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ASSESSMENT OF IRRIGATION WATER ALLOCATION BASED ON OPTIMIZATION AND EQUITABLE WATER REDUCTION APPROACHES TO REDUCE AGRICULTURAL DROUGHT LOSSES: THE 1999 DROUGHT IN THE ZAYANDEH RUD IRRIGATION SYSTEM (IRAN)†

M. MOGHADDASI[1], S. MORID[1]*, S. ARAGHINEJAD[2] AND M. AGHA ALIKHANI[1]

[1]*College of Agriculture, Tarbiat Modares University, Tehran, Iran*
[2]*College of Agriculture, Tehran University, Karaj, Iran*

ABSTRACT

Drought is common to Iran and the agricultural sector is its main victim. Reducing demand for irrigation water is considered the best management practice to alleviate losses. An equitable water reduction approach has been traditionally applied in the management of irrigation systems. This research work examines and compares this approach with that based on the optimization method to manage agricultural water demand during drought to minimize damage. To evaluate these methodologies, the 1999 drought in the Zayandeh Rud irrigation system was selected and the required models developed. In the optimization method, crop growth stages and their sensitivity to water stress at different stages are embedded in the calculations. The results show that the optimization method resulted in 42% more income for the agricultural sector using the same amount of water allocated in the 1999 drought. This difference emphasizes the importance of water allocation with respect to growth stages rather than simply cutting allocations on an equitable basis to combat water scarcity. However, managing the system using the optimization method is more complex and requires a new framework and planning to make it operational. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS: water allocation; irrigation systems; optimization; drought; Zayandeh Rud

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RÉSUMÉ

La sécheresse est commune en Iran et le secteur agricole en est la principale victime. La réduction de la demande en eau d'irrigation est considérée comme la meilleure pratique de gestion pour atténuer les pertes. Une approche équitable des réductions d'allocation en eau a été traditionnellement appliquée à la gestion des systèmes d'irrigation. Ce travail de recherche examine et compare cette approche avec celle qui est fondée sur une méthode d'optimisation minimisant les dommages dans la gestion de la demande en eau agricole au cours de la sécheresse. Pour évaluer ces méthodes, la sécheresse de 1999 dans le système d'irrigation Zayandeh Rud a été sélectionnée et les modèles ont été développés. La méthode d'optimisation intègre dans les calculs les stades de croissance des cultures et leur sensibilité au stress hydrique. Les résultats montrent que l'optimisation conduit, pour la sécheresse de 1999, à un supplément de revenu agricole de 42% en utilisant la même quantité d'eau. Cette différence montre l'importance de l'allocation de l'eau en fonction des stades de croissance plutôt que de simplement couper l'eau sur une base équitable pour lutter contre la pénurie d'eau. Toutefois, la gestion d'un système optimisé est plus

* Correspondence to: S. Morid, College of Agriculture, Tarbiat Modares University, Tehran, Iran. E-mail: morid_sa@modares.ac.ir
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MOTS CLÉS: allocation d'eau; systèmes d'irrigation; optimisation; sécheresse; Zayandeh Rud

INTRODUCTION

Iran frequently experiences drought and the agricultural sector is the main victim of this natural disaster. Optimal water allocation is an efficient measure to overcome water scarcity under drought conditions and mitigate consequent losses. For instance, Mohan and Arumugam (1997) and Shangguan *et al*. (2001) reported 50% reductions in water demand during water scarcity using revised irrigation planning and optimization techniques. Rescheduling irrigation by taking into consideration factors such as available water, growth stage and plant production function can be more effective in decreasing both water consumption and drought damage.

A review of the literature shows that these factors have rarely been considered for drought management. However, some research optimized irrigation depth or cropping patterns to simultaneously reduce water consumption and maximize incomes. Yaron and Dinar (1982) presented a recurrence method using linear programming (LP) and dynamic programming (DP) to resolve water allocation across crops. Similarly, a recurrence method was developed by Yuan (1991) using nonlinear programming (NLP) and DP to save irrigation. Ghahraman and Sepaskhah (2002) built a modelling system for optimal water allocation from a single-purpose reservoir for an irrigation system with predetermined multiple cropping patterns. This model was applied to Ardak reservoir in Iran. These researchers also developed an efficient NLP optimization model with integrated soil-water balance to reduce water demand for the same area (Ghahraman and Sepaskhah, 2004).

Based on progress in deficit irrigation research, Shangguan *et al*. (2002) developed a recurrence control model for regional optimal allocation of irrigation water resources aimed at overall maximum efficiency using the decomposing-harmonization principle for large systems. Their model consisted of three layers that optimized crop irrigation scheduling, optimally allocating water for the various crops and irrigation subsystems. Kumar *et al*. (2006) compared LP and genetic algorithms (GAs) for optimum water allocation of a single-purpose reservoir. The objective function was to maximize relative crop yields. They introduced river inflow, effective rainfall, seasonal water competition among crops, available soil moisture content in different fields, soils heterogeneity and crop sensitivity to water deficit as inputs to their model. The results showed that the performance of the LP and GA models were not significantly different.

In addition to the optimization approach to reduce irrigation during water scarcity, there is another approach that applies equitable water reduction among various crops. This method is more routine and convenient for water managers and is applied in Iran and other countries, such as Mexico, during droughts (Palmer *et al*., 2002; Vigerstol, 2003). The objective of this study is to compare these approaches. The 1999 drought in the Zayandeh Rud irrigation system in Iran was selected to explore the results of the proposed modelling system.

DATA AND METHODS

Study area

The Zayandeh Rud basin with an area of 41 500 km^2 is located in central Iran (Figure 1). The Chadegan dam has been the area's main water reservoir since 1971 with a 1450 million cubic metres (MCM) capacity. The availability of water resources in the basin, even after construction of the dam, was not sufficient, thus inter-basin transfer has been applied by diverting parts of neighbouring water resources (the Karoon and Dez rivers). Tunnels divert 300–400 MCM of water per year and two more tunnels are under construction.

The network includes eight irrigation units (IUs); Nekooabad LB, Nekooabad RB, Mahyar, Borkhar, Abshar LB, Abshar RB, Rudasht, and small-scale systems for a total area of about 205 000 ha. Wheat, barley, sugar beet, alfalfa and rice are the primary crops in the network. Table I shows the cropping calendar of the various crops within the IUs (Murray-Rust *et al*., 2004).

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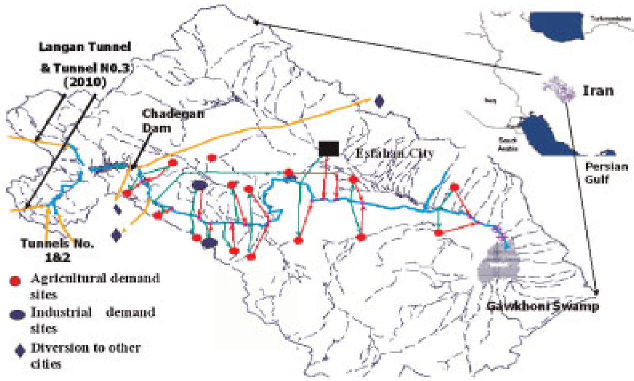

Figure 1. Zayandeh Rud irrigation system and related infrastructures. This figure is available in colour online at wileyonlinelibrary.com

Water allocation based on the optimization approach (OPM)

To apply the OPM, a top-down approach (Shangguan *et al*., 2002) is applied such that the total allocated water for the agricultural sector is optimally distributed among the eight IUs. The water delivered to each unit is then optimally distributed among the crops and, finally, the allocated water for each crop is optimally circulated among the irrigation periods. The objective for these optimization processes is to maximize crop yield and income. Although the water should be distributed from the top down, the sub-models and related calculations operate bottom-to-top as explained below.

Nomenclature

A_K = acreage for each crop (ha)
A_{Max} = maximum acreage for each crop (ha)
A_{Max} = minimum acreage for each crop (ha)
DP = deep percolation (mm/10days)
$\mathrm{ET}a_{\mathrm{c,g}}$ = actual evapotranspiration for growth stage g of crop c in stage g (mm/10 days)
$\mathrm{ETmax}_{\mathrm{c,g}}$ = maximum evapotranspiration for growth stage g of crop c in stage g (mm/10 days)
ET_0 = crop reference evapotranspiration (mm)
FC = field capacity (mm)

Table I. Typical crop calendars and maximum crop yields in Zayandeh Rud basin (Farshi *et al*., 1997)

Crop	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Maximum yield (t ha^{-1})
Wheat		*	*	*	*	*	*	*	*				9 000
Barley		*	*	*	*	*	*	*	*				7 000
Sugar beet							*	*	*	*	*	*	70 000
Potato						*	*	*	*	*			50 000
Alfalfa (1st cutting)	*	*											2 833
Alfalfa (2nd cutting)		*	*										2 833
Alfalfa (3rd cutting)							*	*					2 833
Alfalfa (4th cutting)								*	*				2 833
Alfalfa (5th cutting)									*	*			2 833
Alfalfa (6th cutting)											*	*	2 833
Rice	*									*	*	*	10 000

DOI: 10.1002/ird

$F_K\ (V_K)$	= functional relation between maximum relative yield and allocated irrigation water
$F_n\ (V_n)$	= functional relation between maximum benefit and allocated water for each unit
IR	= optimal allocated irrigation water (mm/10 days)
I_t	= annual inflow to the reservoir (MCM)
K	= total number of crops
K_c	= crop coefficient
Ky_g	= water sensitivity coefficient for growth stage g
n	= total number of growth stages
N	= total number of irrigation systems
P_k	= marketing price per kilogram (US$)
P	= soil water depletion
PWP	= permanent wilting point
R_t	= output from the reservoir for all demands
r	= planting depth (for the study area it is 7 cm for wheat and barely, 5 cm for alfalfa and sugar beet and 15 cm for potato)
SM	= available soil water content (mm)
SM'	= constant soil water content of deeper layers prior to cultivation (mm)
S	= reservoir storage (MCM)
T	= total of growth time in each of stage (day)
TAW	= total available water (MCM)
t	= operation time (one year)
Y_{ac}	= actual yield per unit area (kg ha^{-1})
$Y_{\max c}$	= maximum yield per unit of area (kg ha^{-1})
Y_{MAXK}	= maximum yield (kg ha^{-1})

Sub-model 1: Optimal irrigation scheduling

This model determines the irrigation scheduling for the dominant crops during the growing season based on a 10-day irrigation period (the usual irrigation period in the study area). The objective function is subjected to the following system equations and constraints:

$$MAX : \frac{Y_{ac}}{Y_{\max}c} = 1 - \sum_{g=1}^{n} Ky_g \left(1 - \frac{ETa_{c,g}}{ET\max_{c,g}}\right) \tag{1}$$

During the growing season, root depth (Root$_{c,t}$) in time interval t (irrigation period) is (Borg and Grimes, 1986)

$$\mathrm{Root}_{c,t} = 10^{*}(r + \mathrm{Root}_{Max}(0.5 + 0.5^{*}\mathrm{Sin}(3.03^{*}t^{*}/T - 1.47))) \tag{2}$$

The soil-water balance equation is

$$SM_{c,t+1}\mathrm{Root}_{c,t+1} = SM_{c,t}\mathrm{Root}_{c,t} + \mathrm{IR}_{c,t} - ETa_{c,t} - \mathrm{DP}_{c,t} + SM'(\mathrm{Root}_{c,t+1} - \mathrm{Root}_{c,t}) \tag{3}$$

The maximum crop evapotranspiration is computed as follows:

$$ET\max_{c,t} = Kc_{c,t} * ET_O \tag{4}$$

Reference crop evapotranspiration (ET_0) is calculated using the Penman–Monteith method, using records from the Esfahan synoptic station (Allen *et al*., 1998). The 10-day values of Kc over the growing period are calculated using the method described by Doorenbos and Pruitt (1984).

Actual evapotranspiration is always smaller or equal to maximum evapotranspiration:

$$ETa_{c,t} \leq ET \max_{c,t} \tag{5}$$

DOI: 10.1002/ird

Table II. Individual growth stages for crops in the Zayandeh Rud basin (days)

Crop	Vegetative stage	Flowering stage	Yield formation stage	Ripening stage	Maximum root depth (cm)
Wheat	130	40	30	20	70
Barley	120	30	30	20	70
Sugar beet	50	—	100	50	70
Potato	70	—	60	20	40
Alfalfa	20	—	20	—	100

The response of crop yield to water supply is quantified through the yield response factor (Ky) (Doorenbos and Kassam, 1977). This varies during the growing stage (Ky_g) and depends on $ETa_g/ET\ \max_g$(Table II). Since Ky_g is stage based, the following constraint is applied during the 10-day periods:

$$\frac{ETa_{t+1}}{ET\ \max_{t+1}} \leq \frac{ETa_t}{ET\ \max_t} \tag{6}$$

The duration of the growth stages of crops and their maximum root depth were detected, using information available from the Esfahan Agricultural Organization (Table III) (Farshi *et al*., 1997).

Actual evapotranspiration is smaller than the ratio of maximum evapotranspiration:

$$ETa_{c,t} \leq \frac{ET\ \max_{c,t}}{(1-P_c)(\mathrm{FC}_c - \mathrm{PWP}_c)}\left[SM_{c,t} - \mathrm{PWP} + \left(\frac{\mathrm{IR}_{c,t} - \mathrm{DP}_{c,t}}{\mathrm{Root}_{c,t}}\right)\right] \tag{7}$$

The available soil-water content can only change within the following range:

$$\mathrm{PWP}_c \leq SM_{c,t} \leq \mathrm{FC}_c \tag{8}$$

Irrigation application efficiency (*Eff*) less than 100% causes some percolation of water:

$$\mathrm{DP}_{c,t} \geq \mathrm{IR}_{c,t}(1 - Eff_c) \tag{9}$$

The total amount of irrigation water at consecutive time intervals cannot exceed the total available water:

$$\sum_t \mathrm{IR}_{c,t} \leq TAW_c \tag{10}$$

Sub-model 2: Optimal water allocation and planted acreage

This sub-model maximizes the summed benefit of the crops within an IU. Here area (A_k) is also the most important decision variable. The objective function and constraints are as follows:

$$MAX\left\{\sum_{k=1}^{K} F_K(V_K)A_K Y_{\max k} P_K\right\} \tag{11}$$

Table III. Yield response factor of individual growth periods of crops, Zayandeh Rud basin (Doorenbos and Kassam, 1997)

Crop	Vegetative stage	Flowering stage	Yield formation stage	Ripening stage
Wheat	0.2	0.6	0.5	0.01
Barley	0.2	0.6	0.5	0.01
Sugar beet	2.0	—	0.36	0.12
Potato	0.8	—	0.7	0.2
Alfalfa	0.2	—	0.7	—

DOI: 10.1002/ird

Total planted acreage allocated to each crop cannot exceed the cultivated acreage of an IU:

$$\sum_{k=1}^{K} A_k \leq A_{\text{total}} \tag{12}$$

Total allocated water to a crop cannot exceed the total irrigation water allocated to an IU:

$$\sum_{k=1}^{K} V_k \leq V_{\text{total}} \tag{13}$$

The planted acreage allocated to each crop can only change within the following range:

$$A_{\min k} \leq A_k \leq A_{\max} k \tag{14}$$

Finally, in the case of alfalfa, the planted acreage of each cutting stage cannot exceed the previous one:

$$A_{A6} \leq A_{A5} \leq A_{A4} \leq A_{A5} \leq A_{A4} \leq A_{A3} \leq A_{A2} \leq A_{A1}$$

Sub-model 3: Optimal water allocation optimization among the IUs

This sub-model optimally distributes the total release of the reservoir among the IUs. The objective function maximizes the summed benefit of the units:

$$MAX\left\{\sum_{n=1}^{N} F_n(V_n)\right\} \tag{15}$$

The total allocated water to an IU cannot exceed the entire reservoir release:

$$\sum_{n=1}^{N} V_n \leq V_{\text{total}} \tag{16}$$

The total amount of the reservoir release is calculated using a continuity equation:

$$S_{t+1} = I_t + S_t - R_t \tag{17}$$

It should be noted that based on the current priorities of the Esfahan Water Organization, the total domestic and industrial water requirement as well as rice demands are subtracted from the available water (i.e. their water requirements are fully met) and only the remaining water is introduced into the allocation model.

Equitable reductions method (ERM)

To calculate the amount of irrigation water according to this method, rations (REW) are calculated for the maximum demand (MD) of the IUs by the maximum available water (MAW) from the dam during 1999 (REW = MD/MAW). Then, the amount of (1- REW)*100% is reduced from the MD of each unit. A similar amount of water is consequently reduced from the maximum water requirements of the crops. Finally, crop yield is estimated by substituting REW with ETa/ETmax in Equation (1). This approach does not make any changes in planted acreages of the IUs.

DOI: 10.1002/ird

RESULTS AND DISCUSSION

To execute the developed model, the most important information is the amount of available water for the agricultural sector. The river inflow for 1999 was 1070 MCM, and storage behind the dam was 697 MCM at the beginning of the year and 300 MCM at the end of the year. The total water allocated for the city, industry and rice was 416 MCM, meaning that 1050 MCM was available for other crops within the IUs and our modelling simulations (Araghinejad, 2004).

Water allocation using the optimization method (OPM)

For the OPM method, sub-model 1 (irrigation scheduling optimization) was executed for the crops at different water volumes and their respective yields were calculated. These were then used to define the crop production function ($F_K(Q_K)$) as in Equation (11). The resulting polynomial equations are shown in Figure 2.

Next, these functions were applied to sub-model 2. Similarly, this sub-model was executed for different volumes of water and the consequent incomes of the IUs were calculated ($F_n(Q_n)$) as in Equation (15). These results are shown in Figure 3.

Finally, sub-model 3 was executed using the results of sub-model 2 to optimally distribute water among the IUs.

The outputs of these computations include the optimum allocated water for each IU (Table IV) and the optimum allocated water for each crop and planted acreage within the IUs (Figure 4, Table V). Optimized irrigation scheduling for the crops for a 10-day period was also calculated. For example, the optimized irrigation depths for the various crops at different growing stages in Nekooabad (LB) are shown in Table VI.

Water allocation using the equitable reduction method (ERM)

Using the usual planted areas and climate conditions for 1999 in the calculations produced a maximum water requirement of 2030 MCM (Table IV). Since the total allocated water for the agricultural sector was 1060 MCM in 1999, a 48% reduction in irrigation was required. The reduced irrigation depth was applied to the different growing stages of the crops regardless of their sensitivities and to the IUs. Using Equation (1) and ETa/ETmax = 0.52, the crop yields were estimated. Sub-model 1 is applied here which makes it possible to compare the OPM and ERM in a similar computation status.

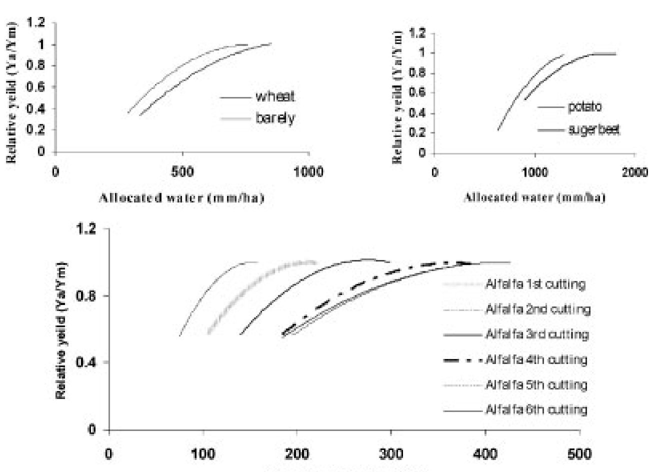

Figure 2. Yield functions of Zayandeh Rud basin main crops in 1999

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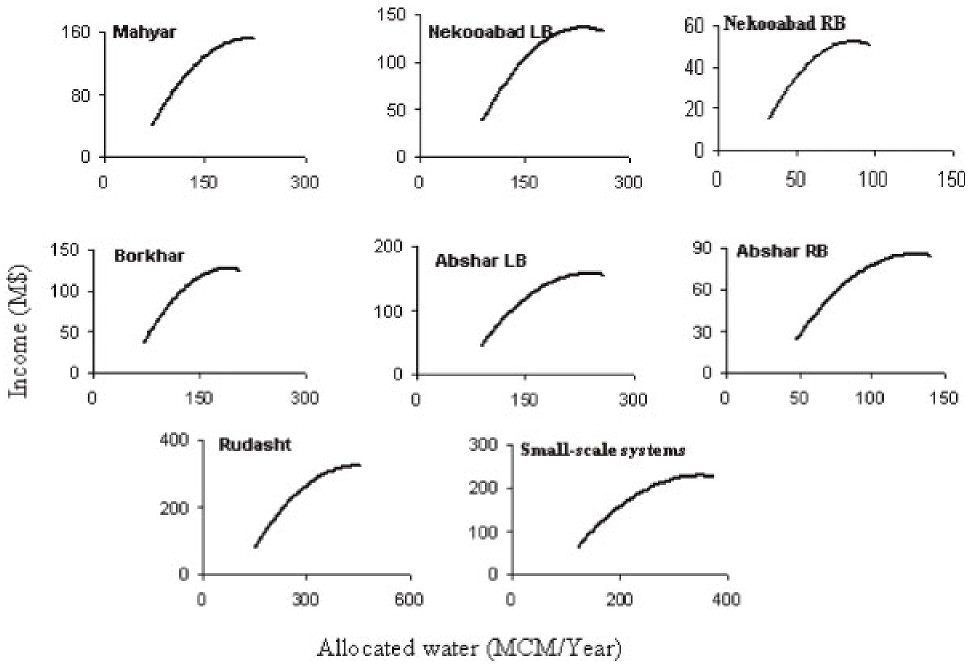

Figure 3. Income function of networks in 1999 for the Zayandeh Rud basin.

Comparison of IU performance using the OPM and ERM methods

Table IV shows the distribution of water among the IUs for the two approaches. While the ERM applies equitable 52% reductions in irrigation, the OPM reduced it from 48 to 56% in the IUs. It was observed that the OPM provided minimum irrigation reduction for potato crops and maximum irrigation reduction for barley. The water allocated to the crops is similar for all IUs, making management of the system easier.

The optimized planted acreages are shown in Table V. There are two numbers in each cell. The upper one is for OPM and the lower one is the ERM (i.e. the current acreage). It can be observed that minimum changes are applied to the planted area of wheat (0–5%), while the minimum areas (A_{min}) are determined for other crops (A_{min} is 20% smaller than the current acreage). The model shows that reducing crop area is an effective means of alleviating drought losses.

Table IV. Maximum demand (MCM) of networks and water distribution for the Zayandeh Rud basin in 1999 using OPM and ERM methods

Irrigation system	Maximum demand (V_M)	Optimization		Equitable reduction	
		V_{OPM}	V_{OPM}/V_M	V_{ERM}	V_{ERM}/V_M
Nekooabad LB	260	130	0.48	140	0.52
Nekooabad RB	100	50	0.5	50	0.52
Mahyar	220	120	0.54	110	0.52
Borkhar	210	110	0.52	110	0.52
Abshar LB	260	130	0.52	130	0.52
Abshar RB	140	70	0.52	70	0.52
Rudasht	460	260	0.56	240	0.52
Small-scale systems	380	180	0.49	200	0.52
Total	2030	1050	0.52	1050	0.52

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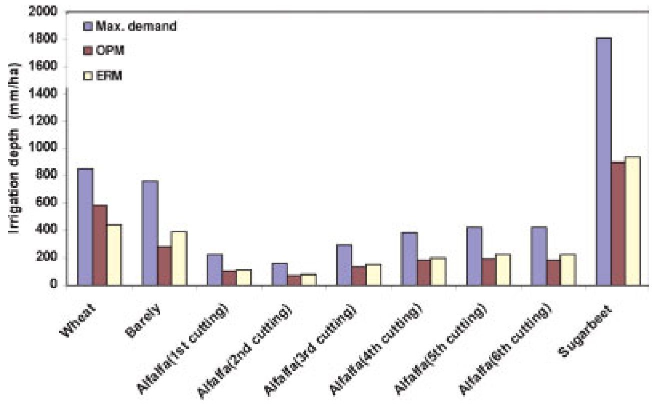

Figure 4. Comparison of maximum crop water demand and allocated water based on OPM and ERM methods during the 1999 drought in the Zayandeh Rud irrigation system. This figure is available in colour online at wileyonlinelibrary.com

Table V. Planted acreage (ha) using the OPM (upper) and ERM (lower) methods (ha)

Crops	Network						Rudasht	Small-scale systems
	Nekooabad LB	Nekooabad RB	Mahyar	Borkhar	Abshar LB	Abshar RB		
Wheat	11 900	5 000	15 400	11 000	13 600	7 900	28 800	19 600
	12 500	5 100	15 400	11 000	13 600	7 900	28 800	19 600
Barley	3 800	2 100	5 000	1 800	2 200	1 000	7 400	12 400
	4 700	2 700	6 300	2 200	2 800	1 200	9 200	15 500
Alfalfa	4 000	1 400	1 200	2 000	2 500	1 700	3 300	3000
	5 000	1 700	1 500	2 500	3 100	2 100	4 200	3 700
Sugar beet	1 200	—	700	2 200	2 800	1 100	—	950
	1 500		850	3 500	3 500	1 400		1 200
Potato	—	—	—	—	—	—	3 900	—
							4 800	

Table VI. Water calculated (MCM) for crop growing stages using the OPM (upper) and ERM (lower) methods

Crop	Vegetative	Flowering	Yield formation	Ripening
Wheat	15	240	250	80
	80	260	330	180
Barley	20	25	160	80
	45	185	320	210
Alfalfa (1st cutting)	70	—	30	—
	165		60	
Alfalfa (2nd cutting)	60	—	10	—
	130		25	
Alfalfa (3rd cutting)	80	—	60	—
	160		135	
Alfalfa (4th cutting)	185	—	—	—
	390			
Alfalfa (5th cutting)	100	—	90	—
	200		220	
Alfalfa (6th cutting)	100	—	80	—
	206		220	
Sugar beet	140	520	240	—
	170	1 130	510	
Potato	—	—	—	—

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Table VII. The total crop yield (t) using the OPM and ERM methods in Nekooabad LB

Crop	OPM	ERM
Wheat	807 600	385 600
Barley	89 500	117 700
Alfalfa (1st cutting)	31 000	38 300
Alfalfa (2nd cutting)	30 000	38 300
Alfalfa (3rd cutting)	30 900	38 300
Alfalfa (4th cutting)	25 800	38 300
Alfalfa (5th cutting)	30 300	38 300
Alfalfa (6th cutting)	29 800	38 300
Sugar beet	342 000	359 500
Potato	146 100	44 600

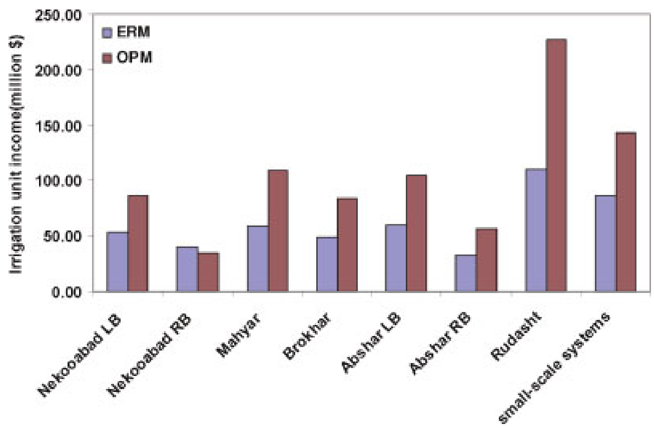

Figure 5. Resulting incomes from the IUs using the OPM and ERM approaches. This figure is available in colour online at wileyonlinelibrary.com

As pointed out above, the above calculations resulted in a new irrigation schedule for the IUs during the drought of 1999. The summarized output in Table VI shows the irrigation depths for the crops at different growing stages in Nekooabad (RB) using the two methods.

The final yields using the two approaches are shown in Table VII. A significant increase in potato and wheat production can be seen with application of the OPM irrigation schedule (up to 200%). However, production of alfalfa, sugar beet and barley declined up to 20%. These OPM changes increased the total income from the IUs by about 72% (Figure 5).

CONCLUSION

This research work compared the optimization and traditional equitable reduction methods to reduce drought losses in the Zayandeh Rud irrigation networks during the 1999 drought. The following conclusions can be drawn from this study:

- The three-layer modelling set-up adequately performs the required calculations for water allocation within the IUs and presents the irrigation scheduling in detail;
- The OPM approach increased the network income up to 42% compared with the traditional method and should be considered for developing drought planning in agricultural areas;

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- The responses of the wheat and potato crops were more significantly positive for water allocation based on the OPM;
- The results show the importance of drought planning to alleviate losses and it revealed how changes in irrigation scheduling and crop acreage can be effective mitigation measures;
- Although the scope of the paper deals with droughts, it has a generic methodology and can be applied to evaluate different scenarios for deficit irrigation and other irrigation systems with minor modifications;
- In spite of the positive results for the OPM, execution of the ERM method remains easier for water authorities. To improve the operational capability of the OPM method, training programmes for the basin's water managers and extension learning programmes for farmers should be considered;
- Forecasts of annual stream flow and temperature can improve the capability of the OPM. This is currently being studied by the authors.

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