IRRIGATION AND DRAINAGE
Irrig. and Drain. **57**: 411–423 (2008)

OPTIMAL WATER PRODUCTIVITY OF IRRIGATION NETWORKS IN ARID AND SEMI-ARID REGIONS[†]

ALIASGHAR MONTAZAR* AND ALI RAHIMIKOB
Irrigation and Drainage Engineering Department, College of Aboreyhan, University of Tehran, Pakdasht, Iran

ABSTRACT

The aim of this paper is develop a nonlinear optimisation model for the determination of the optimised water allocation and cropping pattern under adequate and limited water supplies. The water productivity index defined as the net profit to the volume of water used was considered as the objective function. The proposed model was executed for the Ghazvin Irrigation Network located in a semi-arid region in Iran. The results showed that among the crop types grown in the region, onion and alfalfa have the highest and lowest water productivity value, respectively. These values under drought conditions for the optimal cropping pattern of the two crops were estimated at 75 068.86 and 3054.18 Rls m^{-3}. The findings indicated that the overall water productivity of the irrigation network with relevant cropping pattern management might be raised to as high as 12 700 Rls m^{-3} under drought conditions. In normal and wet years, depending on the water available and the optimal cropping pattern, the values for this index were estimated to be 15 600 and 12 900 Rls m^{-3}, respectively. For the existing cropping pattern, overall irrigation network productivity is estimated at 10 600 Rls m^{-3}. Hence, the results demonstrated that the water productivity of an irrigation network could be improved as result of the optimal cropping pattern and deficit irrigation. For the study area, the maximum variations of this index may be fixed around 18% for different water regimes. The evaluations emphasise the important role of optimisation models in improving irrigation network efficiency and managing water in a sustainable manner. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: cropping pattern; irrigation scheduling; water productivity; irrigation network; optimisation model

Received 10 March 2007; Revised 28 October 2007; Accepted 30 October 2007

RÉSUMÉ

Le but de cet article est de développer un modèle d'optimisation non linéaire pour la détermination de l'allocation d'eau et de l'assolement optimaux dans des conditions d'approvisionnement en eau correctes ou limitées. L'index de productivité de l'eau, défini comme le bénéfice net rapporté au volume d'eau utilisé, a été considéré comme la fonction objectif. Le modèle proposé a été utilisé pour le réseau d'irrigation de Ghazvin situé dans une région semi-aride en Iran. Les résultats montrent que parmi les types de cultures développés dans la région, l'oignon et la luzerne ont respectivement la valeur la plus élevée et la plus basse de productivité de l'eau. Ces valeurs, en condition de sécheresse avec un assolement optimal pour les deux cultures, ont été estimées à 75 068.86 et 3054.18 Rls m^{-3}. Les résultats montrent que la productivité globale de l'eau du réseau d'irrigation avec un assolement optimisé en condition de sécheresse peut être augmentée jusqu'à 12 664.94 Rls m^{-3}. Pour les années normales et humides, selon la disponibilité de l'eau et l'assolement, les valeurs de cet index sont respectivement de 15 592.24 et 12 881.16 Rls m^{-3}. Pour l'assolement existant, la productivité globale du réseau d'irrigation est estimée à 10 553.42 Rls m^{-3}. Par conséquent, les résultats ont démontré que la productivité de l'eau du réseau

---

* Correspondence to: Aliasghar Montazar, Irrigation and Drainage Engineering Department, College of Aboreyhan, University of Tehran, P.O. Box 4117, Pakdasht, Iran. E-mail: almontaz@ut.ac.ir

[†] Productivité optimale de l'eau des réseaux d'irrigation dans des régions arides et semi-arides.

d'irrigation peut être améliorée par une optimisation de l'assolement et une irrigation limitante. Pour le secteur étudié, les variations maximales de cet index se situent autour 18% pour différents régimes d'irrigation. Ces estimations montrent le rôle important des modèles d'optimisation dans l'amélioration de l'efficacité de réseaux d'irrigation et la gestion durable de l'eau. Copyright © 2008 John Wiley & Sons, Ltd.

MOTS CLÉS: assolement; pilotage de l'irrigation; productivité de l'eau; réseau d'irrigation; modèle d'optimisation

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 utilisation. 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 agricultural 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 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 periods;
- changes in farm management practices;
- rapid technological advances resulting in agricultural mechanisation;
- changes in major national/regional policies in the agricultural 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, an 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. An analytical framework and associated terms were proposed to better serve the needs of technical specialists from all water-using sectors, policy-makers and planners in achieving more productive use of water and tracing the implications of interventions on all uses and users (Perry, 2007).

Over the past two decades, different methodologies as well as simulation and optimisation models have been developed for designing, planning, and operating water resources. A number of these models focus on water distribution optimisation while others concentrate on economic optimisation, 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 and Brown, 1996). The simplest optimisation model is one that allows for calculation of optimal water application depth for a single crop with the objective of maximising the profit function regardless of any water limitation (Young, 1996). Some researchers have used analytical optimisation methods in which changes in optimisation conditions are possible for cases where limitations in land and water resources have to be considered (Yaron and Bresler, 1983; English, 1992). According to economic optimisation models, cropping pattern is considered for water and land allocations among different crops at the farm or at the irrigation area levels.

Carvallo *et al*. (1998) have developed a nonlinear optimisation problem for the determination of optimal cropping patterns. They have used the GAMS-MINOS software package to solve the problem. Kuo *et al*. (2000) proposed a genetic algorithm optimisation model for the optimal cropping pattern in an irrigation scheme. Sabu and

Sudhindra (2000) proposed a model based on both stochastic and deterministic dynamic programming for the optimal cropping pattern in a canal command area.

Reca *et al*. (2001b) proposed an optimisation 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 and Kodal (2003) developed a nonlinear optimisation model for water distribution at the farm level with limited water resources in the south-east of the agricultural site in Anatolia, Turkey. They compared the results obtained from the model with those from a nonlinear model to show that the nonlinear optimisation yielded better results than the linear one. 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), Amir and Fisher (1999), Singh *et al*. (2001), Kipkorir *et al*. (2002), Ghahraman and Sepaskhah (2004) and Li *et al*. (2005) used both linear and nonlinear optimisation techniques in their studies of optimal cropping pattern to maximise net profit from farms.

The purpose of the present paper is to develop and execute a simple optimisation model to determine the optimal cropping pattern under adequate and limited water supplies for a real irrigation network. The water productivity index defined as net profit to volume of water used is taken to be the objective function of the model. A standard piece of common software called Ms Excel Solver has been used in order to solve the objective functions.

MATERIALS AND METHODS

Theory

In developing the model, crop response to actual evapotranspiration function was used as proposed by Stewart and Hagan (1973). This is one of the most practical relations used in the field and confirmed by the FAO, which is also used by other researchers including Doorenbos and Kassam (1979), De Juan *et al*. (1996), and Reca *et al*. (2001a). The relation is expressed as follows for a single crop:

$$\frac{Y_\mathrm{a}}{Y_\mathrm{p}} = \prod_{i=1}^{m} \left[1 - k_{yi} \left(1 - \frac{\mathrm{ET}_{\mathrm{a}i}}{\mathrm{ET}_{\mathrm{p}i}} \right) \right] \tag{1}$$

where Y_a designates actual crop yield; Y_p, potential crop yield; K_{yi}, crop response coefficient to deficit irrigation; and $\mathrm{ET}_{\mathrm{a}i}$ 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 ($W_\mathrm{a}/W_\mathrm{p}$) for $\mathrm{ET}_\mathrm{a}/\mathrm{ET}_\mathrm{p}$ in Equation (1) will yield:

$$\frac{Y_\mathrm{a}}{Y_\mathrm{p}} = \prod_{i=1}^{m} \left[1 - k_{yi} \left(1 - \frac{W_{\mathrm{a}i}}{W_{\mathrm{p}i}} \right) \right] \tag{2}$$

Here, the Agro-Ecological Zone Method (AEZM) (FAO, 1978–81) was used to compute potential crop yields, employing radiation data along with corrections for the climate and the crop. Potential evapotranspiration for each growth stage was also determined using the Penman-FAO method as explained in Doorenbos and Pruitt (1977) with relevant crop coefficients affected.

The distribution of applied water can be assumed as a uniform function. This typical distribution is shown in Figure 1. In practice, a gross irrigation depth (H_g) is applied to compensate for a soil water depletion or required depth (H_n). However, a deficit irrigation depth (H_d) is producted due to non-uniform irrigation. A deficit coefficient ($C_\mathrm{d} = H_\mathrm{d}/H_\mathrm{n}$) quantifies the magnitude of this factor. Mantovani *et al*. (1995) proposed a relation between the deficit coefficient and evapotranspiration deficit as follows:

$$1 - \frac{\mathrm{ET}_{\mathrm{a}i}}{\mathrm{ET}_{\mathrm{p}i}} = C_{di}(1 - p_i) \tag{3}$$

DOI: 10.1002/ird

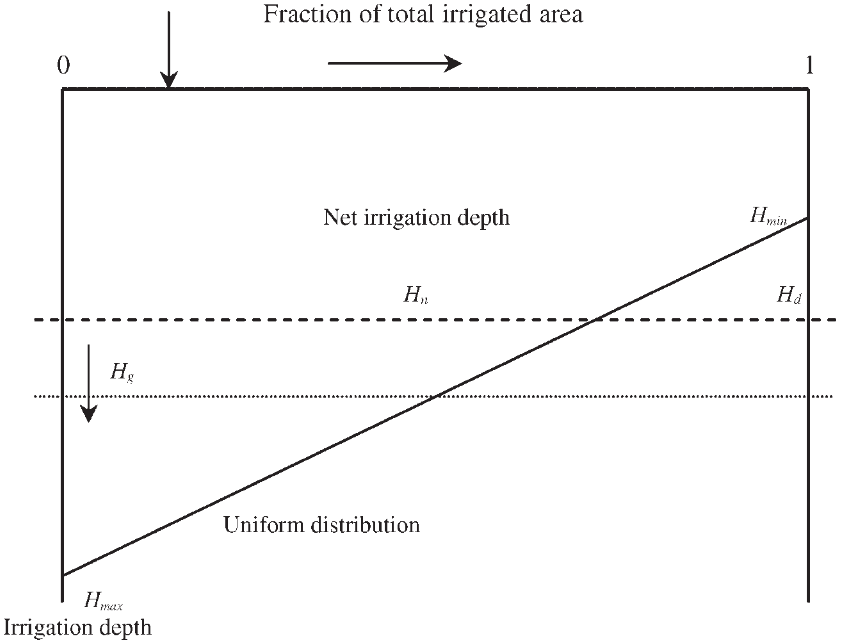

Figure 1. Uniform distribution of applied water

where p is the fraction of $\mathrm{ET_p}$ supplied by other sources from irrigation (e.g. rainfall and capillary rise). Substituting Equationr. (3) into Stewart and Hagan's simple empirical model yields

$$\frac{Y_\mathrm{a}}{Y_\mathrm{p}}=\prod_{i=1}^{m}\left[1-k_{yi}C_{di}(1-p_i)\right] \tag{4}$$

The C_d quality index depends just on the uniformity of water distribution in the irrigation system, on the H_g, H_n (Mantovani *et al*., 1995; Li, 1998). The C_d value may be determined by the following equations.

If $H_\mathrm{n}\langle H_\mathrm{max}$,

$$C_\mathrm{d}=\frac{H_\mathrm{d}}{H_\mathrm{n}}=\left[\left(1-2CU_\mathrm{ch}+H_\mathrm{n}/H_\mathrm{g}\right)/\left(8-8CU_\mathrm{ch}\right)\right]\left[1-\left(\left(H_\mathrm{g}/H_\mathrm{n}\right)\left(2CU_\mathrm{ch}-1\right)\right)\right] \tag{5}$$

If $H_\mathrm{n}\rangle H_\mathrm{max}$,

$$C_\mathrm{d}=\frac{H_\mathrm{d}}{H_\mathrm{n}}=1-\frac{H_\mathrm{g}}{H_\mathrm{n}} \tag{6}$$

The objective function for a single crop of the cropping pattern can be expressed in terms of the difference between potential and actual performance of that crop (Equation 7). In this equation, Z is the objective function and $y_{\mathrm{p}i}$ and $y_{\mathrm{a}i}$ are the potential and actual yield values at the growth stage i, respectively.

$$Z=\sum_{i=1}^{m}\frac{1}{y_{\mathrm{p}i}}\left(y_{\mathrm{p}i}-y_{\mathrm{a}i}\right)^2 \tag{7}$$

Equations (7) and (2) yield

$$Z=\sum_{i=1}^{m}\frac{k_i^2}{W_\mathrm{p}^2}\left(W_{\mathrm{p}i}-W_{\mathrm{a}i}\right) \tag{8}$$

For *n* crops, Equation (8) may be showed as the following equation:

$$Z = \sum_{j=1}^{\mathrm{n}} \sum_{i=1}^{m} \frac{k_i^2}{W_{\mathrm{p}ij}^2} (W_{\mathrm{p}ij} - W_{\mathrm{a}ij})^2 \tag{9}$$

Minimising the value for this objective function (Equation 9) will determine the optimal irrigation depth at every growth stage as well as the total irrigation depth of the crop under all water regimes. Optimisation of the function was accomplished using Ms Excel Solver. Water constraint functions can be simply represented as below. W_{T} designates total depth of water available from both surface and subsurface resources.

$$\sum_{j=1}^{\mathrm{n}} \sum_{i=1}^{m} W_{(\mathrm{a}i)j} \leq W_{\mathrm{T}} \tag{10}$$

$$\sum_{i=1}^{m} W_{\mathrm{a}i} \leq \sum_{i=1}^{m} W_{\mathrm{p}i} \tag{11}$$

$$W_{\mathrm{a}i} \rangle 0 \tag{12}$$

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 cropping pattern:

$$\mathrm{Max}((B/\mathrm{Vol})_S) = \mathrm{Max}\left(\frac{\sum_{j=1}^{\mathrm{n}} B_j.A_j}{\sum_{j=1}^{\mathrm{n}} A_j.D_{\mathrm{g}j}} \right) \tag{13}$$

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_j, the cultivated area for crop *j*; $D_{\mathrm{g}j}$, gross optimal irrigation depth for crop *j*; and *k* is the crop number in the pattern. Net profit from each crop (B_j) is obtained from the following relation:

$$B_j = (B_m + B_l)_j - (C_l + C_w)_j \tag{14}$$

where B_{m} and B_{l} are profits from the main crop and the secondary crop *j*, respectively; and C_{l} is labour costs and all other associated costs including land, planting, growing, and harvesting costs, and C_{w} is irrigation water cost of crop *j*. Irrigation water cost is a function of the total allocated water to the crop (Rls m^{-3}). All profit and cost values were considered from the reports presented by the Office of Statistics and Information Technology, Ministry of Jihad-Agriculture of Iran (2005, 2006).

In order to maximise the above objective function (Equation 13), the following constraints had to be taken into account:

$$A_j \geq 0 \tag{15}$$

$$A_{\mathrm{Min}(j)} \leq A_j \leq A_{\mathrm{Max}(j)} \tag{16}$$

$$\sum\nolimits_{j=1}^{m} W_j.A_j \leq W_{\mathrm{T}}.A_{\mathrm{T}} \tag{17}$$

where A_j is cultivated area for crop *j*; A_{T} is total cultivated area irrigated by the network; and $A_{\mathrm{Min}(j)}$ and $A_{\mathrm{Max}(j)}$ are minimum and maximum possible cultivable area for crop *j*, respectively.

Study area and crop data

The model developed in this study was executed for the irrigation network located in the Ghazvin plain in the north-west of Iran. Figure 2 shows the location of irrigation network in province of Gazvin, Iran. Annual

DOI: 10.1002/ird

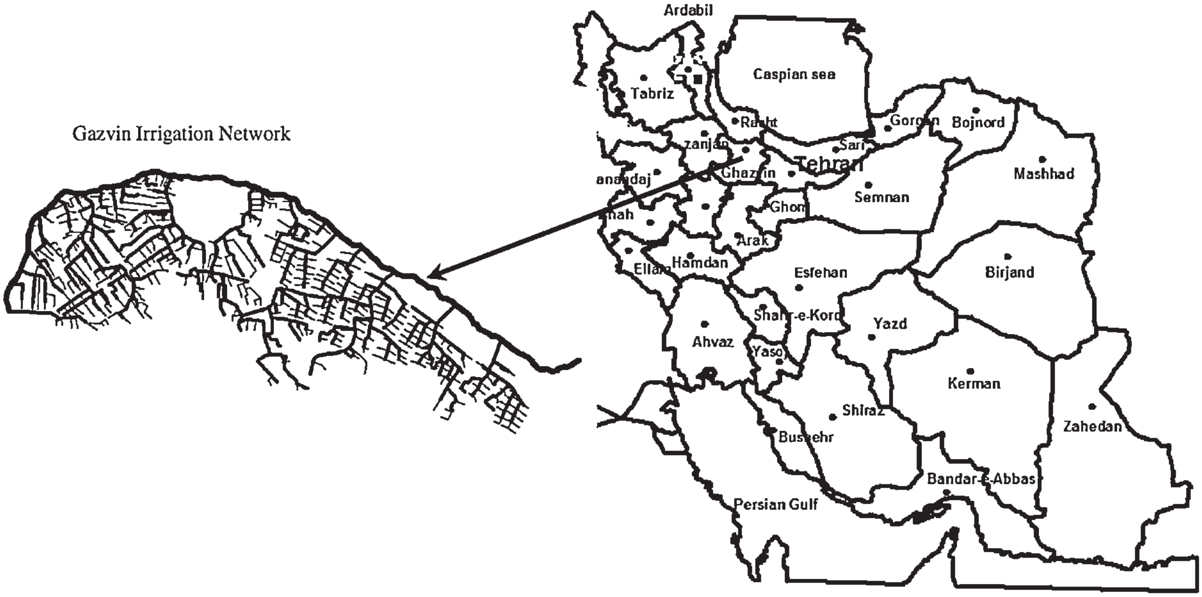

Figure 2. Location of irrigation network in province of Gazvin, Iran

precipitation and evaporation in the region are 312 and 1345 mm, respectively, and the average annual temperature is 13.2°C. The network covers an area of 57 000 ha and its water is supplied from the Taleghan Dam and 102 integrated wells scattered over the network area (Figure 3). The main channel has a design capacity of $30\,\mathrm{l\,s^{-1}}$. The volume of water supplied from the integrated wells across the network is equal to 30 million m^3. Thanks to the considerable amount of water available, around 70% of the land along the network is annually allocated to crops while the remaining 30% is allocated to orchards or left fallow. The crops of the cropping pattern in the region often include: wheat, barley, pear, corn, sugar beet, alfalfa, 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%.

Table I presents typical characteristics of the crops of the cropping pattern practised in the region. Winter crops include wheat and barley; and summer crops include pear, corn, sugar beet, alfalfa, sunflower, cucumber, onion, potato, bean and lentil. The values for the crop response coefficients to deficit irrigation were also estimated from the values proposed in Doorenbos and Pruitt (1977) with regional corrections effected. The values for the period of each growth stage and maximum root depths were selected on the basis of field investigations. Also relative crop areas under cultivation were determined from the minimum and maximum percentages of observed cultivated areas in the region during a recent 15-year period.

RESULTS AND DISCUSSION

Total water availability

In order to investigate the conditions of the water resources in the study area, 30-year (1976–2005) statistics of the meteorological stations in the region were used. The SPI (Standardized Precipitation Index) was used to analyse water regimes during the studied period. However, the years of 1998, 1990 and 2001 were considered as wet, drought and normal years in the study area, respectively. Based on the analysis, the volume of water available from integrated wells (groundwater resources) in the region is determined at 21 MCM for the wet regime over different months of the year. The volume of yearly water available from both surface and groundwater resources for the

DOI: 10.1002/ird

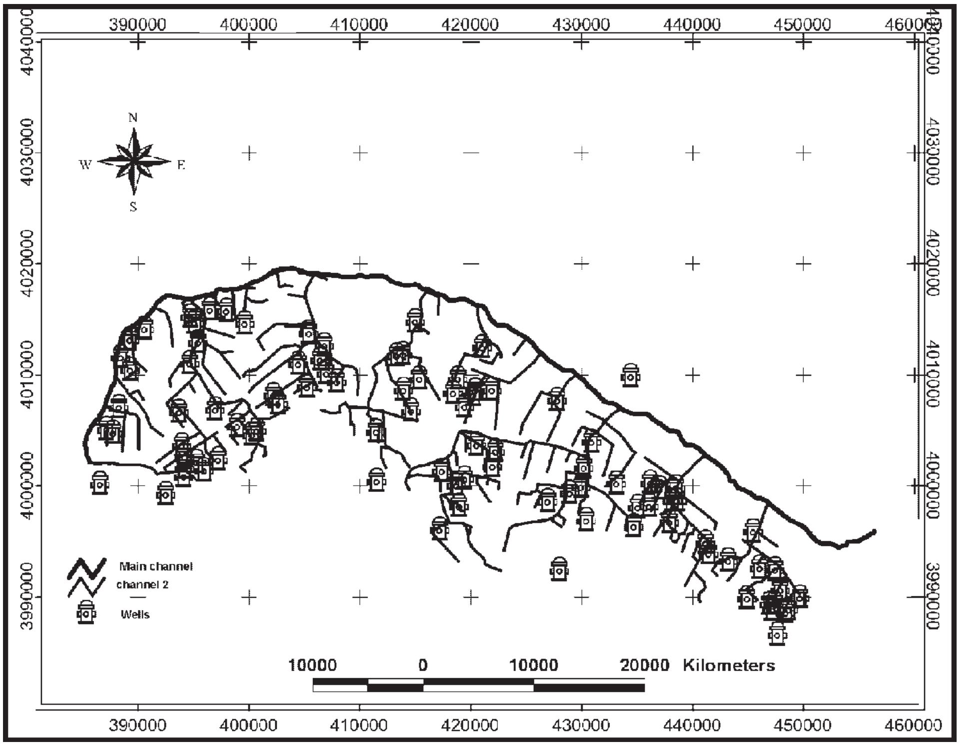

Figure 3. Location of integrated wells in irrigation network

different water regimes are presented in Table II. The results from investigations show that in dry years, the water available across the irrigation network will reduce by 47 and 37%, respectively, for wet and normal years in the region, a finding that must be taken into account in selecting the cropping pattern.

Effect of water application uniformity on crop production function

Using Equations (4)–(6), the Y_a/Y_p values of each crop were calculated as a function of H_g/H_n for the different water application uniformities. The results for the wheat crop are shown in Figure 4. As can be seen, the influence of CU became evident when the value of H_g/H_n exceeded 0.5. Below 0.5, water sources other than irrigation are dominant, resulting in a lack of response to water uniformity variations for crop yield. This figure also indicates that the amount of required irrigation depth to achieve a given level of yield increases as the CU decreases. The irrigation depths for maximum yield were determined for the ranges of $CU = 30$–90% on the proposed production model. The irrigation depths were about 302, 478, 668 and 737 mm for CU values of 90, 70, 50 and 30%, respectively (given 291 mm of H_n for drought conditions). The results are similar to that of Li (1998) and Mantovani *et al*. (1995) for a uniform model in sprinkler irrigation. Under wet conditions, the irrigation depths were about 360 and 877 mm for CU values of 90 and 30%, respectively. Here, the p value was assumed as 0.2.

Optimal allocated water and cropping pattern

The optimal allocated water of crops was determined using Equation (9). The objective function (Equation 9) was solved taking the limiting functions of Equations (10)–(12). Figure 5 shows the optimal allocated water of each crop. The values for wheat were estimated at 292, 367 and 377 mm for drought, normal and wet years, respectively. The highest values were related to the alfalfa crop, which were 707 and 902 mm for drought and wet water regimes,

Table I. Typical characteristics of the crops

	Parameter	Wheat	Barley	Pear	Lentil	Corn	Sun-flower	Sugar beet	Cucumber	Onion	Potato	Tomato	Alfalfa	Bean
Potential evapotranspiration	ET_p (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		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	K_y	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)	D_{rz}	0.96	1	0.6	0.9	1.2	1.8	1.05	1.2	0.6	0.6	1.8	1.8	0.9
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–.0.1	0.25–0.45	2.5–3.7	7–11	1.4–2

Table II. Volume of yearly water available from surface water and groundwater resources (MCM)

Water regime	Wet	Normal	Drought
Water available from surface resources	145	118	68
Water available from groundwater resources	21	30	43

respectively. The optimal allocated water values of the irrigation network were assumed as 5500 mm (drought water conditions), 6700 mm (normal water conditions), and 6750 mm (wet conditions).

In order to maximise the overall productivity index defined as net profit to water use in the network, Equation (13) was solved taking account of Equation (14) and the limiting functions of Equations (15)–(17) using Ms Excel Solver. The results from optimisation of the cropping pattern are presented in Table III. This table shows the optimal cultivated area values for each of the crops in the cropping pattern under each of the water regimes. The results show that the greatest cultivated areas belonged to wheat, which were 23 599 and 19 350 ha for wet and dry years, respectively. The calculations indicate that reducing the cultivated area for wheat under drought conditions will yield a productivity value $(B/\mathrm{Vol})_{\mathrm{wheat}}$, of 11 074.4 Rls m^{-3} (850 Rls = 1 US dollar) which shows a reduction of 2935.8 Rls m^{-3} as compared to the same index for wet years (8138.58 Rls m^{-3}). The lowest cultivated areas were obtained for sunflower, which were 5.2 and 6.5 ha for drought and wet years, respectively. Sugar beet stood second to wheat in terms of area under cultivation (430 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, the productivity was computed for each crop under the different water regimes under study. The results are presented in Figure 6. Examination of the results shows that under drought conditions, the onion crop with 75 068.86 Rls m^{-3} has the highest value, while alfalfa with 3054.17 Rls m^{-3} has the lowest value of

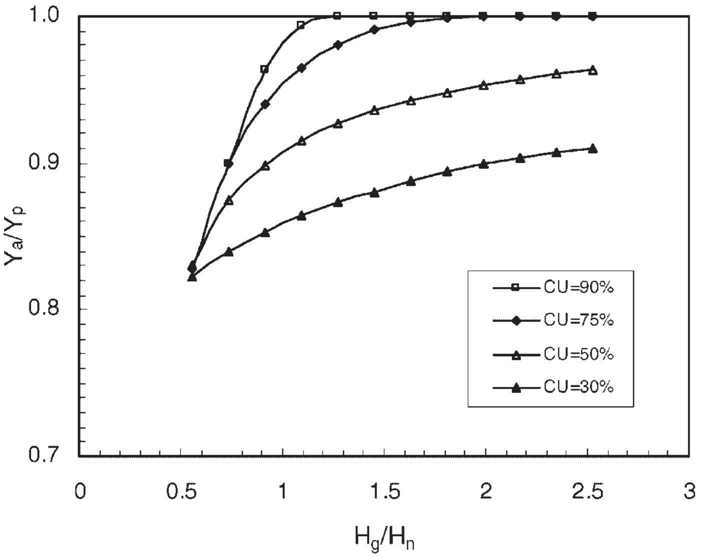

Figure 4. Relative yield Y_a/Y_p of wheat crop as a function of H_g/H_n under different CU values

DOI: 10.1002/ird

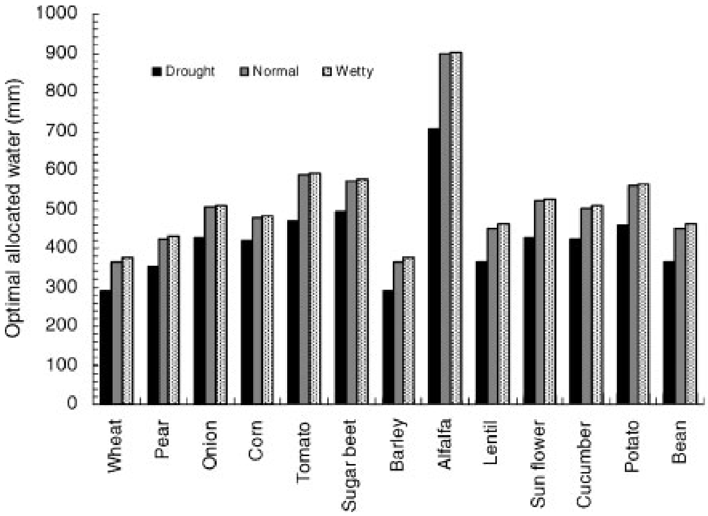

Figure 5. Optimal allocated water of each crop under different water regimes

productivity defined as profit to water used. Under wet years, these ranks belong to the crops onion (89 049.57 Rls m^{-3}) and alfalfa (7001.5 Rls m^{-3}), respectively.

The values for the overall irrigation network productivity ($(B/\mathrm{Vol})s$) for the optimal cropping pattern and under different water regimes considered in this study are compared in Figure 7. As seen in this figure, the value for the overall irrigation network productivity under cropping management can rise to as high as 12 664.94 Rls m^{-3} for drought conditions. For the existing cropping pattern (2005), overall irrigation network productivity is estimated at 10 553.42 Rls m^{-3}. In normal and wet years and when the optimal cropping pattern is put into practice, the values for this index are estimated to be as high as 12 881.16 and 15 592.24 Rls m^{-3}. In other words, under drought conditions and with the optimal cropping pattern in practice and with appropriate deficit irrigation, the network productivity can be raised. The results demonstrated that the water productivity of irrigation networks could be improved as a result of optimal cropping pattern and deficit irrigation. The maximum variations of this index may be fixed around 18% for different water regimes.

Table III. Optimal cropping pattern (cultivated area) under different water regimes (ha)

Crop	Area (ha)		
	Drought	Normal	Wet
Wheat	19 350	21 153	23 599
Barley	2 800	2 800	2 800
Corn	1 053	1 053	1 500
Pear	774	774	774
Lentil	77	77	77
Sunflower	5.2	6.5	6.5
Sugar beet	1 204	1 634	1 634
Cucumber	645	860	860
Potato	107	193.5	193.5
Onion	43	43	43
Tomato	1 300	1 591	1 591
Alfalfa	3 010	3 010	3 010
Bean	602	860	860

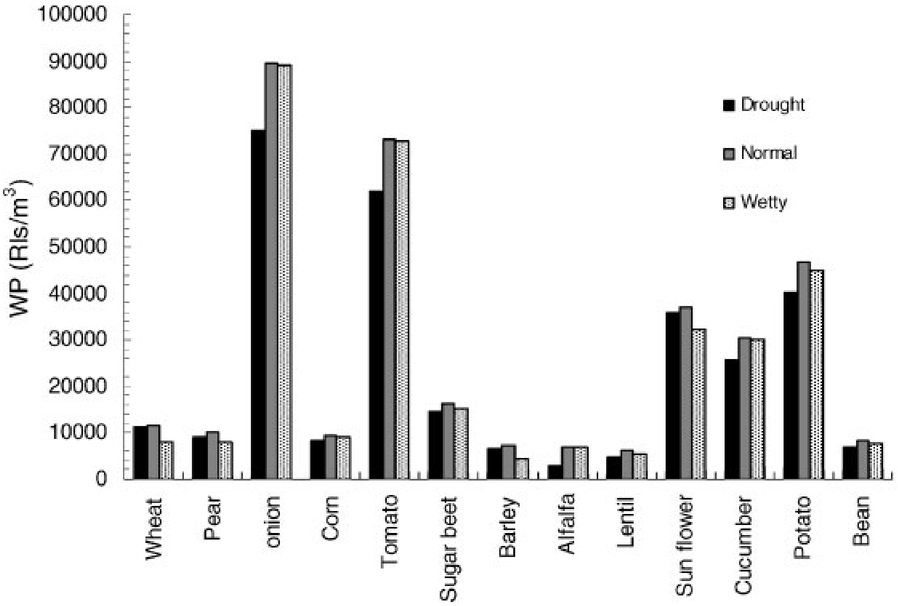

Figure 6. Comparison of crop productivity according to optimal cropping pattern under different water regimes

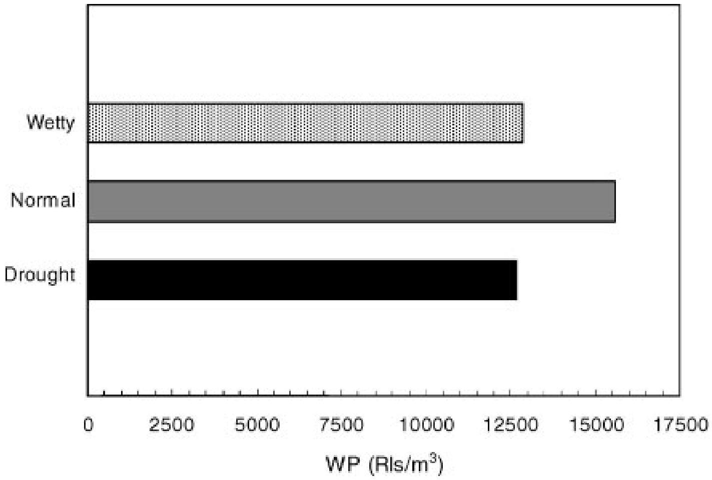

Figure 7. Comparison of overall irrigation network productivity based on optimal cropping pattern under different water regimes

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 utilisation of soil and water resources. In the present study, a simple 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 in Iran under different water regimes of wet, drought and normal years was compared with the existing cropping pattern employed in the system. The results show that the highest cultivated areas are the wheat crop with 23 599 and 19 350 ha for wet and drought years, respectively. The lowest values for the productivity studied were in the alfalfa, which were estimated at 3054.18 and 7001.5 Rls m^{-3} for drought and wet years, respectively. Analysis of the results indicates that under drought conditions, the overall network productivity under optimal cropping pattern could be increased to as high as 12 664.94 Rls m^{-3}. In wet and normal years, and if an optimal cropping pattern is practised, the values for this index will be 12 881.16 and 15 592.24 Rls m^{-3}, respectively. This means that under drought conditions and under an optimal cropping pattern, the water productivity could be raised to as high as the wet water conditions and that the economic value of a unit of water could thus be improved. The findings from this study lay greater emphasis than ever on the need for application of optimisation models to determine optimal cropping pattern and optimal water distribution systems in accordance with the potential of existing water resources, on the one hand, and on the important role played by an appropriate cropping pattern in improving irrigation network productivity.

ACKNOWLEDGEMENTS

This study is the part of work of research grant No. 7305002/1/01 supported by the University of Tehran fund. The authors gratefully acknowledge the Vice-president for Research, College of Aboreyhan, University of Tehran, for financial support.

REFERENCES

Amir I, Fisher FM. 1999. Analyzing agricultural demand for water with an optimizing model. *Agricultural Systems* **61**: 45–56.

Benli B, Kodal S. 2003. A non-linear model for farm optimization with adequate and limited water supplies application to the south-east Anatolian project (GAP) region. *Agricultural Water Management* **62**: 187–203.

Carvallo HO, Holzapfel EA, Lopez MA, Marino MA. 1998. Irrigated cropping optimization. *Journal of Irrigation and Drainage Engineering* **124**(2): 67–72.

De Juan JA, Tarjuelo JM, 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. *Agricultural Water Management* **31**: 115–143.

Diaz GE, Brown TC. 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 WO. 1977. Crop water requirement. FAO Irrigation and Drainage Paper 24. FAO, Rome; 144 pp.

Doorenbos J, Kassam AH. 1979. Yield response to water. Irrigation and Drainage Paper No. 33, FAO, Rome; 193 pp.

English MJ. 1992. Deficit irrigation. I. Analytical framework. *Journal of Irrigation and Drainage Engineering* **116**(3): 399–412.

FAO. 1978–81. *Report on the Agro-Ecological Zones Project*. World Soil Resources Report 48, FAO, Rome.

Ghahraman B, Sepaskhah AR. 2004. Linear and non-linear optimization models for allocation of a limited water supply. *Irrigation and Drainage* **53**: 39–54.

Kipkorir EC, Sahli A, Raes D. 2002. MIOS: a decision tool for determination of optimal irrigated cropping pattern of a multicrop system under water scarcity conditions. *Irrigation and Drainage* **51**: 155–166.

Kuo SF, Merkley GP, Liu CW. 2000. Decision support for irrigation project planning using a genetic algorithm. *Agricultural Water Management* **45**: 243–266.

Leenhardt D, Trouvat JL, Gonzales G, Perarnaud V, Prats S, Bergez JE. 2004. Estimation irrigation demand for water management on a regional scale. I. ADEAUMIS, a simulation platform based on bio-decisional modeling and spatial information. *Agricultural Water Management* **68**: 207–232.

Li J. 1998. Modeling crop yield as affected by uniformity irrigation system. *Agricultural Water Management* **38**: 135–146.

Li QS, Willardson LS, Deng W, Li XJ, Liu CJ. 2005. Crop water deficit estimation and irrigation scheduling in western Jilin province, Northeast China. *Agricultural Water Management* **71**: 47–60.

Mainuddin M, Das Gupta A, Raj Onta P. 1997. Optimal crop planning model an existing groundwater irrigation project in Thailand. *Agricultural Water Management* **33**: 43–62.

Mantovani EC, Villalobos FJ, Orgaz F, Fereres E. 1995. Modelling the effects of sprinkler irrigation uniformity on crop yield. *Agricultural Water Management* **27**: 243–257.

Office of Statistics and Information Technology. 2005. *A Report on Prices of Agricultural Crops*. Ministry of Jihad-Agriculture of Iran (in Persian).

Office of Statistics and Information Technology. 2006. *A Report on Production Costs of Agricultural Crops*, vol. 2. Ministry of Jihad-Agriculture of Iran (in Persian).

Perry C. 2007. Efficient irrigation; inefficient communication; flawed recommendations. *Irrigation and Drainage* **56**: 367–378.

Reca J, Roldan J, Alcaide Mi, Lopez R, Camacho E. 2001a. Optimisation model for water allocation in deficit irrigation systems. I. Description of the model. *Agricultural Water Management* **48**: 103–116.

DOI: 10.1002/ird

Reca J, Roldan J, Alcaide Mi, Lopez R, Camacho E. 2001b. Optimisation model for water allocation in deficit irrigation systems. II. Application to the Bembezar irrigation system. *Agricultural Water Management* **48**: 103–116.

Sabu P, Sudhindra NP. 2000. Optimal irrigation allocation: a multilevel approach. *Journal of Irrigation and Drainage Engineering* **126**(3): 149–156.

Singh DK, Jaiswal CS, Reddy KS, Singh RM, Bhandarkar DM. 2001. Optimal cropping pattern in a command area of Shahi distributory. *Agricultural Water Management* **50**: 1–8.

Stewart JI, Hagan RM. 1973. Function to predict effects of crop water deficits. *Journal of Irrigation and Drainage* **99**: 421–439.

Yaron D, Bresler E. 1983. Economic analysis of on-farm irrigation using response functions of crops. In *Advances in Irrigation*, vol. 2, Hillel D (ed.). Academic Press: New York; 223–255.

Young J. 1996. Water economics. In *Water Resources Handbook*, Mays LW (ed.). MacGraw-Hill: New York.

DOI: 10.1002/ird