maximum irrigation water (W_m) was higher than the amount of irrigation water applied to treatment I_1 (see Figure 2). If the applied irrigation water had reached the maximum level, the calculated maximum irrigation water (W_m) would have been close to the irrigation water amount applied to treatment I_1. The economic optimum level of applied water for land-limiting (W_l) and water-limiting (W_w) cases were 815 and 752 mm, respectively. W_l, with 21% deficit, was determined between I_1 and I_2, and W_w, with 27% deficit, was between I_2 and I_3 treatment levels. W_l for maximising the net income under the land-limiting case was 211 mm less water than W_m and, therefore, this amount of irrigation may not be recommended for sustainable use of water resources in areas where water is scarce. This study showed that the lower limit of the optimum level of applied water deficit would be about 27%. In the optimal water strategy condition, water deficit with 27% in the water-limiting case was larger than the land limiting case with a 21% deficit, and its average net income increase was 142% in total farm income. Hence, the W_w strategy requires less water with a 10% reduction in the calculated red pepper DY, and thus it is more suitable for areas with limited water supplies. For the water-limiting case, W_w, maximum net farm income would be realised by

Table 1. Irrigation water, red pepper dry yield, and variable cost for irrigation treatments (\$ ha^{-1}).

Irrigation treatments	I_1	I_2	I_3	I_4	I_5
Irrigation water (mm)	913	791	624	369	296
Dry yield (kg ha^{-1})**	1358a	1115ab	1037b	717c	284d
			Variable costs		
Ploughing	219.8	219.8	219.8	219.8	219.8
Fertiliser + labour	159.0	159.0	159.0	159.0	159.0
Seed + Sowing	97.5	97.5	97.5	97.5	97.5
Water + labour	336.0	290.8	229.4	135.7	108.8
Protection	25.3	25.3	25.3	25.3	25.3
Hoeing	317.9	275.2	217.1	128.4	102.9
Pesticide + labour	72.3	62.5	49.3	29.2	23.4
Harvesting	397.4	326.1	303.5	209.8	83.1
Drying	54.2	44.5	41.4	28.6	11.3
Transportation	36.1	29.7	27.6	19.1	7.6
Circulation capital interest	207.2	170.1	158.2	109.4	43.3
Total variable costs	1922.7	1700.5	1528.1	1161.7	882.0

**; values followed by the different letters are significantly different ($P < 0.01$) by LSD.

Table 2. Fixed and total costs, and red pepper dry yield income for irrigation treatments (\$ ha^{-1}).

Irrigation treatments	I_1	I_2	I_3	I_4	I_5
			Fix costs		
Field rent	433.5	433.5	433.5	433.5	433.5
Management	58.0	58.0	58.0	58.0	58.0
Irri. equipment amortisation	25.6	25.6	25.6	25.6	25.6
Irri. equipment interest	3.0	3.0	3.0	3.0	3.0
Total fix cost	520.2	520.2	520.2	520.2	520.2
Total cost	2442.9	2220.6	2048.3	1681.8	1402.1
Income	2943.6	2415.8	2247.8	1554.5	615.6
Net income	500.8	195.2	199.5	-127.7	-786.5

Average crop price of red pepper (Pc) was 2.17 \$ kg^{-1}

reducing applications from W_m to W_w. The resulting average application was 752 mm and 27% deficit (Table 3). At that point, net income per unit of water increased from 0.19 to 0.46 \$ m^{-3}. In land-limiting situations, the estimated optimal water deficit was 21% and calculated yield reduction was 6%. The gain in net income was 84% and net income per unit of water increased from 0.19 to 0.44 \$ m^{-3}.

The equivalent deficit level for W_{el} and W_{ew} were 603 and 551 mm of water. W_{el}, with 41%, was close to I_3 and W_{ew}, with 46% deficit, which took place between I_3 and I_4. Calculated yield reduction in W_{el} and W_{ew} levels were 23% and 29%, respectively. In terms of yield reduction, W_{el} and W_{ew} took place between I_2 and I_4 irrigation treatments. The result revealed that the lower limit of the equivalent deficit level of applied water was about 46%. Net income per unit of water in the equivalent deficit level for W_{el} and W_{ew} was 0.32 and 0.19 \$ m^{-3}, respectively. English and Raja (1996) evaluated deficit irrigation for wheat grown in Oregon, cotton in California, and maize in Zimbabwe. Deficit levels of W_l, W_w, W_{el}, and W_{ew} were calculated as 16%, 39%, 31%, and 62% for wheat, and 15%, 28%, 30%, and 48% for cotton, 15%, 59%, 30%, and 81% for maize. Deficit levels of this study ranged between 15% and 81%, whereas the same levels for our study ranged between 21% and 46%. Deficit levels of W_{el} for the 3 crops were greater than that of our study W_{el}. English (1990) determined alternative water levels (W_m, W_l, W_w, W_{el}, and W_{ew}) for winter wheat grown in the Columbia Basin and found water depths of W_m, W_l, W_w, W_{el}, and W_{ew} of 615, 416, 415, 218, and 281 mm, respectively. In the present study, there was a decreasing trend in the alternative water levels, except W_{el}. Gençoğlan et al. (2005) analysed deficit irrigation of cotton grown in the Harran Plain and found W_m, W_l, W_w, W_{el}, and W_{ew} to be 1475, 1263, 1010, 1052, and 692 mm, respectively. In that study, W_m determined from field application was greater than calculated W_m; in the present study, the values were reversed. Zhang and Oweis (1999) performed deficit irrigation analysis of wheat grown in northern Syria in consideration of rainfall and W_m, W_l, W_w, and W_{ew} were measured as 430, 336, 260 and 161 mm, when rainfall was 250 mm.

Net income calculated for all the alternative water levels (Table 3) and irrigation treatments (Table 2) were between 105 and 361 \$ ha^{-1}, and -787 and 501 \$ ha^{-1}, respectively. Net income obtained from treatment I_1, which received the most water, was the highest. The highest net income from per unit of land was calculated from W_l (Table 3) and treatment I_1 (Table 1). The net income in treatment I_1 was higher than that of W_l. The highest income (2944 \$ ha^{-1}) and net income (501 \$ ha^{-1}) were taken from treatment I_1. Moreover, the highest net income from per unit of water was achieved with W_w.

While W_m water level irrigated a 1.00 ha field, W_w and W_{ew} irrigated 1.36 and 1.86 ha fields, as shown in Table 4. As irrigation water is reduced, additional land can be brought into pepper production, increasing total pepper DY production. In other words, DY increases for W_w and W_{ew} were 23% and 31%.

Optimum and equivalent levels of irrigation water may change depending on production and cost functions, and crop price. The economic analysis showed that it was better to distribute the water resource over the entire farm, rather than to concentrate it to maximise yields on particular parts of the farm. For sustainable agricultural development, it is important to improve deficit irrigation management.

Table 3. Analysis of alternative levels of irrigation water, net income, and net income increase for red pepper dry yield.

WL	CIW (mm)	WD (%)	CY kg ha^{-1}	CYR (%)	i_l(w) \$ ha^{-1}	NIW \$ m^{-1}	NIILL (%)	NIIWL (%)
W_m	1026		1304		196	0.19062		
W_l	815	21	1227	6	361	0.44278	84	
W_w	752	27	1176	10	346	0.46043		142
W_{el}	603	41	999	23	196	0.32443		
W_{ew}	551	46	920	29	105	0.19062		

W_l: Water levels; CIW: Calculated irrigation water; WD: Water deficit; CY: Calculated yield determined from production function using CIW; CYR: Calculated yield reduction; i_l(w): Net income to land; NIW: Net income to water NIILL: Net income increase at land-limiting; NIIWL: Net income increase at water-limiting

Table 4. Alternative levels of calculated water, area, and red pepper dry yield.

WL	CIW mm	CY kg ha^{-1}	IL ha	TP kg	PI %
W_m	1026	1304	1.00	1304	
W_w	752	1176	1.36	1604	23
W_{ew}	551	920	1.86	1712	31

CIW: Calculated irrigation water; CY: Calculated yield; IL: Irrigated land
TP: Total production; PI: Production increase

Conclusions

The potential benefits of deficit irrigation appear to be significant for production of red pepper yield in Kahramanmaraş. When irrigable fields are abundant and water is scarce, the optimum water deficit strategy would be to irrigate by 27% deficit. If water supplies are not limited, the optimum water deficit strategy would be 21%. The equivalent deficit level for W_{el} was 41% and for W_{ew} it was 46%. At the W_{ew} level, the irrigated field was 1.86 times greater than at W_m level. Optimum and equivalent levels of irrigation water may change depending on production and costs functions, and crop price. The potential advantages of deficit irrigation appear to be quite significant, particularly in a water-limiting case. The economic analysis showed that it was better to distribute the water resource over the entire farm, rather than to concentrate it to maximise yields on particular parts of the farm; thus, in irrigation scheduling, all farmers benefit from water resources.

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