# Optimal water productivity of irrigation systems in a semi-arid region

**Montazar A., Nazari Far M.H., Mardi E.**

*in*

**Lamaddalena N. (ed.), Bogliotti C. (ed.), Todorovic M. (ed.), Scardigno A. (ed.).**
**Water saving in Mediterranean agriculture and future research needs [Vol. 3]**

**Bari : CIHEAM**
**Options Méditerranéennes : Série B. Etudes et Recherches; n. 56 Vol.III**

**2007**
pages 87-98

**To cite this article / Pour citer cet article**

Montazar A., Nazari Far M.H., Mardi E. **Optimal water productivity of irrigation systems in a semi-arid region.** In : Lamaddalena N. (ed.), Bogliotti C. (ed.), Todorovic M. (ed.), Scardigno A. (ed.). *Water saving in Mediterranean agriculture and future research needs [Vol. 3].* Bari : CIHEAM, 2007. p. 87-98 (Options Méditerranéennes : Série B. Etudes et Recherches; n. 56 Vol.III)

# OPTIMAL WATER PRODUCTIVITY OF IRRIGATION SYSTEMS IN A SEMI-ARID REGION

**A. Montazar*, M.H. Nazari Far**and E. Mardi****
*Irrigation & Drainage Engrg. Dept., University College of Aboureyhan,
**University of Tehran, P.O. Box 4117, Pakdasht, Iran

**SUMMARY** -Optimal water productivity can be achieved if crop type and plant density are optimized. This optimization will make it possible to plan and to make decisions regarding revision of and changes in cropping pattern over short periods in order to realize a demand-oriented water distribution system in irrigation networks. It is the objective of the present study to develop a non-linear model for determining optimal cropping pattern under different water regimes. The objective function of the model is the water productivity index defined as the net profit to the volume of water used. Using the data and information collected from Ghazvin irrigation network located in a semi-arid region in Iran, the developed model was executed and the results obtained were evaluated. The results show that among the crop types grown in the region, sunflower had the highest water productivity value while tomato had the lowest. These values under drought conditions for optimal cropping pattern of the two crops were estimated at 1778.96 and 353.22 Rials/m$^3$. The overall water productivity of the irrigation network with relevant cropping pattern management can rise to as high as 504.38 Rials/m$^3$ under drought conditions. This is while in normal and wetty years, depending on the water available and the optimal cropping pattern, the values for this index are estimated to be 535.352 and 667.13 Rials/m$^3$, respectively. Investigations show that under drought conditions, the water productivity of the irrigation network could be raised to as high as the value in normal years.

**Key words:** Cropping pattern, irrigation scheduling, water productivity, irrigation network, non-linear model

***RESUME -*** *La productivité optimale d'eau peut être atteinte si recadre la densité de type et plante est optimisée. Cette optimisation le fera possible de planifier et faire des décisions en ce qui concerne la révision de et les changements dans recadre le modèle par-dessus les périodes courtes afin de rendre compte un système de distribution d'eau demande-orienté dans les réseaux d'irrigation. C'est l'objectif de l'étude présente pour développer un modèle non linéaire pour déterminer optimal recadre le modèle sous les régimes d'eau différents. La fonction objective du modèle est l'index de productivité d'eau a défini comme le bénéfice net au volume d'eau utilisée. L'utilisation des données et l'information ont recueilli de Ghazvin le réseau d'irrigation a localisé dans une région à demi aridecontine dans Iran, le modèle développé a été exécuté et les résultats obtenus ont été évalués. Les résultats montrent que parmi les types de récolte grandis dans la région, le tournesol a eu la plus haute valeur de productivité d'eau pendant que la tomate a eu le plus bas. Ces valeurs sous les conditions de sécheresse pour optimal recadrent le modèle des deux récoltes a été estimé à 1778,96 et 353,22 Rials/m3. La productivité générale d'eau du réseau d'irrigation avec pertinent recadre la direction de modèle peut s'élever à aussi haut que 504,38 Rials/m3 sous les conditions de sécheresse. Ceci est pendant que dans normal et les années de wetty, dépendre de l'eau disponible et l'optimal recadre le modèle, les valeurs pour cet index sont estimées pour être 535,352 et 667,13 Rials/m3, respectivement. Les investigations montrent que sous les conditions de sécheresse, la productivité d'eau du réseau d'irrigation pourrait être élevée à aussi haut que la valeur dans les années normales.*

***Mots clés :*** *Recadrer le modèle, la planification d'irrigation, la productivité d'eau, le réseau d'irrigation, le modèle non linéaire*

## INTRODUCTION

Cropping pattern is one of the most important parameters involved in irrigation network design. It is directly related to productivity of irrigation systems and greatly contributes to improved soil and water utilization. In its initial design stages, the cropping pattern for each locality is developed on the basis of local and temporal considerations with due attention to major policies of the agriculture sector and then used as the basis for designing the physical structure of the irrigation works. Once in operation, the cropping pattern may undergo great changes in terms of crop type and crop density. The major causes for these changes may be summarized as follows:

- Changes in economic value of crops;
- Variations in quantity of supplied water over different water period;
- Changes in farm management practices;
- Rapid technological advances resulting in agricultural mechanization;
- Changes in major national/regional policies in the agriculture sector;
- Inadequacies and failures of irrigation network operational management

Appropriate and timely planning and decision-making for revisions and changes in cropping patterns over short periods (especially over drought periods) will enhance the system productivity and will additionally make it possible to exercise a demand-based water management with due consideration for impacts on water resources. Furthermore, optimal cropping pattern interacts with water consumption and crop yield, as well as with optimal profitability, and can, therefore, play an important role in improving irrigation network management through its impacts on increased income levels and water use efficiency.

Economic evaluation of irrigation management often requires the quantification of crop response to irrigation. Study of plant response to irrigation management practices has been going on for more than a century now and a great many recommendations and different relations have been proposed, along these lines, to investigate and determine irrigation water demand and plant response to different combinations of planting dates, quantities of resources, and decision-making criteria. Over the past two decades, different methodologies as well as simulation and optimization models have been developed for designing, planning, and operating water resources. A number of these models focus on water distribution optimization while others concentrate on economic optimization, and still others aim at both objectives simultaneously. An inadequacy in most of these models is their failure to capture the logical and practical relationship between the water quantity that can be supplied and the demand for water (Diaz & Brown, 1996). The simplest optimization model is one that allows for calculation of optimal water application depth for a single crop with the objective of maximizing the profit function regardless of any water limitation (Young, 1996). Some researchers have used analytical optimization methods in which changes in optimization conditions are possible for cases where limitations in land and water resources have to be considered (Yaron & Bresler, 1983; English, 1992). According to economic optimization models, cropping pattern is considered for water and land allocations among different crops at the farm or at the irrigation area levels.

Reca *et al.* (2001b) proposed an optimization model for the distribution of water in an irrigation network under dry conditions. The objective was to determine the maximum water use of single crops. Leenhart *et al.* (2004) proposed the ADEAUMIS model to estimate the water demand for water resources management on a regional scale and used it for a region in southern France. Benli & Kodal (2003) developed a non-linear optimization model for water distribution at the farm level with limited water resources in the southeast of the agricultural site in Anatolia, Turkey. They compared the results obtained from the model with those from a non-linear model to show that the non-linear optimization yielded better results than the linear one did. Many software packages have also been developed as a result of studies of irrigation water supply and demand. SIMIS, OPDM, and WEAP are among these models. Mainuddin et al (1997), Raju & Kumar (1999), Amir & Fisher (1999), Singh et al (2001), Kipkorir et al (2002), Ghahraman & Sepaskhah (2004), and Li *et al.* (2005) used both linear and non-linear optimization techniques in their studies of optimal cropping pattern to maximize net profit from farms.

Carvallo *et al.* (1998) have developed a non-linear optimization problem for the determination of optimal cropping patterns. They have used GAMS-MINOS software package to solve the problem. Kuo *et al.* (2000) proposed a genetic algorithm optimization model for the optimal cropping patterm in an irrigation scheme. Sabu and Sudhindra (2000) proposed a model based on both stochastic dynamic programming and deterministic dynamic programming for the optimal cropping pattern in a canal command area.

The objective of the present paper is to develop and execute a non-linear optimization model to determine the optimal cropping pattern under different water periods for a real irrigation network. For this purpose, the water productivity index defined as net profit to volume of water used is taken to be the objective function of the model and optimization is accomplished to maximize this index.

## MATERIALS AND METHODS

### *Water demand and crop performance*

In developing the model, crop response to actual evapotranspiration function was used as proposed by Stewart et al (1977). This is one of the most practical relations used in the field and confirmed by FAO, which is also used by other researchers including Doorenbos & Kassam (1979), De Juan et al (1996), and Reca et al (2001a). The relation is expressed as follows for a single crop:

$$\frac{Y_a}{Y_p} = \prod_{i=1}^{m} \left[ 1 - k_{yi} \left( 1 - \frac{ET_{ai}}{ET_{pi}} \right) \right] \tag{1}$$

Where, $Y_a$ designates actual crop yield; $Y_p$, potential crop yield; $K_{yi}$, crop response coefficient to underirrigation; and $ET_{ai}$ is actual evapotranspiration at growth stage *i*. The above relation will be used in this study for computations in a model. Substitution of the ratio of water used to potential water demand ($W_a/W_p$) for $ET_a/ET_p$ in Eq. (1) will yield:

$$\frac{Y_a}{Y_p} = \prod_{i=1}^{m} \left[ 1 - k_{yi} \left( 1 - \frac{W_{ai}}{W_{pi}} \right) \right] \tag{2}$$

The objective function for a single crop of the planting pattern can be expressed in terms of the difference between potential and actual performances of that crop (Eq. 3). In this equation, $Z$ is the objective function and $y_{pi}$ and $y_{ai}$ are the potential and actual performance values at the growth stage *i*, respectively. Minimizing the value for this objective function will determine the optimal irrigation depth at every growth stage as well as the total irrigation depth of the crop under all water regimes. Optimization of the function was accomplished using Ms Excell Solver.

$$Min(Z) = Min \left( \sum_{i=1}^{m} \frac{1}{y_{pi}} (y_{pi} - y_{ai})^2 \right) \tag{3}$$

Limitation functions can be simply represented as below. $W_T$ designates total depth of water available from both surface and underground resources.

$$\sum_{i=1}^{m} W_{ai} \leq W_T \qquad , \qquad \sum_{i=1}^{m} W_{ai} \leq \sum_{i=1}^{m} W_{pi} \tag{4}$$

De Wit method (1958) was used to compute potential crop yields, employing radiation data along with corrections for the climate and for the crop. Potential evapotranspiration for each growth stage was determined using Penman-FAO method as explained in Doorenbos & Pruitt (1977) with relevant crop coefficients effected.

The net irrigation requirement of crops was calculated individually as follows:

$$I_n = ET_a - (P_e + W_s) \tag{5}$$

Where $I_n$ is the net irrigation requirement of crop, $P_e$ the effective rainfall, and $W_s$ the stored soil water. The effective rainfall was taken as rainfall at 50% cumulative probability (Singh, 1996). It was assumed that there is no change in the value of stored soil water before and after the crop cultivation.

Reca *et al.* (2001b) expressed that the deficit coefficient (The ratio of the deficit irrigation depth to the required irrigation depth) is related to the evapotranspiration deficit. Other hand, the relationship between this coefficient and the gross irrigation depth depends on the type of irrigation water distribution and on irrigation uniformity. This relationship can be found either by means of field irrigation evaluations, or by the use of simulation models. Here, it is assumed the normal distribution function.

### Optimization of the water productivity

We used the objective function of the productivity ratio of net profit to volume of water used in the irrigation network as expressed below in order to determine the optimal planting pattern.

$$WP = (B/Vol)_S = \left( \frac{\sum_{j=1}^{k} B_j . A_j}{\sum_{j=1}^{k} A_j . D_{gj}} \right) \tag{6}$$

Where, *(B/Vol)s* is the ratio of net profit to volume of water used in the system (*WP*); $B_j$ is the net profit resulting from growing crop *j*; $A_s$, the cultivated area for crop *j*; $D_{gj}$, gross optimal irrigation depth for crop *j*; and *k* is the crop number in the planting pattern. Net profit from each crop is obtained from the following relation:

$$B_j = (B_m + B_l)_j - (C_l + C_p)_j \tag{7}$$

Where, $B_m$ and $B_l$ are profits from the main crop *m* and from the secondary crop *j*, respectively; and $C_l$ and $C_m$ are, respectively, labor costs and all other associated costs including land, irrigation, planting, growing, and harvesting costs. Irrigation and labor costs are functions of the water used and number of irrigation times. The relation obtained in this study between net profit and net irrigation depth is nonlinear and of second order.

In order to maximize the above objective function (Equation 6), the following limit functions had to be taken into account:

$$\sum_{j=1}^{m} A_j \le A_T , \qquad A_j \ge 0 \quad , \qquad A_{Min(j)} \le A_j \le A_{Max(j)} \tag{8}$$

$$\sum_{j=1}^{m} W_j . A_j \le W_T . A_T \tag{9}$$

$$D_{Ming(j)} \le D_{gj} \le D_{Maxg(j)} \tag{10}$$

In the above relations, $A_j$ designates cultivated area for crop *j*; $A_T$, total cultivated area irrigated by the network; $A_{Min(j)}$ and $A_{Max(j)}$ are minimum and maximum possible cultivable area for crop *j*, respectively; and $D_{Maxg(j)}$ and $D_{Ming(j)}$ are maximum and minimum possible water application depths allocated to crop *j*, respectively.

## Study area

The model developed in this study was executed for the irrigation network located in Ghazvin plain in the northwest of Iran (Fig. 1). Annual precipitation and evaporation in the region are 312 and 1345 mm, respectively, and the average annual temperature is 13.2º C. The network covers an area of 57,000 hectares and its water is supplied from Taleghan Dam and 102 integrated wells scattered along the network area. The main channel has a design capacity of 30 *l/s*. The volume of water supplied from the integrated wells across the network is equal to 18 million cubic meters. Thanks to the considerable amount of water available, around 73% of the land along the network is annually allocated to crops while the remaining 23% is allocated to orchards or left on fallow. The crops of the cropping pattern in the region often include: wheat, barley, pear, corn, sugar beet, alfaalfa, sunflower, cucumber, onion, potato, tomato, bean, and lentil. The irrigation systems commonly used across the network are of the furrow and border types. The overall transmission and application efficiency of the irrigation network is estimated at 64%.

Fig. 1. The study area

*Table 1* presents typical characteristics of the crops of the cropping pattern practiced in the region. Winter crops include wheat (planting date 10 Oct. and harvest time 7 June) and barley (planting date 10 Oct. and harvest time 27 May); and summer crops include pear (planting date 1 April and harvest time 20 July), corn (planting date 20 July and harvest time 2 September), sugar beet (planting date 1 April and harvest time 10 Agust), alfaalfa (planting date 1 March and harvest time 12 Oct.), sunflower (planting date 1 April and harvest time 9 August), cucumber (planting date 1 April and harvest time 9 August), onion (planting date 1 April and harvest time 9 August), potato (planting date 1 April and harvest time 9 August), tomato (planting date 1 April and harvest time 24 May), dry bean (planting date 1 April and harvest time 20 July), and lentil (planting date 1 April and harvest time 20 July). Based on the water distribution system by the network, the irrigation cycle is taken to be a fixed cycle of every 10 days. The potential evapotranspiration for the various growth stages was computed using the Penman-FAO method as explained in Doorenbos & Pruitt (1977). The values for the crop response coefficients to underirrigation were also estimated from the values proposed in Doorenbos & Pruitt (1979) with regional corrections effected. The values for the period of each growth stage and maximum root depths were selected on the basis of field observations. Also relative crop areas under cultivation were determined from the minimum and maximum percentages of observed cultivated areas in the region.

Table 1. Characteristics of the crops

| | Parameter | Wheat | Barley | Pear | Lentil | Corn | Sun flower | Sugar beet | Cucumber | Onion | Potato | Tomato | Alfa alfa | Bean |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ETp (mm) | 519.3 | 519.3 | 593.56 | 593.56 | 767.09 | 703.05 | 953.19 | 692.42 | 772.87 | 772.87 | 879.81 | 1105.53 | 593.56 |
| **Establishment** | $K_y$ | 0.07 | 0.1 | 0.2 | 0.07 | 0.12 | 0.25 | 0.12 | 0.2 | 0.15 | 0.45 | 0.12 | 0.3 | 0.07 |
| **Vegetative** | | 0.13 | 0.1 | 0.33 | 0.13 | 0.28 | 0.5 | 2 | 0.42 | 0.3 | 0.8 | 0.28 | 0.7 | 0.13 |
| **Flowering** | | 0.6 | 0.6 | 0.9 | 1.1 | 1.5 | 1 | 1.3 | 1.1 | 1 | 1 | 1.1 | 1.35 | 1.1 |
| **Yield formation** | | 0.5 | 0.5 | 0.7 | 0.75 | 0.5 | 0.8 | 0.36 | 0.45 | 0.8 | 0.7 | 0.8 | 1.2 | 0.75 |
| **Ripening** | | 0.1 | 0.1 | 0.2 | 0.2 | 0.2 | 0.33 | 0.12 | 0.6 | 0.3 | 0.2 | 0.4 | 0.6 | 0.2 |
| **Maximum root depth (m)** | Drz | 0.96 | 1 | 0.6 | .9 | 1.2 | 1.8 | 1.05 | 1.2 | 0.6 | 0.6 | 1.8 | 1.8 | 0.9 |
| **Gross benefit (Rls/ha × $10^{-3}$)** | | 671.71[a] | 543.24 | 3283.63 | 2002. | 1490.33 | 4130.3 | 1211 | 524.7 | 1217.7 | 833.1 | 825.9 | 1956.33 | 2518.85 |
| **Production cost (Rls/ha × $10^{-3}$)** | | 37.48 | 31.93 | 64.71 | 24.88 | 56.1 | 52.12 | 79.08 | 109.9 | 125.92 | 125.6 | 168.15 | 102.9 | 64.62 |
| **Relative cultivated area (%)** | | 45-60 | 6.5-10 | 1.8-3 | 0.18-0.3 | 2.45-3.5 | 0.12-0.15 | 2.8-3.8 | 1.5-2 | 0.04-.1 | 0.25-0.45 | 2.5-3.7 | 7-11 | 1.4-2 |

[a] 850 Rls = 1 US dollar

## RESULTS AND DISCUSSION

### Total water availability

In order to investigate the conditions of the water resources in the study area, 30-year (1975-2005) statistics of the meteorological stations in the region were used and the volume of water available for planning and harvestable for irrigation from surface water resources over both wet and dry years were computed using the statistical data available for normal water regimes in the network (*Table 2*). As already mentioned, the volume of the water from integrated wells in the region and available for irrigation planning is estimated to be 1800 ha.m assuming a constant annual discharge rate from groundwater resources for the water regimes under study and over different months of the year. The results from investigations show that in dry years, the available water across the irrigation network will reduce by 63% and 46%, respectively, for wet years and normal years in the region; a finding that must be taken into account in selecting the planting pattern.

Table 2. Values of the volume of water available from surface water resources for different water periods

| **Total available water (ha.m)** | **Wetty** | **Normal** | **Drought** |
|---|---|---|---|
| | 56941 | 38797 | 20653 |

Fig. 2 represents fluctuations in the quantity of water in the network available from surface resources over different months of the year for the regimes studied. The highest quantity of water available and usable belonged to May and June, which were 9053 and 252 ha.m for wetty and drought conditions, respectively.

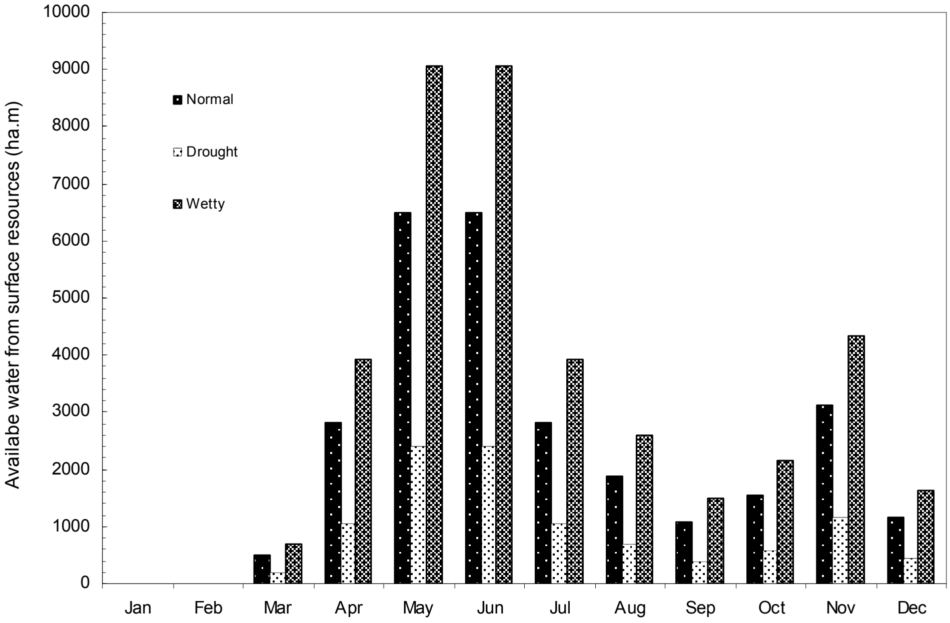

Fig. 2. Volume of monthly water available from surface resources

### Crop water-benefit functions

Based on the volume of water available (from both surface and ground water resources), the values for net water application depths for each crop in the cropping pattern over each of the three water periods were obtained from Eq. (3) with the limiting functions duly taken into account (Eq. 4). Fluctuations in the performance of different crops in the cropping pattern were computed for each water application depth using Eq. (2); the variation curve for these two parameters is given in

Table (3). In these equations, the net water application depth (*Wa*) is expressed in *mm* and the actual crop yield (*Ya*) is given in *kg/ha*.

The curve showing net profit variations against net irrigation water was plotted based on values determined for all the terms in Eq. (7) and on the assumption that the relationship between net profits and net irrigation water was a non-linear one. The results for each crop are also presented in *Table 3*. In these equations, water application depth (*Wa*) is expressed in *mm* and the net profit or income is expressed in $Rls/ha \times 10^{-3}$. Examination of these relationships reveals that from among the crops in the cropping pattern for the region, sunflower has the highest value of productivity defined as net profit to water application depth (*WP*) while tomato has the lowest value for the same index. This finding must be taken into account when selecting optimized cropping pattern for the region.

## Optimal cropping pattern

In order to maximize the overall productivity index defined as net profit to water use in the network, Eq. (6) was solved taking account of Eq. (7) and the limiting functions (8), (9), and (10) using Ms Excell Solver. The results from optimization of the cropping pattern are presented in *Table 4*. This figure also shows the values for the optimal cultivated area for each of the crops in the cropping pattern under each of the water regimes.

Table 3. Relationship between actual crop yield($Y_a$)-net profit (B)and *Wa* for the crops of the cropping pattern

| Crop | Relationship |
|---|---|
| Wheat | $Y_a=0.0001W_a^2+8.217\ W_a+12.5$<br>$B = -0.00002W_a^2 + 8.302W_a - 2$ |
| Barley | $Y_a=0.00002W_a^2+8.302\ W_a-2$<br>$B = -0.0037\ W_a^2 + 3.2722\ W_a^2 – 8$ |
| Corn | $Y_a=0.0071W_a^2+7.66\ W_a-39.3$<br>$B = 0.0005\ W_a^2 + 1.9307\ W_a^2 + 40$ |
| Pear | $Y_a=0.0036W_a^2+6.807\ W_a-53.01$<br>$B = 0.0006\ W_a^2 + 5.8555\ W_a^2x - 7.87$ |
| Lentil | $Y_a=0.0034W_a^2+5.554\ W_a+7.65$<br>$B = 0.0007\ W_a^2 + 3.9563\ W_a^2- 10.13$ |
| Sun flower | $Y_a=-0.0007W_a^2+6.447\ W_a+12.11$<br>$B = -0.0014\ W_a^2 + 8.1371\ W_a^2 + 63.42$ |
| Sugar beet | $Y_a=0.0009W_a^2+5.475\ W_a+1.2$<br>$B = -0.0004\ W_a^2 + 0.7269\ W_a^2 + 14.16$ |
| Cucumber | $Y_a=-0.001W_a^2+8.511\ W_a+56.7$<br>$B = -0.001\ W_a^2 + 1.483\ W_a^2 + 57.52$ |
| Potato | $Y_a=0.0015W_a^2+7.333\ W_a-27.23$<br>$B = -0.0006\ W_a^2 + 1.7295\ W_a^2 - 21.35$ |
| Onion | $Y_a=0.0025W_a^2+12.71\ W_a-21.23$<br>$B = -0.0005\ W_a^2 + 2.2279\ W_a^2 - 7.145$ |
| Tomato | $Y_a=0.0005W_a^2+5.506\ W_a-11.6$<br>$B = -0.0008\ W_a^2 + 1.827\ W_a^2 - 0.04$ |
| Alfaalfa | $Y_a=0.0023W_a^2+5.833\ W_a-68$<br>$B = 0.0002\ W_a^2 + 1.2652\ W_a^2 + 66$ |
| Bean | $Y_a= 0.0062W_a^2+ 2.839W_a+651.5$<br>$B = 0.0002\ W_a^2 + 5.2702\ W_a^2 - 8.3$ |

Table 4. Optimal cropping pattern under different water regimes

| **Crop** | **Area(ha)** | | |
|---|---|---|---|
| | **Drought** | **Normal** | **Wetty** |
| Wheat | 17208.5 | 17208.5 | 19436.2 |
| Barley | 2407.95 | 2407.95 | 2807.45 |
| Corn | 1081.47 | 1263.72 | 1263.72 |
| Pear | 926.977 | 1083.19 | 1083.19 |
| Lentil | 66.68 | 66.68 | 77.74 |
| Sun flower | 46.35 | 55.57 | 55.57 |
| Sugar beet | 1037.27 | 1037.27 | 1209.36 |
| Cucumber | 555.68 | 555.681 | 647.87 |
| Potato | 92.61 | 92.61 | 107.98 |
| Onion | 30.89 | 37.04 | 37.04 |
| Tomato | 1143.27 | 1370.68 | 1370.68 |
| Alfaalfa | 3398.92 | 4074.99 | 4074.99 |
| Bean | 588.94 | 588.94 | 604.68 |

The results show that the greatest cultivated areas belonged to wheat which were 17208.5 and 19436.2 hectares for wet and dry years, respectively. Our calculations indicate that reducing the cultivated area for wheat under drought conditions will yield a productivity value, $(B/Vol)_{wheat}$, of 517.7 $Rls/m^3$ which shows a reduction of 126.7$Rls/m^3$ as compared to the same index for wet years (744.4 $Rls/m^3$). The lowest values for the index was obtained for tomato which were estimated to be 353.22 and 352.77 $Rls/m^3$ for drought and wet years, respectively. Alfaalfa stood second to wheat in terms of area under cultivation (676 ha), wheat having the highest cultivated area in the region for each of the water regimes and, hence, its variations of percentage of cultivated area were very different from those of other crops in both wet and dry years.

### Evaluation of irrigation network productivity

Using the values for the cultivated areas for the crops in the cropping pattern and the values for the water used for each of the crops, we computed the productivity for each crop under the different water regimes under study. The results are presented in Fig. 4. Examination of the results shows that under drought conditions, the crop sun flower with 1778.96 $Rls/m^3$ has the highest value while alfaalfa with 356.26 $Rls/m^3$ has the lowest value of productivity defined as profit to water used. Under wet years, these ranks belong to the crops sun flower (1987$Rls/m^3$) and tomato (352.77 $Rls/m^3$), respectively.

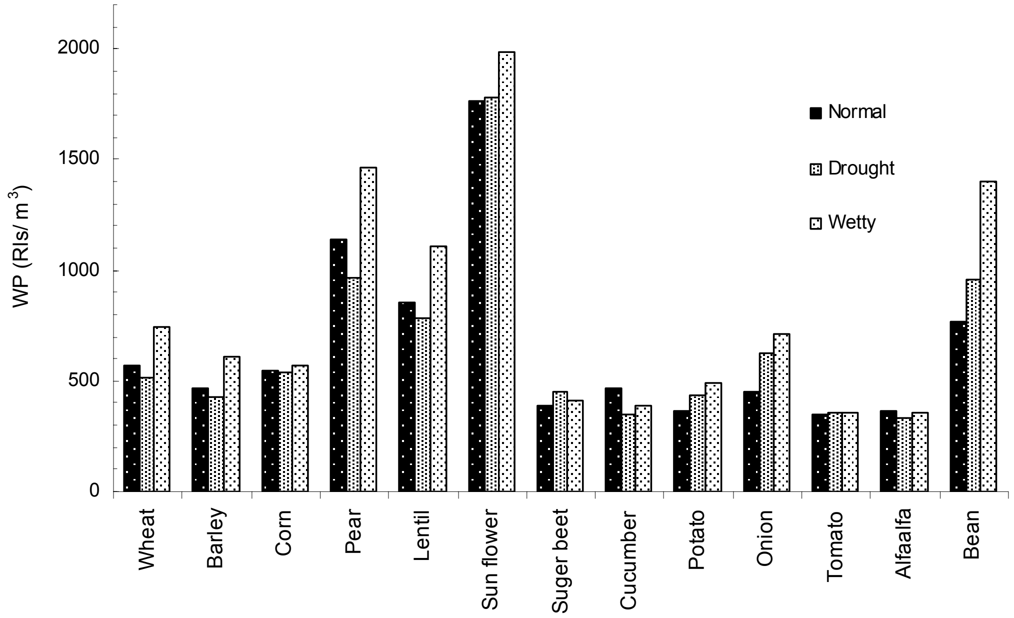

Fig. 4. Comparison of crop productivity according to optimal cropping pattern under differentl water regimes

The values for the overall irrigation network productivity (*(B/Vol)s*) for the optimal planting pattern and under different water regimes considered in this study are compared with those of the current planting pattern in Fig. 5. As seen in this figure, the value for the overall irrigation network productivity under planting management can rise to as high as 504.38 *Rls/m*$^3$ for drought conditions. This is while under normal and wet years and when the optimal planting pattern is put into practice, the values for this index are estimated to be as high as 535.35 and 667.13 *Rls/m*$^3$. In other words, under drought conditions and with the optimal planting pattern in practice and with appropriate deficit irrigation, the network productivity can be raised.

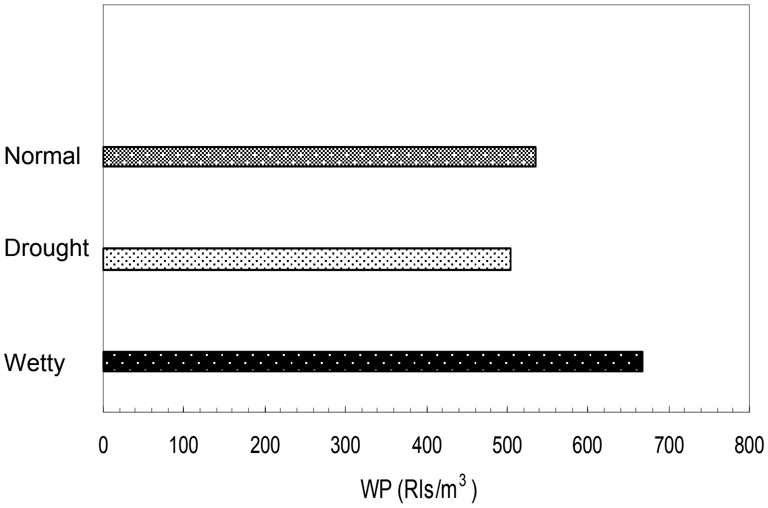

Fig. 5. Comparison of overall irrigation network productivity based on optimal cropping pattern under different water regimes

## CONCLUSIONS

Cropping pattern is one of the most important design and implementation parameters in irrigation network management that is in direct relationship with water use efficiency and optimal utilization of soil and water resources. In the present study, a nonlinear model was developed which involved an objective function of productivity defined as net profit to volume of water used. Using the model proposed, the optimal crop planting pattern developed for the Ghazvin Irrigation Network under different water regimes of wet, drought, and normal years was compared with the current planting pattern employed on the ground. The results show that the highest cultivated areas belong to wheat crop with 17208.5 and 19436.2 ha for dry and wet years, respectively. When the cultivated area for this crop is reduced under drought conditions, the productivity for this crop will be 517.7 $Rls/m^3$, which shows a reduction of 126.7$Rls/m^3$ as compared to the value for this index in wet years. The lowest values for the productivity studied belonged to the tomato, which were estimated at 353.22 and 352.77 $Rls/m^3$ for drought and wet years, respectively. The analysis of the results indicates that under drought conditions, the overall network productivity under planting management could be increased to as high as 504.38 $Rls/m^3$. This is while under normal and wet years, and if optimal planting pattern is practiced, the values for this index will be 535.35 and 667.13 $Rls/m^3$, respectively. This means that under drought conditions and under an optimal cropping pattern, the productivity value could be raised to as high as the value for the same index in normal years and that the economic value of a unit of water could be thus improved. The findings from this study lay emphasis greater than ever on the need for application of optimization models to determine optimal planting pattern and optimal water distribution systems in accordance with the potentials of existing water resources, on the one hand, and on the important role played by an appropriate cropping pattern in improving irrigation network efficiency and performance.

### Acknowledgements

This paper was prepared by financial support from University of Tehran under Research Grant No. 7305002/1/01. The authors would like to express their gratitude to the Vice-president for Research, University College of Aboureyhan, University of Tehran.

## REFERENCES

Amir, I., Fisher, F.M. (1999). Analyzing agricultural demand for water with an optimizing model. Agric. Syst. 61, 45-56.

Carvallo, H.O., Holzapfel, E.A., Lopez, M.A., Marino, M.A. (1998). Irrigated cropping optimization. J. Irrig. Drain. Eng. 124 (2), 67-72.

De Juan, J.A., Tarjuelo, J.M., Valiente, M., Garcia, P. (1996). Model for optimal cropping patterns within the farm based on crop water production functions and irrigation uniformity. I. Development of a decision model. Agric. Water Manag., 31, 115-143.

De Wit, C.T. (1958). Transpiration and crop yields. Modelling Nr. 59. Institute voor Biologisch en Scheikundig Onderzoek van landbouwegwassen, Wageningen.

Diaz, G.E., Brown, T.C. (1996). Aquarius: an object-oriented model for the efficient allocation of water in river basins. Technical report no. 7. Colorado State University.

Doorenbos, J., Pruitt, W.O. (1977). Crop water requirement, FAO irrigation and drainage, paper 24., FAO, Rome, p.144.

Doorenbos, J., Kassam, A.H. (1979). Yield response to water. Irrigation and Drainage Paper No. 33, FAO, Rome, 193 pp.

English, M.J. (1992). Deficit irrigation. I. Analytical framework. J. Irrig. Drain. Eng. 116 (3), 399-412.

Ghahraman, B., Sepaskhah A.R. (2004). Linear and non-linear optimization models for allocation of a limited water supply. J. of Irrig. Drain. 53: 39-54.

Kipkorir, E.C., Sahli, A., Raes, D. (2002). Mois: a decision tool for determination of optimal irrigated cropping pattern of a multicrop system under water scarcity conditions. J. of Irrig. Drain. 51: 155-166.

Kuo, S.F., Merkley, G.P., Liu, C.W. (2000). Decision support for irrigation project planning using a genetic algorithm. Agri. Water Manage. 45: 243-266.

Leenhardt, D., Trouvat, J.L., Gonzales, G., Perarnaud, V., Prats, S., Bergez, J.E. (2004). Estimation irrigation demand for water management on a regional scale. I. ADEAUMIS, a simulation platfirm based on bio-decisional modeling and spatial information. Agric. Water Manag. , 68, 207-232.

Li, Q.S., Willardson, L.S., Deng, W., Li., X.J., Liu, C.J. (2005). Crop water deficit estimation and irrigation schedualing in western Jilin province, Northeast China. Agric. Water Manag. , 71, 47-60.

Mainuddin, M., Das Gupta, A., Raj Onta, P. (1997). Optimal crop planning model an existing groundwater irrigation project in Thailand. Agric. Water Manage. 33, 43-62.

Raju, K.S., Kumar, D.N. (1999). Multicriterion decision making in irrigation planning. Agric. Syst. 62, 117-129.

Reca, J., Roldan, J., Alcaide, Mi., Lopez R., Camacho, E. (2001a). Optimisation model for water allocation in deficite irrigation systems. I. Description of the model., Agric. Water Manag., 48, 103-116.

Reca, J., Roldan, J., Alcaide, Mi., Lopez R., Camacho, E. (2001b). Optimisation model for water allocation in deficite irrigation systems. II. Application to the Bembezar irrigation system. Agric. Water Manag., 48, 103-116.

Sabu, P., Sudhindra, N.P. (2000). Optimal irrigation allocation: a multilevel approach. J. Irrig. Drain. Eng. 126 (3): 149-156

Singh, D.K., Jaiswal C.S., Reddy, K.S., Singh, R.M., Bhandarkar, D.M. (2001). Optimal cropping pattern in a command area of Shahi distributory. Agric. Water Manage., 50, 1-8.

Stewart,J.I., Hagan, R.M. (1973). Function to predict effects of crop water deficits. J. Irrig. Drain. 99, 421-439.

Yaron, D., Bresler, E. (1983). Economic analysis of on-farm irrigation using response functions of crops. In: Hillel, D.(Ed.), Advances in Irrigation, Vol. 2, academic Press, New york, pp. 223-255.

Young, J. (1996). Water economics. In: Mays, L.W.(Ed.), Water Resources Handbook. MacGraw-Hill, New York.

Zwart, S.J., Bastiaanssen, W.G.M. (2004). Review of measured crop water productivity values for irrigated wheat, rice, cotton and maiz. Agric. Water Manag., 69;115-133.