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Full Length Research Paper

Proposed model for efficient water management at Razmgan irrigation project, a semi-arid region in Khorasan, Iran

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Yield decrease caused by crop water deficit, especially in low scale farms and established orchards at semi-arid regions, results in a significant decrease in agricultural productivity. In this study an optimal water release of the reservoir based on prioritization in water allocation to the crop sensitive growth periods was linked to a non-linear optimization model in order to enhance the net income in a given cropping pattern. The proposed model by optimal water allocation for each growth stage of the crop reduced the impact of the imposed water stress in the dry season and increased the net income. The LINGO software has been used to evolve the optimal amounts of both water and land for the existing crops. The proposed model was applied for Razmgan area a semi-arid region which is located 10 km south of the Shirvan city, northern Khorasan province, Iran. Various scenarios of the water release from the existing auxiliary reservoir, to remove/reduce the imposed water-stress during the crop growth stages have been explored. Results show in the optimal case, whole of the existing water deficit is removed in months of July, August, September, October and November, only 13% of the deficit remains in month of May and in month of June the amount of deficit decreases to 42.16%. Also the proposed model is efficient and annual net income will increase to 26.21%, moreover, the total water consumption will decrease to 10.71% than the current status.

Key words: Water deficit, agriculture income, sensitive growth stages, cropping pattern, optimal water release.

INTRODUCTION

In mountainous areas of Iran base flow in rivers is used to supply the irrigation water to the farms. In these regions irrigation needs are received by river intakes as the right of water. Insufficient right of water during the dry season causes crops confront to water-stress phenomenon. When occurrence of the water stress coincides with crop sensitive growth periods, the crop yield and farmers' income decrease. Yield decrease under water deficit conditions has been investigated by many researchers like Doorenbos and Kassam (1979), Nuss and English (1982), Samadi and Sepaskhah (1984), Martin and Heermann (1984), Dierckx et al. (1988), English and Nakamura (1989) and Yuan et al. (1991). An efficient approach against the water stress in the dry season is to utilize the surplus water which is more than the need in the wet season. The surplus water would be stored in an auxiliary reservoir for use in the water deficit period. Regards to the vital importance of these reservoirs in minimizing of the water deficit impact, their optimal operation is a significant factor. Usually, due to the existing limitation, the surplus stored water volume is less than the water deficit volume, so, prioritization for water allocation to sensitive growth periods of the crop can result in an optimal operation for these reservoirs. There are many studies about agricultural water optimization. To allocate a certain amount of a resource, optimally, in order to achieve the proposed objectives (maximizing or minimizing), linear programming (LP)

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Figure 1. Location of Razmgan area on the map of Iran.

models are applied widely.

Hall and Dracup (1970), Kheper and Chaturvedi (1982), Panda and Kheper (1985) and Mainuddin et al. (1997) developed a linear programming model to maximize net return and select an optimal cropping pattern. Vivekanandan and Viswanathan (2007) investigated optimal allocation of land and water for a cropping pattern using LP model. Also Ghahraman and Sepaskhah (1991, 1997a, b), Ghahraman and Sepaskhah (1996) used a simplified form of a non-linear programming for a single crop and for multi-cropping pattern in optimization.

Study area

The proposed model is applied for the Razmgan area $(37^{\circ},18'N$ latitude and $57',55'E$ longitude$)$ which is located in 10 km south of the city of Shirvan, northern Khorasan province, north east of Iran, because of adequate data in this area (Figure 1). In this area, the average annual precipitation is only 287 mm while the mean annual temperature is 11.5°C and annual evaporation from the free water surface reaches to 1679 mm which corresponds to semi-arid conditions. Also average annual evapotranspiration reaches to 1211 mm. Water requirements for irrigated areas are supplied from the Gelyan River. The river watershed area in the Razmgan outlet is 185 km² with 26.71 km long for the main channel in this point. Annual volume of the surface runoff in the Razmgan outlet is 23.45 MCM. For the study area, there is an auxiliary reservoir, which has been

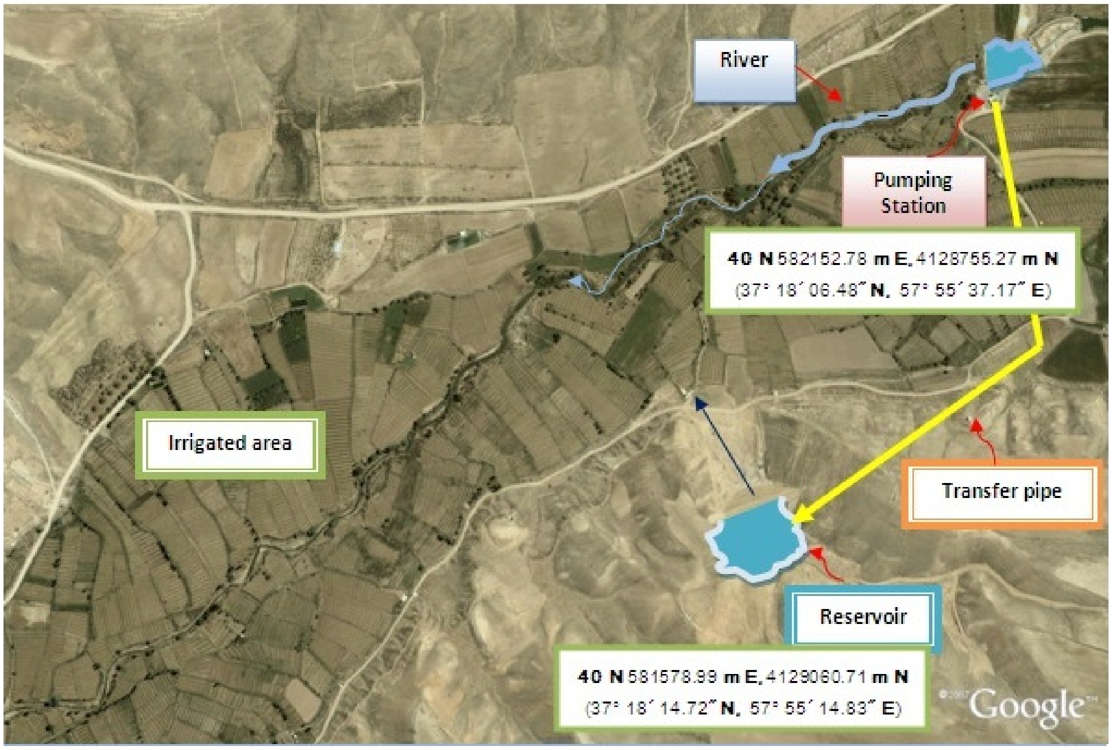

Figure 2. An image of the Razmgan study area including: the river; intake; pumping station; auxiliary reservoir and a part of cultivated area.

constructed out of the river, over the farmlands to store the surplus water which flows in the river in months of November to April (Figure 2). Because of the topographical limitation the total volume of this reservoir is 0.70 MCM. Water is pumped to the reservoir by a pumping station and based on the existing capacity, pumping is started at the beginning of November and continues until the end of April. Pumping capacity for months of November, December, March and April, is 50 lit/sec for 18 h daily, so the total pumped water during these four months will be 388000 m^3 Pumping for months of January and February is carried out with 65 L/s for 18 h daily, so the total transferred water in these two months will be 252000 m^3. Therefore total annual pumped water to the reservoir will be 640000 m^3.

As the total losses during the reservoir operation period, is 60000 m^3 (KPM, 2002), so the total useful volume of the reservoir will be 580000 m^3, which must be distributed between critical months. Also maximum discharge capacity from the reservoir outlet is 100 lit/sec. All of the mentioned limitations result in a limited annual volume of water to decrease the impact of water deficit, so optimal release from the reservoir is very significant.

METHODOLOGY AND MODEL FORMULATION

In the field of agricultural water optimization there are many different water production functions for mathematical modeling. For deriving irrigation scheduling under water deficit conditions, the effects of crop water-stress must be considered on different growth stages of the crop, simultaneously. To estimate yield decrease because of water deficit, one famous water production function which presented by Stewart and Hagan (1973) and used by Doorenbos and Priutt (1977), Rao et al. (1988a), De Juan et al. (1996), Reca et al. (2001) and Ghahraman and Septemberaskhah (2004) is:

$$\frac{Y_a}{Y_m} = \prod_{i=1}^{m}\left[1 - K_{yi}\left(1 - \frac{ET_{ai}}{ET_{mi}}\right)\right] \quad (1)$$

Where Y_a and Y_m are actual and maximum crop yields respectively; i and m are a particular crop growth stage and the total number of these stages respectively; ET_{ai} and ET_{mi} are the actual and maximum evapotranspiration for growth stage i respectively; K_{yi} is the crop yield response factor which is a factor to quantify response of yield to water deficit.

Doorenbos and Kassam (1979), based on experimental field data and respective analysis, derived the values of K_y for 33 crops which validated by FAO and have used by several investigators to predict crop-yield responses at several locations in the world like Hayes et al. (1982), Terjung et al. (1984a, b), Montazar and Rahimikhob (2008) and Montazar and Riazi (2010). As an approximation for Equation 1, the term of $\frac{ET_{ai}}{ET_{mi}}$ can be substituted by the ratio of water used to potential water demand (Montazar and Riazi, 2010), so Equation 1 can be rewritten as:

$$\frac{Y_a}{Y_m} = \prod_{i=1}^{n} [1 - K_{yi}(1 - \frac{W_{ai}}{GIR_i})] \quad (2)$$

Where, W_{ai} is the applied water for growth stage i (water shortage conditions) and GIR_i is the gross irrigation requirement (potential water need) for growth stage i. W_{ai} and GIR_i would be in $(m^3. ha^{-1})$ or $(mm. ha^{-1})$. Equation 2 is a crop production function than water for one crop cultivation pattern and in this Equation the $\frac{Y_a}{Y_m}$ ratio is the yield ratio for one crop. GIR in $m^3. ha^{-1}$ is obtained from the Equation 3:

$$GIR = \left(\frac{NIR}{IEF}\right) * 10 \quad (3)$$

Where, NIR is the net irrigation requirement in $mm. ha^{-1}$ and IEF is the irrigation efficiency.

Maximum yield is obtained when the best conditions would be prepared for the growth. The most important of these conditions are: climate factors, soil moisture and irrigation management. Certainly, choosing an optimal variety of the crop which is well-adapted with growing environmental conditions would be a significant factor to achieve the maximum yield. The crop yield responses to water deficit. When water supply is insufficient for meeting the crop water requirement because of water stress occurrence in different growing periods, the obtained yield (actual yield), will fall below the maximum amount, so in Equation 2 the ratio of $\frac{Y_a}{Y_m}$ is the rate of yield decrease because of water deficit. In this study, the objective function is specified as the net income maximization which is resulted from some crops in the existing cropping pattern, considering the relative constraints. If $= \frac{Y_a}{Y_m}$, then the gross income for *n* crops of a cropping pattern is shown as:

$$GI = \sum_{j=1}^{n} (P_j\, YM_j\, YAP_j)\, A_j \quad (4)$$

Where, GI is the gross income obtained by n crops in an area; P_j is the sale price (farm gate price) of the crop j in USD/kg; YM_j is the maximum crop production (maximum yield) for crop j when maximum gross irrigation need (GIR) is supplied, in kg/ha; YAP_j is the ratio of $\frac{Y_a}{Y_m}$ from Equation 2 for crop j; A_j is the allocated cultivated area of crop j in ha. The production costs for one hectare of each crop can be presented as:

$$PC_j = C_j + C_w . GIR_j \quad (5)$$

Where, PC_j is the production costs of the crop j in USD; C_j is the production costs of crop j without considering water price in USD; C_w is the water price (irrigated water costs) in USD/m^3; GIR_j is the gross irrigation requirement for the crop j in m^3

The net income of the yield for one hectare of each crop is resulted from the difference of gross income and production costs:

$$NI_j = GI_j - PC_j \quad (6)$$

Where, NI_j is the net income of crop j.

So the objective function for n crops of the cropping pattern will be as:

$$MaxNI = \sum_{j=1}^{n} (P_j . YM_j . YAP_j - C_j - C_w . GIR_j)\, A_j \quad (7)$$

The objective function is a non linear function because it has a non linear term (YAP_j), so this model is a problem of non linear programming and constraints are as:

$$\text{land constraint}: \sum_{j=1}^{n} A_j \leq TA \quad (8)$$

$$\text{maximum and minimum allocated land}: 0.8\, a_j \leq A_j \leq 1.2\, a_j \quad (9)$$

C) $$\sum_{j=1}^{n}\sum_{i=1}^{m} W_{ai} . A_j \leq TAW \quad (10)$$

d) $$\sum_{j=1}^{n} MW_{aj} . A_j \leq MAW \quad (11)$$

e) $$MW_{aj} \leq MGIR_j \quad (12)$$

f) $$\left(1 - \frac{W_{ai}}{GIR_i}\right) \leq 0.5 \quad (13)$$

Where, TA is the total cultivated area in *ha*; a_j is the existing cultiveted area for crop j; TAW is the total available water in m^3; MW_{aj} is the monthly applied (allocated) water for crop j in $m^3.ha^{-1}$; MAW is the monthly available water in m^3; $MGIR_j$ is the monthly gross irrigation requierment for crop j in $m^3.ha^{-1}$.

Based on constraint (a) total allocated areas for whole of the crops shouldn't be more than the total existing cultivated area. According to constraint (b) in the study area based on managemental strategy, maximum and minimum allocated area for each crop is 20%. Constraint (c) states the total applied water for whole of the growth stages of the whole of crops can't exceed the total available water. Since the available water is as monthly volums of the river right of water and also the evapotranspiration data for the study area are as monthly values, so monthly applied water for each crop can't exceed the monthly available water and monthly crop gross irigation requiermenr (constraints d and e). Constraint (f) is the maximum allowed water deficit in using values of Ky for

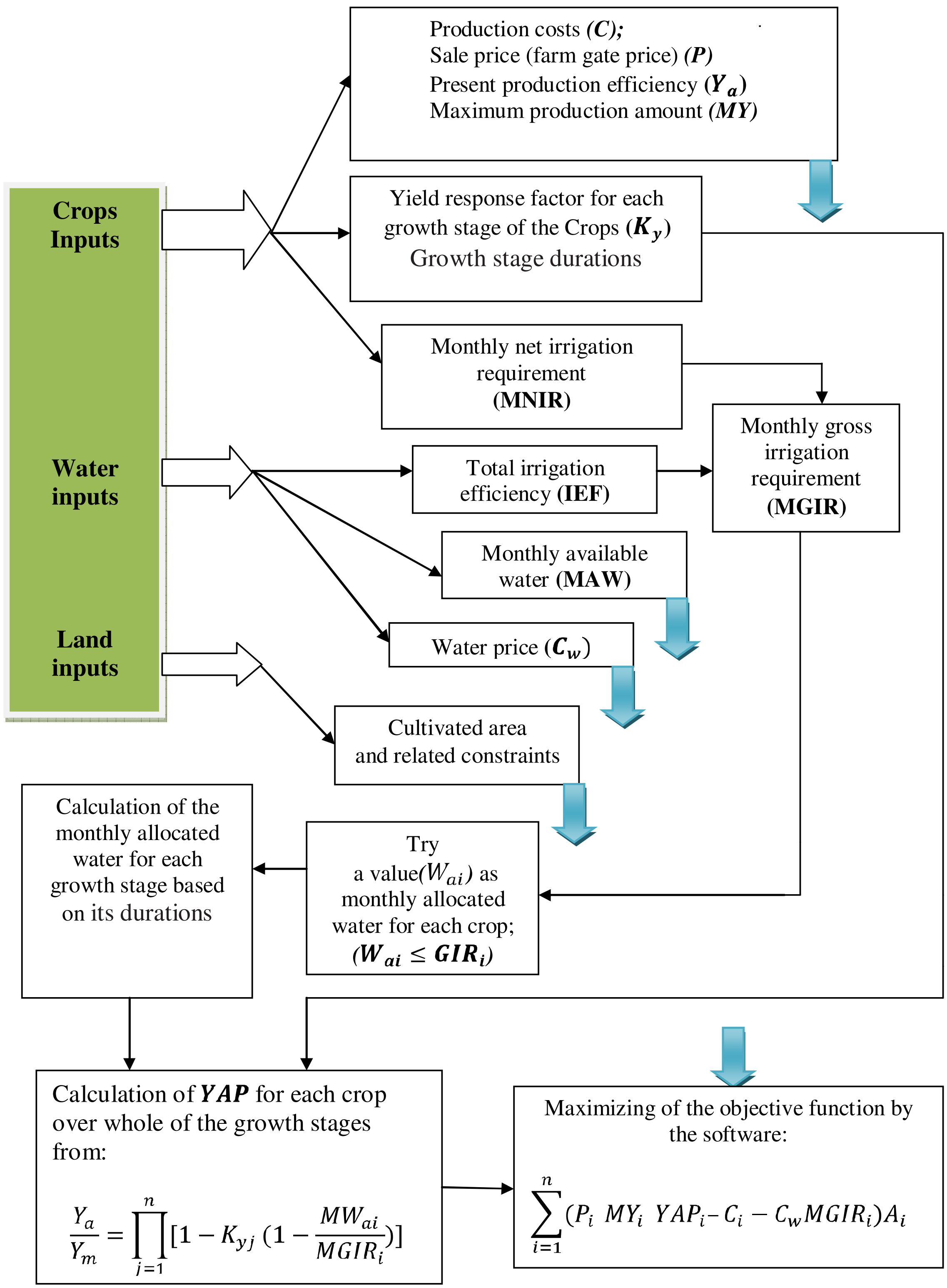

Figure 3. Overall scheme (block diagram) of the proposed model.

33 crops, validated by FAO, which must be 50% (Doorenbos and Kassam 1979). For schematic illustration of the proposed model a block diagram has been shown in Figure 3.

Data and data sources

Potential evapotranspiration (*ETp*), which were calculated from

Table 1. Yield response factor (Ky) for each growth stage of the crops in the study area.

Growth stages	Parameter	Crop			
		Wheat	Barley	Sugar beet	Grape
Establishment (0)*	Ky	0.2	0.2	1.1	-
	d	15	15	30	-
Vegetative (1)	Ky	0.2	0.2	1.1	0.2
	d	45	45	50	30
Flowering (2)	Ky	0.6	0.6	-	0.7
	d	20	20	-	60
Yield formation (3)	Ky	0.5	0.5	1.1	0.85
	d	40	40	30	40
Ripening (4)	Ky	0.5	0.5	1.1	0.4
	d	20	10	30	80

d: Duration of each stage (days), *number of each stage; Source: FAO, paper NO.33 (Doorenbos and Kassam, 1979).

Table 2. Current monthly water shortage after pumping a part of right of water.

Month	MAW (m^3)	Pumped to the reservoir (m^3)	MAW after pumping (m^3)	GIR (m^3)	Water deficit (m^3)	Percentage of deficit (%)
Oct	207000	0	207000	307000	100000	32.57
Nov	207000	97000	110000	135000	25000	18.52
Dec	207000	97000	110000	27000	0	0
Jan	207000	126000	81000	0	0	-
Feb	207000	126000	81000	0	0	-
Mar	207000	97000	110000	45000	0	0
Apr	389000	97000	292000	244000	0	0
May	648000	0	648000	745000	97000	13
Jun	518000	0	518000	963000	445000	46.21
July	260000	0	260000	400000	140000	35
Aug	207000	0	207000	345000	138000	40
Sep	155000	0	155000	293000	138000	47.1
Total	3419000	640000	2779000	3504000	1083000	

reference evapotranspiration (ET_0), based on the Shirvan meteorological station data (19622000) times crop coefficient (K_c), based on the Penman–Monteith equation (Allen et al., 1998). Monthly net irrigation requirement for each crop (MNIR) and total existing irrigation efficiency (IEF = 0.6) which extracted from KPM (2002). Cultivated area data includes total cultivating area and existing area for each crop (Khorasan agricultural statistical year book, 2009). From the total cultivated (irrigated) area (470 ha), the existing cropping pattern in the Razmgan area is composed of grape (31.9% = 150 ha), winter wheat (31.9% = 150 ha), winter barley (31.9% = 150 ha) and sugar beet (4.3% = 20 ha). Yield response factor values for each growth stage of the crop derived by FAO, paper NO.33 (Doorenbos and Kassam, 1979) and duration of each stage in day based on local observations as Table 1. Crops data includes present and maximum production efficiency, production costs and sale price (farm gate price) for each crop (Khorasan agricultural statistical year book, 2009). Monthly right of water data (MAW) for the Gelyan river in the Razmgan location has been extracted from north khaorasan province water resources statistical year book, 2009 (Table 2).

RESULTS AND DISCUSSION

Current water shortage

Table 2 shows the current monthly water deficit. Since according to the existing conditions, pumping is started at the beginning of November, 18.5% (25000 m^3) shortage is imposed in this month and total annual volume of the water deficit will be 1083000 m^3, while the total annual useful storage in the reservoir is 580000 m^3 (53.6% of the deficit volume). So, prioritization for water allocationto sensitive growth periods of the crop can result in an

Table 3. Sensitive growth stages to water deficit for some crops.

Crop	Periods and their priorities
Alfalfa	Just after cutting (and for seed production at flowering).
Cotton	Flowering and boll formation.
Grape	Vegetative period, particularly during shoot elongation and flowering > fruit filling.
Wheat	Flowering > yield formation > vegetative period; winter wheat less sensitive than spring wheat.
Sugar beet	Particularly first month after emergence.
Sunflower	Flowering > yield formation > late vegetative, particularly period of bud development.

Source: FAO irrigation and drainage paper 24 (Doorenbos and Kassam, 1977).

optimal operation for the auxiliary reservoir.

Prioritization for water allocation

Prioritization for water allocation in order to minimize the water deficit impact is carried out based on sensitivity of the crop growth periods to water deficit. Doorenbos and Kassam (1977) presented these sensitive stages for some crops (Table 3). It is observed, some crop growth stages are more sensitive to water deficit than the others. From Table 3, three main priorities can be considered to reduce the impact of water deficit for crops of the study area. According to Table 3 wheat and barley are more sensitive to water deficit in flowering stage which occurs in months of March and April. Sugar beet is more sensitive to water deficit particularly the first month after emergence, which occurs in months June and July. Grape is more sensitive to water deficit in vegetative period, particularly during shoot elongation and flowering which occurs in months of May and June. So, as the first priority to prevent of yield decreasing, water stress in the critical months for each crop must be minimum (June and July for sugar beet, May and June for grape). Also, no water stress occurs in Months of March and April (Table 2). The second priority for minimizing the water stress impact is: months May and June (yield formation stage for wheat and barley), months August and September for sugar beet, months July, August and September (fruit filling period for grape). Also months October and November (vegetative period for wheat and barley), month of May (establishment stage for sugar beet), months October and November for grape are as the third priority. Briefly, the explained prioritization has been intercalated in Table 4.

In Table 4, the last column shows water stress must be removed or minimized up to possible amount in months of May, June and July, as the first step. For the second step, months of August and September and in the third step months of October and November must be considered. For this purpose to release the stored water from the existing auxiliary reservoir in order to reduce the water stress impact based on specified prioritization, four scenarios are recognizable and would be discussed.

Scenario 1

In this scenario stored water is released at the beginning of the water deficit period (month of May). Considering reservoir useful storage (0.58 MCM) and amount of water deficit in the mentioned months (Table 2), release capacity for months of May, June, July and August is 37, 100, 54 and 32 lit/sec, respectively. In the end of August the reservoir will be empty. Because of the large deficit amount in month of July (46.21%), the water will be released with maximum capacity from the reservoir outlet (100 lit/sec), in this month. Consequently, water deficit will be removed in the months of May and July and it will decrease to 19.31 and 17.7% in months of June and August, respectively (Tables 5 and 6). Initial deficit values remain for months of September, October and November (Table 2). In this scenario, stages (0), (1) and (4), for wheat and barley, stages (1), (3) and (4) for sugar beet and stages (2), (3) and (4) for grape are threatened by the water stress (applied numbers for stages are shown in Table 1).

Scenario 2

In this scenario the minimum water deficit (month of May) is ignored and stored water is allocated to remove maximum values of the water deficit (months of September, June, August, July, October and November, respectively). Total water deficit only for months September, June and August is 0.721 MCM (Table 2), which is more than the reservoir useful storage (0.580 MCM), but because of the reservoir outlet limitation (maximum 100 lit/sec), only 259000 m^3 can be released in June, so, considering this recent limitation water deficit will decrease to 19.31%, in month of June and will be removed in months of September and August. Moreover, 0.045 MCM volume will remain for month of July, so, the amount of deficit will decrease to 23.75% in this mount (Tables 5 and 6). For this purpose, release capacity for months of September, June, August and July is 53, 100, 53 and 17 lit/sec, respectively. In the end of September the reservoir will be empty. Previous deficit values remain for months of October and November (Table 2). In this

Table 4. Prioritization to specify critical months for water deficit reduction.

Crop	Wheat	Barley	Sugar beet	Grape	Critical months for all crops
First priority	-	-	June and July	May and June	May, June and July
Second priority	May and June	May and June	August and September	July, August and September	August and September
Third priority	October and November	October and November	May	October and November	October and November

Table 5. Reservoir operation and regulated monthly available water (RMAW) for different scenarios.

Month	MAW (m^3)	Pumped to the reservoir (m^3)	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
			Released from the reservoir (m^3)	RMA (m^3)	Released from the reservoir (m^3)	RMAW (m^3)	Released from the reservoir (m^3)	RMAW (m^3)	Released from the reservoir (m^3)	RMAW (m^3)
Oct	207000	0	0	207000	0	207000	0	207000	100000	307000
Nov	207000	97000	0	110000	0	110000	0	110000	25000	135000
Dec	207000	97000	0	110000	0	110000	0	110000	0	110000
Jan	207000	126000	0	81000	0	81000	0	81000	0	81000
Feb	207000	126000	0	81000	0	81000	0	81000	0	81000
Mar	207000	97000	0	110000	0	110000	0	110000	0	110000
Apr	389000	97000	0	292000	0	292000	0	292000	0	292000
May	648000	0	97000	745000	0	648000	0	648000	0	648000
June	518000	0	259000	777000	259000	777000	259000	777000	39000	557000
July	260000	0	140000	400000	45000	305000	140000	400000	140000	400000
Aug	207000	0	84000	291000	138000	345000	138000	345000	138000	345000
Sep	155000	0	0	155000	138000	293000	43000	198000	138000	293000

Table 6. Monthly water deficit for different scenarios.

Month	GIR (m^3)	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
		RMAW (m^3)	Percentage of deficit (%)	RMAW (m^3)	Percentage of deficit (%)	RMAW (m^3)	Percentage of deficit (%)	RMAW (m^3)	Percentage of deficit (%)
Oct	307000	207000	32.57	207000	32.57	207000	32.57	307000	0
Nov	135000	110000	18.52	110000	18.52	110000	18.52	135000	0
Dec	27000	110000	0	110000	0	110000	0	110000	0
Jan	0	81000	0	81000	0	81000	0	81000	0
Feb	0	81000	0	81000	0	81000	0	81000	0
Mar	45000	110000	0	110000	0	110000	0	110000	0
Apr	244000	292000	0	292000	0	292000	0	292000	0
May	745000	745000	0	648000	13	648000	13	648000	13

Table 6. Contd.

June	963000	777000	19.31	777000	19.31	777000	19.31	557000	42.16
July	400000	400000	0	305000	23.75	400000	0	400000	0
Aug	345000	291000	17.7	345000	0	345000	0	345000	0
Sep	293000	155000	47.1	293000	0	198000	32.4	293000	0

Table 7. Comparison of the model parameters for discussed scenarios.

Scenarios	Cultivated area (ha)	Water consumption (m^3)	Net income (USD)	Production costs (USD)
Scenario 1	470	2993669.00	1639017.41	484623.39
Scenario 2	470	2985129.18	1705450.00	484623.39
Scenario 3	470	3004546.68	1728059.2	486382.15
Scenario 4	470	2999369.00	1778298.00	486381.76

scenario, stages (0), (1), (3) and (4), for wheat and barley, stages (0) and (1) for sugar beet and stages (2), (3) and (4) for grape are threatened by the water stress.

Scenario 3

In this scenario like scenario 2, water release is avoided in months of May but amounts of water deficit in the next months are minimized up to possible, respectively. Similarly, in month of June water deficit will decrease to 19.31%, in months of July and August will be removed and in September will decrease to 32.4%. Water release capacity for months of June, July, August and September will be 100, 54, 53 and 17 lit/sec respectively. The reservoir will be empty at the end of September (Tables 5 and 6). Water deficit for months of October and November will be as shown in Table 2. In this scenario, stages (0), (1) and (3) for wheat and barley, stages (0), (1) and(4) for sugar beet and stages (2), (3) and (4) for grape are threatened by the water stress.

Scenario 4

In this scenario existing water deficit for month of May (13%) remains and the whole of shortages from July to November are removed and finally the rest of stored water in the reservoir is allocated to the month of June. consequently, the amount of water deficit decreases to 42.16% in month of June (Tables 5 and 6). In this scenario, stages (3) and (4) for wheat and barley, stages (0) and (1) for sugar beet and only stage (2) for grape are threatened by the water stress.

Scenarios evaluation by the model

Developed regulated monthly available water by each one of scenarios entered to the proposed model for allocating to different growth stages of each crop, optimally. Using LINGO software (2006) which is an efficient package to solve linear, nonlinear and integer optimization, the proposed model for discussed scenarios was run and developed results have been intercalated in Table 7. It is observed that the objective function value (net income) for scenario 4 is the maximum. So to achieve the maximum net income of the existing crops, water release from the auxiliary reservoir must be carried out under this scenario. Based on scenario 4, whole of the stored water in the reservoir is allocated for months of June, July, August, September and October and irrigation will be carried out from both of the river and auxiliary reservoir with 42.16% deficit for month of June (Figure 4).

Irrigation in months November, December, March, April and May will be carried out from the river, directly (with 13% water deficit in month of May). Because of 25000 m^3 water release and 97000 m^3 pumping in November, simultaneously (Table 5), pumping volume is reduced to 72000 m^3 in November. For this purpose in month of

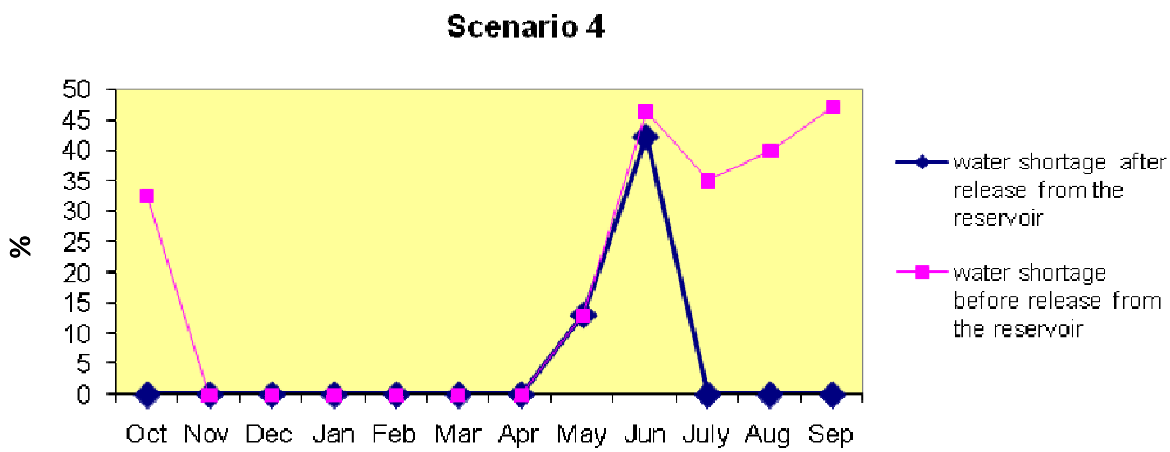

Figure 4. Monthly variation of the water deficit before and after release from the reservoir.

Table 8. Optimal reservoir operation of the auxiliary reservoir.

Month	Pumped to the reservoir (m^3)	Water pumping capacity (L/s)	Released from the reservoir (m^3)	Water release capacity (L/s)
Oct	0	0	100000	39
Nov	72000	50"	0	0
Dec	97000	50*	0	0
Jan	126000	65ª	0	0
Feb	126000	65ª	0	0
Mar	97000	50*	0	0
Apr	97000	50*	0	0
May	0	0	0	0
June	0	0	39000	15
July	0	0	140000	54
Aug	0	0	138000	53
Sep	0	0	138000	53
Total	615000		555000	

"Pumping duration: 22 days with 18 h per day; *pumping duration: 30 days with 18 h per day; ªpumping duration: 30; days with 18 h per day.

November, pumping duration from 30 days is reduced to 22 days and 4 h with the previous discharge (50 lit/sec for 18 h per day). Therefore total annual pumped water to the reservoir and total annual released water from the reservoir will be 615000 and 555000 m^3 respectively.

Table 8 shows the optimal reservoir operation of the auxiliary reservoir.

Optimal allocation of water by the model

In current status whole of the MAW after pumping is used by the farmers (Table 2, column 4). In fact, the farmers according to their working habits consume whole of the right of water from the river, while in months December, January, February, March and April, the water consumption is more than the GIR (Table 2). In the proposed model annual water consumption has decreased 10.71% than the current situation (from 3359000 to 2999369 m^3, Table 7). Figure 5 shows in the optimal case, to remove the existing water deficit for months of July, August, September, October and November, water consumption has increased than the current situation. For months of December, January, February, March and AprilWater consumption has decreased. In month of May irrigation will be carried out with the existing water deficit (13%, Table 2). In month of June because regulated available water is insufficient, so irrigation will be carried out under the water stress conditions (42.16% deficit, Figure 4) and water consumption will be less than the existing conditions.

In Table 9 it is observed that sugar beet in the proposed model is the biggest water consumer with 12081.17 m^3/ha annual volume, the second consumer

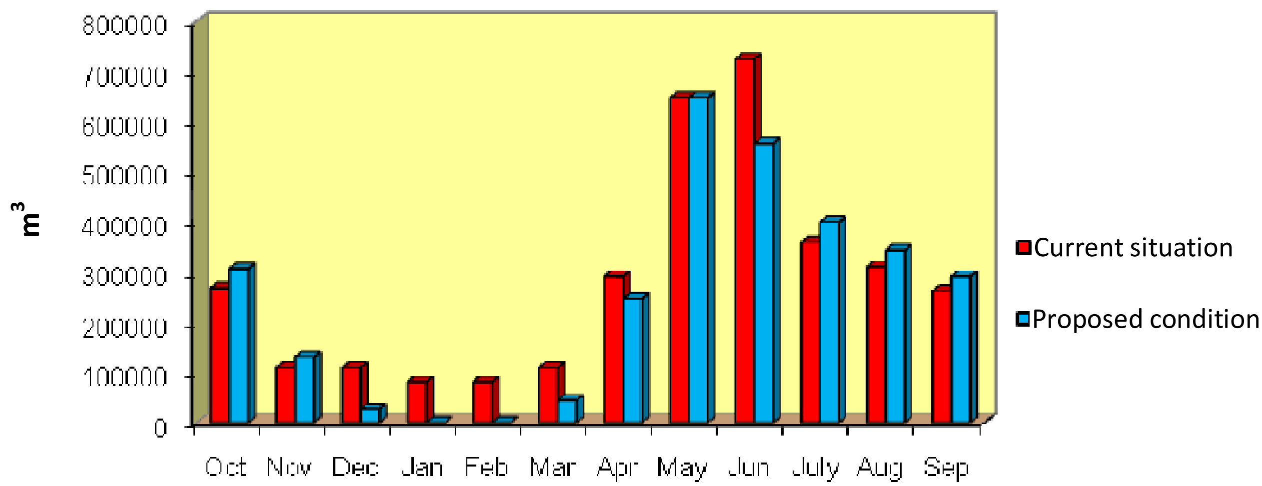

Figure 5. Monthly water consumption in the current situation and optimal case.

Table 9. Optimum monthly allocated water by the model (Monthly Irrigation Scheduling).

Month	Wheat (m^3/ha)	Barley (m^3/ha)	Sugar beet (m^3/ha)	Grape (m^3/ha)
Oct	633.6667	548.6883	0	847.1667
Nov	202.5000	363.3333	0	338.0000
Dec	0	0	0	181.0000
Jan	0	0	0	0
Feb	0	0	0	0
Mar	149.8333	149.8333	0	0
Apr	569.6667	569.6667	0	512.3333
May	1526.638	1838.604	711.3333	922.0000
June	1171.334	244.729	2432.833	1788.167
July	0	0	3551.000	2194.167
Aug	0	0	2948.167	1905.500
Sep	0	0	2437.833	1622.667
Annual	4253.639	3714.855	12081.17	10311.00

is grape with 10311 m^3/ha, wheat is the third one with 4253.64 m^3/ha and barley has the minimum amount of water consumption with 3714.9 m^3/ha, annual volume (Figure 6).

Allocated water for crops growth periods

Optimal allocated water for each growth period of the crop (OAW *period*) has been intercalated in Table 10. Also, OAW *period* has been compared with respective GIR *period* (gross irrigation requirement for each growth period of the crop) in Table 11. As the maximum water deficit during each individual growth period should be 50% (Doorenbos and Kassam, 1979), it is observed for mentioned growth periods in Table 11, condition of (OAW *period* / GIR *period*)> = 0.5 has been satisfied. It is perceived that third growth period for barley has the minimum ratio of the water deficit [(OAW *period* / GIR *period*) = 0.5].

Optimal allocation of the area (land) by the model

Results of the proposed model for scenario 4 (optimum reservoir operation) has been intercalated in Table 12. It is observed that cultivated area for wheat increases (150 to 180 ha), for barley decreases (150 to 120.04 ha), for sugar beet decreases 0.2% (20 to 19.96 ha) and for grape because it is a garden crop it does not change (150 ha). Due to this optimal cropping pattern net income increases 26.21% than the current status, total cultivated area does not change and production costs remains without change, nearly (0.3% increase).

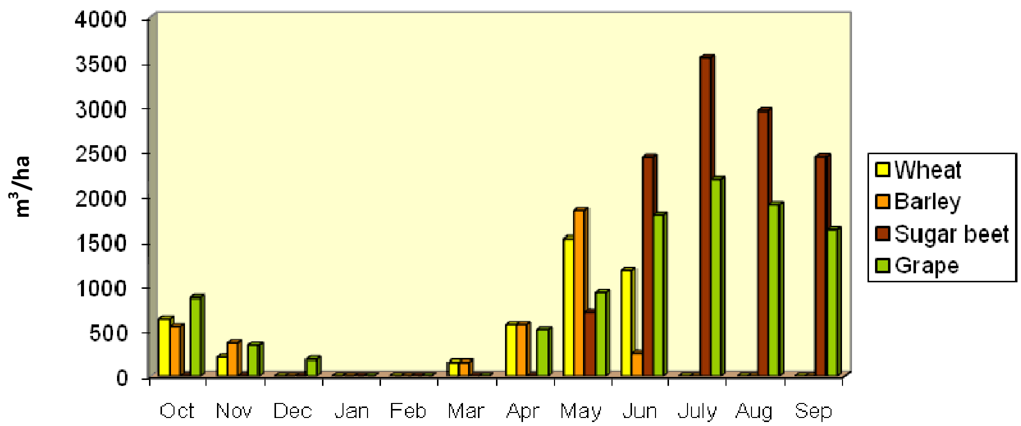

Figure 6. Crop monthly water consumption in the optimal case.

Table 10. Optimal allocated water for the crops growth periods by the model.

	Wheat	Barley	Sugar beet	Grape
First period				
Respective months	Oct and Nov	Oct and Nov	May	Apr
Occurred growth stage/stages	Stages (0) and (1)	Stages (0) and (1)	Stages (0)	Stage (1)
Allocated water (m^3/ha)	836.1667	912.0216	711.3333	512.3333
Second period				
Respective months	Mar and Apr	Mar and Apr	June and July	May and June
Occurred growth stage/stages	Stage (2)	Stage (2)	Stage (1)	Stage (2)
Allocated water (m^3/ha)	719.5000	719.5000	5983.833	2710.167
Third period				
Respective months	May and June	May and June	Aug and September	July and Aug and September
Occurred growth stage/stages	Stages (3) and (4)	Stages (3) and (4)	Stages (3) and (4)	Stage (3)
Allocated water (m^3/ha)	2697.97	2083.33	5386.000	5722.333
Fourth period				
Respective months	-	-	-	Oct and Nov and Dec
Occurred growth stage/stages	-	-	-	Stage (4)
Allocated water (m^3/ha)	-	-	-	1366.167
Crop annual allocated water (m^3/ha)	4253.639	3714.855	12081.17	10311.00

Source: Table 1 and results of the model.

Conclusions

In this study a non-linear optimization model in order to allocate the water for each growth period of the crop to remove/reduce the existing water deficit, under the allowed deficit irrigation in a given cropping pattern was proposed. Water deficit reduction led to enhancement of the crop production efficiency and considering the optimal cultivation area for each crop, the net income was maximized. The proposed model was applied to the Razmgan area, a semi-arid region at the northeast of Iran where irrigation needs are supplied from the river as the monthly right of water and an auxiliary reservoir stores the surplus water in the wet season in order to reduce the water stress impact in the dry season. Monthly irrigation scheduling as an important output of the proposed model to achieve the maximum net income was derived. To achieve the optimal operation of the existing auxiliary reservoir, which has a vital importance in minimizing of the water stress, sensitivity of the crop growth periods to water deficit was considered and based on prioritization for water allocation to sensitive growth periods, the water

Table 11. Comparison of OAW for crop growth periods (OAW *period*) with GIR *period*.

Period	Wheat		Barley		Sugar beet		Grape	
	GIR	OAW	GIR	OAW	GIR	OAW	GIR	OAW
First	836.17	836.17	926.66	912.02	711.33	711.33	512.33	512.33
Second	719.50	719.50	719.50	719.50	5983.83	5983.83	2710.17	2710.17
Third	4081.67	2697.97	4166.67	2083.33	5386.00	5386.00	5722.33	5722.33
Fourth	0	0	0	0	0	0	1366.17	1366.17

Table 12. Results of the proposed model for scenario 4.

Crop	Cultivated area (ha)		Production costs (USD)		Net income (USD)	
	Current situation	Proposed model	Current situation	Proposed model	Current situation	Proposed model
Wheat	150	180.00	66390.45	79668.54	80009.55	125506.19
Barley	150	120.04	58839.75	47087.80	62660.25	59530.48
Sugar beet	20	19.96	16727.92	16693.77	11792.1	19192.82
grape	150	150	342931.65	342931.65	1254568.35	1574068.35
Total	470	470	484889.8	486381.76	1409030.25	1778298.00

stress impact was minimized. For this purpose, four different scenarios for water release were analyzed and the proposed model for these four scenarios was run. Regards to assessment index (net income), scenario 4 because of having the maximum net income value than the others was found most suitable and recommended for the study area. Based on this scenario, whole of the stored water in the reservoir is allocated for months of June, July, August, September and October and irrigation will be carried out from both the river and auxiliary reservoir with 42.16% deficit for month of June.

Irrigation in months of November, December, March, April and May will be carried out from the river, directly (with 13% water deficit in month of May). Application of the proposed model for scenario 4 resulted in 26.21% annual increases in net income than current status. Also in this scenario a significant water saving can be achieved because annual water consumption decreased to 2999369.00 m^3 which shows 10.71% reduction than current status (3359000 m^3) which it makes possible to extend the irrigation facilities for 600 ha rain-fed lands in the command area. Results show yield values because of complete water allocation for grape and sugar beet, have acceded to the maximum amounts (Ya = Ym). For wheat the amount of DCPE (developed crop production efficiency) has acceded to 3737.25 kg/ha (83.05% of MCPE (maximum crop production efficiency), because the existing water stress in the first growth period of this crop (months of October and November) has been removed completely and only, 33.9% water deficit in the third growth period is imposed to the crop. For barley, DCPE has acceded to 3289.57 kg/ha (74.76% of MCPE), because 50% deficit (maximum allowable deficit irrigation) is imposed to the crop in third growth period (months of May and June). Results signify that grape in spite of fixed area, because of having a high sale price (0.710 USD/ha) and maximum yield (because of receiving whole of the monthly water need) enjoys of the maximum net income (USD 1574068.35). Net income for wheat because of 20% increase in the cultivated area and 16.79% increase in DCPE than the current situation, has acceded to USD 125506.19 (56.86% increase than the current status).

For barley, in spite of 9.65% increase in DCPE than PCPE (present production efficiency), net income has reduced to USD 59530.48 (5% decrease than the current situation), because cultivated area for this crop has decreased 20% than the present status. Cultivated area for sugar beet is nearly fixed, but because of adequate water supply and removal of the whole of water stresses for this crop, net income has acceded to USD 19192.82 (62.76% increase than the current situation). Regards to the developed results for increase in annual net income, the proposed model is efficient for those irrigated area which under the water deficit conditions have a low productivity. Application of the proposed model, especially, in the semi-arid regions where, low scale auxiliary reservoirs help to reduce the water stress impact is recommended.

Symbols: $\boldsymbol{Y_a}$, actual crop yield; $\boldsymbol{Y_m}$, potential (maximum) crop yield; $\boldsymbol{ET_{ai}}$, actual evapotranspiration for growth stage I; $\boldsymbol{ET_{mi}}$, potential evapotranspiration for growth stage I; $\boldsymbol{K_{yi}}$, yield reduction coefficient (yield response factor) for growth stage I; $\boldsymbol{W_{ai}}$, applied water for growth stage i (water deficit conditions) in $m^3 . ha^{-1}$;

$\boldsymbol{GIR_i}$; gross irrigation requirement (potential water need) for growth stage i in $m^3.ha^{-1}$; $\boldsymbol{NIR}$, net irrigation requirement; $\boldsymbol{IEF}$; irrigation efficiency; $\boldsymbol{GI}$, gross income; $\boldsymbol{P_j}$, sale price (farm gate price) of the crop j in USD/ kg; YAP_j ratio of $\frac{Y_a}{Y_m}$ for crop j $\boldsymbol{MY_j}$, maximum crop production (maximum yield) for crop j in kg/ha; $\boldsymbol{YAP_j}$, ratio of $\frac{Y_a}{Y_m}$ for crop j; $\boldsymbol{A_j}$, allocated cultivated area of crop j in ha; $\boldsymbol{PC_j}$, production costs for the crop j in USD; $\boldsymbol{C_j}$, production costs for crop j without considering water price in USD; $\boldsymbol{C_w}$, water price (irrigated water costs) in USD/m^3; $\boldsymbol{TA}$, total cultivated area in ha; $\boldsymbol{a_j}$, existing cultiveted area for crop j; $\boldsymbol{TAW}$, total available water in m^3; $\boldsymbol{MW_{aj}}$, monthly applied (allocated) water for crop j in $m^3.ha^{-1}$; $\boldsymbol{MAW}$, monthly available water in m^3; $\boldsymbol{MGIR_j}$, monthly gross irrigation requierment for crop j in $m^3.ha^{-1}$.

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