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Determination of optimal and and water allocation under limited water resources using soil water balance in Ordibehesht canal of Doroodzan water district

Z. Rabie[1], **T. Honar**[1*], **M. Mehdi Bateni**[2]

[1]Department of Water Engineering, College of Agriculture, Shiraz University, Shiraz, I. R. Iran
[2]Department of Water Engineering, College of Agriculture, Urmia University, Urmia, I. R. Iran

* Corresponding Author: toorajhonar@yahoo.com

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ABSTRACT- Inadequate water supply is the major problem for agriculture in arid and semi-arid regions. Thus, effective management should be considered for water resources planning. In this research, a model was provided which is able to estimate optimal land and water allocation in the Doroodzan irrigation network. Optimal water management model was used at farm level to evaluate different deficit irrigation (DI) strategies at various periods of crop growth. Genetic algorithm toolbox by MATLAB (Mathworks, 2009) software was used for benefit optimization considering practical constraints. Results showed that deficit irrigation technique significantly reduced water allocation and increased the crops cultivation area in the region. In addition, increase in water price and the occurrence of drought resulted in cropping pattern change and led to including crops with high economic values. Application of this model ensures the optimal use of available water resources in all conditions, especially under drought condition. The proposed model is capable of defining water management plan with regard to the amount of available water and price of water and product, for simultaneous optimal land and water allocation.

INTRODUCTION

Databases on water use traditionally show three types of water use: water withdrawals in the domestic, agricultural and industrial sectors, respectively (Gleick, 1993; Shiklomanov, 2000; FAO, 2003).

Proper management of existing water resources is very important, especially in the agriculture sector that is the predominant consumer of water in most countries (Shiklomanov, 2000).

A proper solution for optimum allocation and utilization of water resources in arid and semi-arid areas is application of deficit-irrigation. Proper water management and optimal cropping pattern is achieved by using the mathematical model and software facilities. Since 1960s, linear programming (LP) has been widely used to determine the optimal cropping pattern. The goal of LP is maximizing or minimizing the objective functions by considering constraints and decision variables. Linear programming is based on the certainty assumption, but some of the variables such as the amount of available water and agricultural water prices are uncertain. Thus, LP does not calculate the cropping pattern for optimization, precisely. A new method in optimization has been proposed which includes nonlinear programming, positive mathematical programming and possibilistic programming.

In previous investigations, some of the proposed methods have been used for optimization of cropping pattern. Hall and Butcher (1968) developed a dynamic programming (DP) model to allocate irrigation water over different periods of crop growth. Fogel et al. (1976) established a direct link between irrigation water management and inventory theory. Ghahraman and Sepaskhah (1991) were probably the first who proposed a nonlinear programming (NLP) algorithm, based on Lagrangian multiplier accompanied with Kuhn-Tucker conditions, for partial irrigation scheduling. Ghahraman and Sepaskhah (2004) developed two LP and NLP stochastic DP algorithmes which were convenient mathematical optimization methods for irrigation water management. This algorithm determines the optimal reservoir storage at the end of each season for a maximized annual performance of the system under the conditions of reservoir storage at the beginning of the season and disaggregated seasonal rainfall and river inflow. In fact, Ghahraman and Sepaskhah's (2004) model was used to optimize water allocation for a specified cultivation pattern and the model cannot estimate the optimal land and water allocation in different stages of crop growth simultaneously.

To optimize the cropping pattern, Shabani and Honar (2006) designed four models for different conditions. They used LP and genetic algorithm (GA) in their research in Ordibehesht canal of Doroodzan water district; however, these models could not optimize land and water allocation simultaneously. In fact, irrigation trategies were predefined as 131 scenarios for the problem.

The main purpose of the present research is to maximize the farmers' farm benefits with computing acreage and deficit-irrigation in different periods of crop growth. Therefore, the proposed model is able to simultaneously optimize land and water allocation through millions of scenarios.

MATERIALS AND METHODS

In this study, the optimal cropping pattern, deficit irrigation strategy and water allocation are simultaneously determined in the Ordibehesht canal of Doroodzan irrigation networks.

Study area

This study was conducted in an irrigation network located in the north part of Fars Province which was fed by Doroodzan Reservoir. Multipurpose Doroodzan Reservoir project is located on the Kor River, in Marvdasht plain, Fars province. Doroodzan dam includes a main channel and three main irrigation channels, including the primary left channel, the primary right channel (Ordibehesht) and the secondary right channel (Hamoon). The Ordibehesht main channel was considered in this study, which includes 12 of the third degree channels.

A previous study conducted in the same region showed that the average field size is 2-15 ha (Shaabani, 2008). The dominant cultivated crops in the studied area are wheat, barley, grain maize, silage maize, sugar beet, and rice. Information about water sensitivity factor at different crop growth stages is given in Table 1.

Table 1. Yield response factor (K_y) at different growing periods

Crop	Used resource	Establishment	Beginning of vegetative	End of vegetative	Flowering	Yield formation	Ripening
Wheat	Aryan (1992)	0	0.12	0.15	2.1	0.33	0.2
Barley	Aryan (1992)	0	0.12	0.15	1.5	0.4	0.14
Sugar beet	Hill et al. (1983)	0.12	2	2	-	0.36	0.12
Grain maize	Honar and Sepaskhah, (1996)	0.1	1.42	1.42	0.87	0.91	0.3
Silage maize	Honar and Sepaskhah, (1996)	0.1	1.42	01.42	0.87	0.91	0.3
Rice	Sepaskhah's personal communication, (2003)				1.35		

Objective function

The objective function, which is net benefit in this case, is as follows:

$$Z=\sum_{i=1}^{ncrop}\left[Y_{p_i}\times P_{c_i}\times\Pi_{j=1}^{kperiod}\left(1-\mathrm{K}y_{i,j}\times X_j\right)-C_i\right]A_i-P_W\sum_{i=1}^{ncrop}IR_i \quad (1)$$

where Y_p is potential yield (Kg ha^{-1})); P_c is price (Rial kg^{-1}); A is area of crop cultivation (ha); C is total fixed costs except water cost of crop (Rial ha^{-1}); P_w is unit price of irrigation water (Rial m^{-3}); IR is total irrigation water (m^3 ha^{-1}) and K_y is yield response factor. Subscript i stands for specific crop and subscript j is due to different growth stages. X is the amount of relative reduction in irrigation (smaller or equal to 1).

In Eq (1), land (A) and water allocation (X) are unknown variables. The objective function is non-linear and there are too few degrees of freedom; i.e., more unknown parameters than constraints.

In this study, the following equation was used to calculate water production function (Doorenbos and Kassam, 1979):

$$\frac{Y_a}{Y_p}=\Pi_{j=1}^{kperiod}\ [1-ky_j(1-\frac{ET_a}{ET_p})j] \quad (2)$$

where Y_a and Y_p are actual and potential yields; respectively, ET_a and ET_p are actual and potential evapotranspiration, respectively; other variables and their subscripts are defined the same as those in Eq (1).

Constraints

Soil water balance

Soil water balance equation may be used as a constraint for each given crop (Eq. 3). It is assumed that the occurrence of surface runoff was ignored under deficit irrigation. The equation is as follows (Ghahraman and Sepaskhah, 2004):

$$SM_{i,t+1}Root_{i,t+1}=SM_{i,t}Root_{i,t}+Rain_t+IR_{i,t}-Eta_{i,t}-DP_{i,t}+SM_i\,(Root_{i,t+1}-Root_{i,t}) \quad (3)$$

where SM is the available soil water per unit depth, Root is the average root depth, Rain is the rainfall amount, IR is the gross irrigation water allocated, and AET and DP are the actual evapotranspiration and deep percolation, respectively. Subscript i stands for specific crop and subscripts t and t+1 are due to the beginning and end of the irrigation time interval, respectively. Subscript i stands for specific crop and subscripts t and t+1 are due to the beginning and end of the irrigation time interval, respectively.

Irrigation application efficiency (Ea) of less than 100% causes some percolation of water to below root zone. Therefore, the following constraint must be included in the model structure to guarantee deep percolation occurrence:

$$Dp\ i,t \geq IR\ i,t.\ (1\text{-}Ea) \tag{4}$$

In the study area with semi-arid climatic conditions, a calendar year is usually divided into two distinct seasons of unequal lengths; i.e., the dormant season (between November 22 and February 9) and non-dormant season (between February 9 and November 22 of the next year). Due to higher rainfall during the dormant season, it is assumed that soil water content at the beginning of the non-dormant season is at FC. This is supposed to be an initial condition for summer crops as well as for winter ones as they become active at the beginning of the non-dormant season. Winter crops (wheat), however, require an extra boundary condition. They are cultivated at mid-autumn prior to which there is nearly as long a period of no rainfall. Therefore, permanent wilting point (PWP) for soil water content is considered as boundary condition in this case (Ghahraman and Sepaskhah, 2004).

A sine function to assess the dynamic aspect of root growth and its temporal variation (Borg and Grimes, 1986) was used in the model.

The available soil water content for any crop i and at any time interval t cannot exceed water content at field capacity (FC) and must be greater than minimum soil water content (PWP);

$$Pwp \leq SM_{i,t} \leq FC \qquad \forall\, i\ \&\ t \tag{5}$$

Actual evapotranspiration constraints

It is assumed that ET_a is equal to ET_P until the p fraction of the total available soil water (FC-PWP) over the root depth has been depleted. For a given crop, ET_a, is determined by the evaporative demand of the air when available soil water does not restrict evapotranspiration. Beyond the p depletion fraction of the soil total available water, ET_a will fall below ET_P and ET_a will depend on the remaining soil water content and $ET_{P.}$ In general, the following constraints are governed:

$$ETa_{i,t} \leq \frac{[(SM_{i,t} - PWP_C)Root_{i,t} + Rain_t + IR_{i,t} - DP_{i,t}]}{[(1-P_i)(FC_i - PWP_i)Root_{i,t}]} ETp_{i,t} \quad \forall i\,\&\,t \tag{6}$$

where (FC–PWP) is total soil available water, and P is the soil water depletion fraction, the value of which depends on specific crop and ETp (Doorenbos and Kassam,1979).

Water allocation constraints

Total amount of irrigation water at consecutive time intervals (IR) for all crops cannot exceed the seasonal available water for allocation (R):

$$\textstyle\sum_i \sum_t IR_{c,t} \quad A_c = R.E_c \tag{7}$$

where IR and R have the units of mm and million cubic meter, respectively, and E_c is conveyance efficiency.

Maximum reduction of irrigation water

Maximum reduction of irrigation water based on allowable level of yield reduction is different for various crops. Previous studies showed that this value is 40% for wheat (Hosseini, 2005), 20% for barley, 36% for rice (Sepaskhah et al., 2006), 30% for grain maize, 30% for silage maize (Parand and Sepaskhah, 2006), and 20% for sugar beet (Sepaskhah and KamgarHaghighi, 1994; Jalilian et al., 2001).

The genetic algorithm parameters required to achieve the best answer were: generation 200, population 100, composition percentage 0.5, which were determined through trial and error over reasonable range.

RESULTS AND DISCUSSION

Wheat and barley received higher levels of deficit-irrigation in fall. In fact, the model suggested full-irrigation strategy during spring cultivation. This may be due to the type of crops grown in fall and favorable distribution of spring rainfall and long growing season of wheat and barley. Since barley is more resistant to drought stress, higher levels of deficit-irrigation were applied on barley based on the model simulation. Finally, the final net benefit out of one ha of the cropping pattern over one year cultivation was obtained as $3010. The deficit-irrigation levels were 2, 40 and 24 percent during establishment, and end of vegetative and ripening stages, respectively (Table 2). During establishment period of wheat when yield response factor is negligible ($K_y \approx 0$), the most severe deficit–irrigation was applied. Insignificant water shortage during the vegetative period of wheat when K_y value is relatively small had a negligible effect on crop development. Applying deficit-irrigation during the ripening period had a small effect on wheat yield.

The flowering period is the most sensitive growth stage to water stress because seed formation of pollen and fertilization happens simultaneously which can reduce the final yield. In this period, water shortages can reduce the root growth and may even completely stop. In this case, the crop suffers from significant damages. Hot air and dry winds, if combined with water shortages, cause incomplete grain filling and development of bad and wrinkled grains, as shown in Table 2. The model has not considered any deficit–irrigation in flowering and yield formation stages to achieve greater profits.

During the establishment and vegetative periods, both crops had similar K_y values (Table 1). In vegetative period, barley received higher levels of deficit–irrigation. This was mainly due to the lower economic price of barley compared to that of wheat. This shows that the model is capable of considering the price and also includes it during simulation (Table 2).

Sugar beet received no acreage due to the lower net benefits achieved by sugar beet planting (low final prices and higher costs in comparison to those of other crops). Grain maize was allocated the most acreage in the second period of cultivation by applying a deficit-irrigation of 9% during the establishment period and 4.4 ha acreage. These show that farmers are recommended not to grow sugar beet.

The optimal cropping pattern suggested 1 ha acreage for rice and full irrigation, and no silage maize. However, it should be noted that the model considered full irrigation for rice because the coefficient K_y at different growth periods of rice was not available. It is concluded that the model can choose acreage and deficit–irrigation in different periods in order to achieve the greatest net benefits.

The impact of water price changes on the optimal model is shown in Table 3. The water price changed from current value of $2.3 to $2.8 and then to $3.7(20% and 60% increases). The second value is one which is intended to be the next future price and the ultimate price is approximately one which is free of any subsidy or support. In addition, the model showed the same results for up to $4.6. Barley acreage decreased due to lower profits and higher level of deficit–irrigation when the water price increased by 20% (Table 3). Deficit–irrigation increased from 2% to 34% for barley. At the beginning of the vegetative growth, acreage of wheat and maize was added due to more profits, and deficit–irrigation of maize increased from 9% to 24.5% during the establishment period (Table 3). Finally, final net benefit for optimal land and water allocation was $2968. But, with 60% rise in water price, the model tended to increase the acreage of those crops with high yield and low water consumption, the result of the acreages of wheat and grain maize was reduced while that of barley and silage maize was increased. In this case, final net benefit was $2579. The most important point of increasing the water price was changing the deficit–irrigation strategy during the cultivation period. In the previous models, due to manually entering the deficit-irrigation strategies during the cultivation period, it was not possible to precisely determine the impacts of water price which increases the amount and time of irrigation. Entering the amounts of deficit-irrigation manually in the previous models has decreased the possibility of making optimal decision and only could lead to optimal selection among the pre-determined strategies. Thus, based on the results of this study, it can be concluded that with increasing water prices and getting closer to the actual price, the deficit–irrigation strategies are more favorable and deficit–irrigation practices are more effective than the current status in reducing water consumption and increasing farmers' income.

Table 2. Results of optimal cropping pattern

Crop	Establishment	Beginning of vegetative	End of vegetative	Flowering	Yield formation	Ripening	Area(ha)
X(%)		Level of Deficit-irrigation					
Wheat	40	0	2	0	0	24	4.54
Barley	40	2	24	0	0	40	2.2
Sugar beet	0	0	0	-	0	0	0
Grain maize	9	0	0	0	0	0	4.4
Silage maize	0	0	0	0	0	0	0
Rice	0	0	0	0	0	0	1

Table 3. Results of the impact of price increases on cropping pattern

	Crop	Establishment	Beginning of vegetative	End of vegetative	Flowering	Yield formation	Ripening	Area(ha)
	X (%)			Level of Deficit-irrigation				
20% price increase	Wheat	40	0	2	0	0	24	4.54
	Barley	40	2	24	0	0	40	2.2
	Sugar beet	0	0	0	-	0	0	0
	Grain maize	9	0	0	0	0	0	4.4
	Silage maize	0	0	0	0	0	0	0
	Rice	0	0	0	0	0	0	1
60% price increase	Wheat	40	0	0	0	0	21	1.0195
	Barley	40	30.7	29.7	0	0	40	5.8
	Sugar beet	0	0	0	-	0	0	0
	Grain maize	12.53	0	0	0	0	0	0.39
	Silage maize	0	0	0	0	0	0	5.35
	Rice	0	0	0	0	0	0	1

Effect of water shortage on model results

Considering the reduced applied irrigation water from 140017 m^3 to 80487 m^3 for the 7 ha area and 1 year growing season, results of optimal land and water allocation are indicated in Table 4. The acreage was reduced by reducing the total amount of water (total acreage was less than 7 ha) and deficit–irrigation level of wheat increased from 24% to 39.2% in ripening stage and for barley, from 2% to 15% at the beginning of vegetative stage; sugar beet with zero acreage and grain maize with 0.74 ha and 5.2% deficit-irrigation level at establishment stage, silage maize with 0.121 ha acreage and 3% of deficit-irrigation at establishment stage and rice with 1 ha acreage and full irrigation. In fact, drought caused the acreage of wheat to increase in fall and reduce in spring crops. In contrast to the status that water is normally available for farmers, drought condition leads the deficit-irrigation level to increase during fall cultivation. The higher economic value of wheat and its higher net benefit per area are the reason for increasing its cultivation acreage in fall. Therefore, the model suggested the crops with higher economic value and leads to more optimal use of available water by farmers for higher economic productivity. This strategy gave $2257 as final net benefit out of each ha of the proposed cropping pattern over one growth season (Table 4).

Table 4. Results of the impact of water shortage in cropping water

Crop	Establishment	Beginning of vegetative	End of vegetative	Flowering	Yield formation	Ripening	Area(ha)
X (%)			Level of Deficit-irrigation				
Wheat	40	0	2	0	0	39.2	5.23
Barley	40	15	19	0	0	21	0.168
Sugar beet	0	0	0	-	0	0	0
Grain maize	5.2	0	0	0	0	0	0.74
Silage maize	2.8	0	0	0	0	0	0.121
Rice	0	0	0	0	0	0	1

Furthermore, for a similar cropping pattern, the amount of consumed water was compared between the full irrigation and deficit-irrigation strategies. For this purpose, deficit-irrigation strategy in the model was selected from Table 2 and compared to the full irrigation. It should be noted that crops proposed as the optimal deficit–irrigation pattern in Table 2 were also evaluated for full irrigation scenario. According to the comparison of the two states, reduced applied water can be used to increase the cultivation area by 12.24% (Table 5)

Table 6 summarizes the optimal land/water allocation strategy achieved via application of the proposed model.

Table 5. Comparison of full and deficit-irrigation states of consuming water

Crop		Wheat	Barley	Sugar beet	Grain maize	Silage maize	Rice	Consumed water	Reduction of consuming water after the appliance of deficit-irrigation (m^3/ha)
Area		4.54	2.2	0	4.4	0.08	1	35260.01	
Deficit-irrigation		0	0	0	0	0	0		
Growth stages crop		Establishment	Beginning of vegetative	End of vegetative	Flowering	Yield formation	Ripening	Consumed water	
Water reduction percentage for	Wheat	40	0	2	0	0	24	34035.43	12.24
	Barley	40	2	24	0	0	40		
	Sugar beet	0	0	0	0	0	0		
	Grain maize	9	0	0	0	0	0		
	Silage maize	0	0	0	0	0	0		
	Rice	0	0	0	0	0	0		

Table 6. Optimum strategy for land/water allocation of the selected crops

Crop	Acreage	Percentage of deficit–irrigation during			
		Establishment stage	Beginning of vegetative stage	End of vegetative stage	Ripening stage
Wheat	4.54	40	---	2	24
Barley	2.2	40	2	24	40
Sugar beet	---	---	---	---	---
Grain Maize	4.4	9	---	---	---
Silage Maize	---	---	---	---	---
Rice	1	0	0	0	0

CONCLUSIONS

Based on the model results, in the area studied, deficit-irrigation can reduce applied irrigation water and increase the acreage of cultivated crops simultaneously. The model allocated most of the cultivated land to wheat and grain maize at the first and second cultivation season, respectively. By determining the optimal land and water allocation simultaneously, the proposed model leads to more precise selections of the acreage which is important in agricultural water resources management.

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تحقیقات کشاورزی ایران (۱۳۹۴) ۳۴(۲) ۲۱-۲۸

تخصیص بهینه زمین و آب در شرایط کمبودمنابع آب با استفاده از روابط بیلان آب در خاک در منطقه کانال اردیبهشت شبکه درودزن

زهرا ربیعی[1]، تورج هنر*[1]، محمد مهدی باطنی[2]

[1]بخش آبیاری، دانشکده کشاورزی، دانشگاه شیراز، شیراز، ج. ا. ایران.
[2]گروه مهندسی آب، دانشکده کشاورزی، دانشگاه ارومیه، ارومیه، ج. ا. ایران

*نویسنده مسئول

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واژه های کلیدی:
مدیریت آب کشاورزی
کم آبیاری
آلگوریتم ژنتیک
الگوی کشت بهینه

چکیده- عدم تأمین آب کافی مشکل عمده کشاورزی در مناطق خشک و نیمه خشک است. لذا مدیریت مؤثری باید برای برنامه‌ریزی منابع آب در نظر گرفته شود. در این تحقیق، مدلی ارائه شد که قادر به برآورد تخصیص بهینه زمین و آب در شبکه آبیاری درودزن است. مدل بهینه مدیریت آب در مقیاس مزرعه به منظور بررسی راهکارهای مختلف کم آبیاری (DI) در مراحل مختلف رشد گیاه مورد استفاده قرار گرفت. جعبه ابزار الگوریتم ژنتیک MATLAB (محصول Mathworks، ۲۰۰۹) به عنوان نرم افزار بهینه سازی با وجود محدودیت‌ها استفاده شد. نتایج نشان داد که روش‌های کم‌آبیاری، تخصیص آب را به طور قابل توجهی کاهش و سطح زیر کشت محصولات زراعی را در منطقه افزایش می‌دهد. علاوه بر این، افزایش قیمت آب و وقوع خشکسالی منجر به تغییر الگوی کشت و کشت محصولات با ارزش اقتصادی بالا می‌گردد. استفاده از این مدل استفاده بهینه از منابع آب در دسترس را در همه شرایط، بخصوص تحت شرایط تنش خشکی، تضمین می‌کند. مدل پیشنهادی قادر به تعریف طرح مدیریت آب با توجه به مقدار آب در دسترس، قیمت آب و محصول، برای تخصیص همزمان بهینه زمین و آب است.