

# Development of Management Schemes in Irrigation Planning: Economic and Crop Pattern Consideration

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**Abstract.** Increasing population has dramatically increased the request for agricultural products. In addition, lands and water resources with suitable quality are limited. Therefore, optimal allocation of limited resources to different demands has become very important in recent years. In this study, a model is developed to optimize a water resources allocation scheme considering the conjunctive use of surface water and groundwater resources, as well as determining a suitable crop pattern. The economic objective function of the optimization model is to maximize the net benefit, considering the water pumping cost, crop cultivation cost and the benefit of total crop production during the study time horizon. The effect of a marginal water deficit in the reduction of crop yield and water table fluctuations are considered. A genetic algorithm is used to solve the optimization model. The proposed model is applied to the Varamin plain to determine the optimal crop mix and water allocation from surface and groundwater. In order to evaluate the results of the model, the performance indices are calculated. The effect of imposed policies on the crop pattern is investigated through the definition of two scenarios and the results are compared. Also, the potential of the study area, for applying deficit irrigation strategies using economic analysis, is investigated.

**Keywords:** Conjunctive use; Water allocation; Optimization model; Crop pattern; Genetic Algorithm; Water pricing.

## INTRODUCTION

Surface and groundwater conjunctive use and land use planning are vital and unavoidable tasks due to increasing water demand for food growth and the limitation of water resources with acceptable quality and quantity. It is necessary to achieve maximum returns from cropping activities and to resolve the problems of water-logging and water table depletion.

System analysis tools have been utilized in the work of Male and Mueller [1], Watkins and McKinney [2], Belaineh et al. [3], Reca et al. [4] and Benli and Kodal [5] for resource allocation and economic analysis.

The planning of conjunctive use has been attended to by many researchers, such as Onta et al. [6], Latif and James [7], Reichard [8], Singh et al. [9], Karamouz et al. [10] Syaukt and Fox [11] and Vedula et al. [12].

Besides planning for water allocation, many attempts have been devoted to optimizing crop pattern configuration. Karamouz et al. [13] developed a systematic approach to surface and groundwater resource allocations in a study area, considering the effect of crop pattern on irrigation water demand. Khare and Ediwayunan [14] analyzed the feasibility of conjunctive use management using a linear optimization model. A simple economic-engineering optimization model is presented to explore the possibilities of the conjunctive use of surface and groundwater with hydrological and management constraints, and to arrive at an optimal cropping pattern for the optimal use of water resources for the maximization of net benefits. Sethi et al. [15] developed two deterministic linear programming and chance-constrained linear programming models to allocate available land and water resources optimally on a seasonal basis, so as to maximize the net annual return

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from the study area, considering the net irrigation water requirement of crops as a stochastic variable.

Recently, more attention has been given to soft computing techniques, such as Evolutionary Algorithms (EA) and, principally, Genetic Algorithms (GA). Genetic Algorithms are search algorithms based on the mechanism of natural selection and natural genetics. GA modeling is gaining importance because of its robust random search capability and near global optimal values. It originated in the mid 1970s [16] and emerged as a powerful optimization approach. An excellent introduction to GA is given by Goldberg [17], and several other investigators have summarized the essentials of genetic algorithm modeling. GA optimization methods have been employed in different fields of water resources management, such as Kerachian and Karamouz [18], Afshar and Marino [19], Afshar [20] and Karamouz et al. [21].

Raju and Kumar [22] used GA techniques to evolve an efficient cropping pattern for maximizing benefits for an irrigation project in India. Constraints include a continuity equation, land and water requirements, crop diversification and restrictions on storage. Wu et al. [23] developed optimal strategies to balance the need for discharge of sufficient groundwater for irrigation with the need to improve the local environment by managing the water table fluctuation. Two simulation-optimization models have been formulated and a Genetic Algorithm (GA) is applied to search for the optimal groundwater development strategies [24]. A methodology for the conjunctive use of surface and groundwater resources is developed using a combination of GA and Artificial Neural Networks (ANN) as groundwater response functions. Water supplies on agricultural demand, reduction of pumping costs and the control of groundwater table fluctuations are considered in the objective function of the optimization model.

In this study [13], work is extended to include the deficit irrigation potential. The strategic policies on crop pattern are also considered as a constraint in the model formulation and a management scheme is developed. In this paper, the feasibility of the conjunctive use is evaluated and a GA-based optimization model has been developed for maximizing net benefits under various physical and economic constraints. The proposed model is utilized to obtain an optimal water allocation and crop pattern in the Varamin plain. Then, the effects of regulatory limitations on the optimum crop patterns are assessed. For this purpose, a scenario is defined, addressing the restrictive policies to maintain a minimum level of a strategic crop. For evaluating the model performance in the defined scenarios, performance indices, namely reliability, resiliency and vulnerability have been calculated and the results are compared. The paper is organized

as follows: First, the structure of the proposed model is presented. Then, the description of a case study is given, and the results of the implementation of the proposed model are discussed. Finally, a summary and a conclusion are provided.

## Methodology

In this paper, an optimization model is developed to determine the optimum crop pattern and water allocation for maximizing net benefit. The net benefit is equal to the difference between the benefit of selling crops and crop production costs, which include the pumping cost from surface and aquifer water and the cost of cultivation. The variation of the groundwater table is calculated based on a continuity equation considering the return flow of agricultural lands to the aquifer. Monthly water table fluctuation and their ultimate value at the end of the planning time horizon are considered as constraints in determining optimal groundwater allocation. The variation of monthly water demand in a region during the study horizon has been considered. The crop yield is calculated based on the supplied portion of water demand considering crop sensitivity to water deficit. A genetic algorithm is used as the optimization technique, via its ability in the problems with a high number of decision variables and nonlinearity.

## Structure of Optimization Model

The main objective of the proposed model is to maximize the difference between the gross benefit of crop production and the pumping from surface and groundwater and their associated cultivation costs. In the proposed optimization model, water allocations from surface and groundwater during each month of the time horizon planning, as well as a fixed crop pattern mix for the planning period, are decision variables. The structure of the proposed optimization model consists of two parts: costs of crop production and water supply ( $C$ ) and the gross benefit of crop cultivation ( $B$ ) (\$). The structure of the optimization model for a region during  $y$  years is as follows:

$$\max Z = B - C, \quad (1)$$

$$\begin{aligned} C = & \sum_{t=1}^y \sum_{k=1}^m \left( \frac{G_{tk} \times H_{tk} \times hr_{tk}}{\eta \times 3.67 \times 10^{-4}} \times pr \right. \\ & \left. + \frac{S_{tk} \times H'_{tk} \times hr'_{tk}}{\eta' \times 3.67 \times 10^{-4}} \times pr \right) \\ & + \sum_{t=1}^y \sum_{p=1}^c (\cos t_{pt} \times \alpha_p \times A), \end{aligned} \quad (2)$$

$$B = \sum_{t=1}^y \sum_{p=1}^c (Y_{ap} \times T_p \times \alpha_p \times A), \quad (3)$$

where  $Z$  is net income (\$);  $G_{tk}$  is the volume of groundwater withdrawal from wells in month  $k$  and year  $t$  (MCM);  $S_{tk}$  is the volume of surface withdrawal from a river in month  $k$  and year  $t$  (MCM);  $H_{tk}$  and  $H'_{tk}$  are depth of groundwater table and pumping head from the river in month  $k$  and year  $t$  (m), respectively;  $pr$  is the price of electricity for water pumping from groundwater and surface water (\$), respectively;  $\eta$  and  $\eta'$  are pumping efficiencies for groundwater and surface water (%);  $hr_{tk}$  and  $hr'_{tk}$  are total number of hours of pumping from groundwater and surface water, respectively, in month  $k$  and year  $t$ ;  $Y_{ap}$  is the actual yield for crop  $p$  in year  $t$  (Kg/ha/yr);  $T_p$  is price of crop  $p$  (\$/Kg);  $\alpha_p$  is percentage of allocated area for crop  $p$  (%);  $A$  is agricultural area (ha);  $cost_{pt}$  is the fixed cost of crop  $p$  in year  $t$  for agricultural acts, such as, preparing land, pesticide, herbicide, labor etc. (\$);  $n$  is the total number of crops in the region;  $y$  is the total number of years in the planning horizon; and  $m$  is the total number of months.

The constraints of the proposed model are formulated as follows:

1. Summation of areas under different crop production should be equal to the total area that could be utilized.

$$\sum_{p=1}^n \alpha_p = 1. \quad (4)$$

2. Groundwater fluctuations are calculated using the water continuity equation for the aquifer (Equation 5). The amount of return flow ( $\lambda$ ) is assumed to be equal to thirty percent of the total allocated water to the lands. This value is determined based on the data in the hydrometric stations and expert opinion. The maximum of monthly and total water table fluctuations should be less than the maximum allowable downward presented in Equations 6 and 7, respectively:

$$\Delta H_{tk} = (\lambda \times (S_{tk} + G_{tk}) - G_{tk} - GD_{tk} + Ch_{tk}) \times 100 / (Ss \times A),$$

$$k = 1, \dots, m, \quad t = 1, \dots, y, \quad (5)$$

$$|\Delta H_{tk}| \leq \Delta H_{\max},$$

$$k = 1, \dots, m, \quad t = 1, \dots, y, \quad (6)$$

$$\sum_{t=1}^y \sum_{k=1}^m \Delta H_{tk} < \text{total } \Delta H, \quad (7)$$

where  $\Delta H_{tk}$  is the water table fluctuation in month  $k$  and year  $t$  (m);  $Ch_{tk}$  is the aquifer recharge in month  $k$  of year  $t$  (MCM);  $GD_{tk}$  is aquifer discharge through drainage in month  $k$  of year  $t$  (MCM);  $Ss$  is the storage coefficient of the aquifer;  $\Delta H_{\max}$  is maximum monthly allowable fluctuation of water table (m); and total  $\Delta H$  is the maximum of the cumulative allowable water table fluctuations in the planning horizon (m) (5 m in this study).

3. The amount of the crop yield is a function of allocated water to the crops. A production function developed by Dorenbos and Kassam [25] which considers the relation between actual and potential evapotranspiration is used. Ghahraman and Sepaskhah [26] extended the Dorenbos and Kassam function [25], as shown in Equation 8, based on allocated water and crop water demand.

$$\left( \frac{Y_a}{Y_m} \right)_{pt} = \prod_{i=1}^f \left( 1 - Ky_i \left( 1 - \frac{\text{Allocate}_i}{WD_i} \right) \right), \quad (8)$$

where  $f$  is the number of stages for crop growth;  $(Y_a)_{pt}$  and  $(Y_m)_{pt}$  are crop yield and potential crop production of crop  $p$  in year  $t$  (Kg/ha/yr), respectively;  $WD_i$  is water demand in month  $i$  (MCM);  $\text{Allocate}_i$  is the allocated water in month  $i$  (MCM); and  $Ky_i$  is crop sensitivity to the water deficit in month  $i$ . This equation is applied for each crop to estimate annual yield.

## Genetic Algorithm

Considering the non-linear and the complex objective function of the optimization model and the large number of decision variables, the genetic algorithm is used to solve the optimization model. The genetic algorithm is an adaptive method trying to imitate biological and genetic processes and can successfully be applied to optimization problems.

GA is a population of individuals, named *chromosomes*. Each chromosome represents a potential solution to a problem. This solution is evaluated by its fitness function. As each chromosome represents a potential solution, the fitness of each chromosome, as a candidate solution, should be evaluated by a random search process to form the decision space. Through successive generation, fitness should progressively be improved towards an optimum solution. The new population is generated using the genetic operators including selection, crossover and mutation. Genetic algorithms usually consist of the following steps:

1. Encoding of the decision variables and placing them in a chromosome: Although binary encoding is the most common method among other encoding approaches in this study, real value encoding is

used. In binary encoding, the discretization of state variables is usually required. In the case of a large number of state variables, the length of each chromosome and, therefore, the convergence time, will be long. But, in real value encoding, the discretization of state variables and the decoding process is not required and, thus, will provide the optimal solutions with more precision and lower computational time.

2. Creating an initial population (first generation): The initial population is generated through a random procedure.
3. Determination of fitness for every chromosome in the current population (fitness evaluation).
4. Selecting the chromosomes as the parents for generation of the next population: Several approaches have been proposed for a selection operator, such as the Roulette Wheel and Tournament methods. The selection operator can affect the convergence and run time of the method and maintain the diversity of the population in each generation. In this study, the Tournament selection method is used.
5. Setting the probabilities for crossover: Crossover operators randomly take one pair that perform well from the mating pool and by exchanging important building blocks between two strings, a new pair is obtained. Crossover occurs between two selected strings with a specific probability ( $P_c$ ). A one point crossover, which has been selected for this study, randomly chooses a position in the string and new chromosomes are obtained by swapping all Genes after the position.
6. Performing mutation for selected chromosomes: Mutation is an important process that can provide diversity and new genetic information to the population and prevent premature convergence to local optimal solutions. The mutation operator changes the Gen value randomly in the range of variation, which is usually considered as a percentage of the maximum range of Gen variation.
7. Repeating steps 3-6 until finding the optimal or near optimal solutions.

More details of genetic algorithms can be obtained in the works of Michalewicz [27] and Gen and

Cheng [28]. The schematic of one chromosome used in the GA model in the proposed optimization model is shown in Figure 1. The number of genes in a chromosome for a  $y$ -year planning horizon with  $P$  dominant crops is equal to  $P + 2 \times m \times y$ . The first set of  $P$  genes presents the percentage of each crop in the plain. The remaining genes are filled with the amount of allocated water from the surface and groundwater resources for  $m$  months of  $y$  years.

### Evaluation of System Performance

In order to evaluate the results of the optimization model in real time operation, certain performance criteria are utilized. Hashimoto et al. [29] described systems performance from three different viewpoints:

1. How often the system succeeds (reliability);
2. How quickly the system returns to a satisfactory state once a failure has occurred (resiliency);
3. How significant the consequences of failure are (vulnerability).

The appropriate definition for performance indices depends on the main issues and the objectives of the planning. In a definition of these indices, the operational status of water resources systems can be classified as satisfactory (in this case, supplying water demand) and unsatisfactory or a failure (shortage in supplying water demand). The system status in time period  $t$  is expressed by the stochastic variable,  $X_t$ . It is a member of the  $S$  set if it belongs to a set of satisfactory outputs otherwise it is included in set  $F$ , which is the set of all unsatisfactory outputs [30]. In this case, when the allocated water is equal to or greater than water demand, no failure occurs, otherwise failure occurs.

**Reliability** is the probability that no failure occurs within a specified period of time:

$$\theta = \Pr[X_t \in S], \quad \forall t. \quad (9)$$

In other words, reliability is the probability that no failure occurs within the planning horizon. Based on the above definition, in this study, it is a measure of the system performance in supplying the water demand

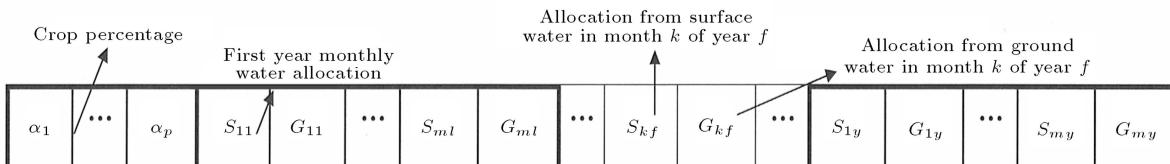


Figure 1. Schematic of one chromosome used in the proposed GA model.

and it is estimated as:

$$\theta = \frac{\sum_i^T d_i}{T} \begin{cases} d_i = 1 & \text{if } (\text{Allocate}_i \geq WD_i) \\ d_i = 0 & \text{otherwise} \end{cases} \quad (10)$$

where  $\theta$  (reliability) is defined as the number of months supplying water demand out of total months ( $T$ ) in the planning horizon, and  $d_i$  is a binary variable indicating the state of supplying water demand.

**Resiliency** describes how quickly a system recovers from failure, once failure has occurred. The resiliency of the system can be defined in the planning horizon as follows:

$$\beta = \Pr\{X_{t+1} \in S | X_t \in F\}. \quad (11)$$

According to Equation 10, resiliency is basically a measure of satisfactory condition duration.

$$\beta = \frac{\sum_i^T e_i}{T - \sum_i^T d_i} \begin{cases} e_i = 1 & \text{if } (d_{i-1} = 0 \text{ and } d_i = 1) \\ e_i = 0 & \text{otherwise} \end{cases} \quad (12)$$

where  $\beta$  (resiliency) is the ratio of failure months followed by a satisfactory state, out of total months with non-supplying water demand.

**Vulnerability** measures the magnitude of a failure. In water supply systems, vulnerability can be defined as the total shortage volume during the planning horizon. This index is formulated as follows:

$$v = \sum_i^T V_i$$

$$\begin{cases} V_i = 0 & \text{if } (\text{Allocate}_i \geq WD_i) \\ V_i = (\text{Allocate}_i - WD_i) & \text{otherwise} \end{cases} \quad (13)$$

where  $V_i$  is the distance of the current system situation from the desired situation (MCM).

## CASE STUDY

The Varamin plain, located in the eastern part of the Tehran metropolitan area in Iran, has been considered as the case study. In this plain, the precipitation

is partially affected by Mediterranean systems in the winter and warm Arabian systems in the summer. The average amount of precipitation in the Varamin plain is about 131.4 millimeter per year and the temperature varies from -14.4 to 45.5°C. The minimum and maximum relative humidity values are 15 and 75 percent in summer and winter, respectively.

The surface water resources of Varamin are limited to the Jajroud and Shoor River flows in the west and north of the plain, respectively (see Figure 2). Table 1 shows the average monthly discharge of the Jajroud and Shoor rivers upstream of the Varamin plain and also the average monthly agricultural water demand under existing conditions. There are 5 dominant crops in this plain, namely; wheat, barley, cucumber, tomato and maize (corn) and the irrigation efficiency is 39% based on local investigations. Eleven years of available data regarding river discharges in the Varamin plain have been utilized in the optimization model.

Even though there are fertile lands and enough water resources in the case study, the crop yield is less than the crop production potential. This might be because of the allocation of surface and groundwater without considering an appropriate scheme of con-



Figure 2. The rivers resources of Varamin plain.

Table 1. Average monthly discharge of Jajroud and Shoor Rivers at the upstream of the Varamin plain.

		Average Monthly (MCM)											
River	Jajroud	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
Discharge	Shoor	8.27	20.68	28.56	22.26	24.53	23.92	22.99	21.22	5.93	3.69	0.74	1.42
Water Demand	57.66	69.26	17.31	3.06	7.21	29.20	55.52	42.91	9.13	5.73	12.39	32.06	

junctive use. Therefore, developing optimal temporal schemes for allocation from both resources are the challenges of irrigation planning in the case study, which could improve agricultural net benefit and restore the aquifer water table in the region.

The total number of decision variables of the proposed model for the Varamin plain is 5 (number of dominate crops) + 2 (water resources)  $\times$  12 (number of months)  $\times$  11 (number of years) = 269. The proposed model is applied to the case study without considering the minimum required wheat cultivation as a state/province policy. It is called Scenario A.

Constraints related to economic and social limitations are also considered in order to comply with some strategic policies of the region. Scenario B is defined based on these policies. The results of the GA-based optimization model include the percentage of different allocated crop coverage areas, surface and groundwater allocations, monthly water table fluctuations and accumulated water table variations. In the GA method, the initial population size, crossover and mutation probabilities are the main parameters of the optimization model that are selected by trial and error in this study. The related initial population size, the values of crossover and mutation probabilities are equal to 100, 0.9, and 0.003, respectively. The program terminates by reaching 10000 iterations and the proposed model is written in the Fortran environment. The performance of the proposed water allocation scheme is evaluated through reliability, resiliency and vulnerability indices.

## RESULTS

At first, the proposed optimization model was implemented for determination of a water allocation scheme and a crop pattern configuration in the case study. In order to investigate the effect of strategic constraints on the optimal crop pattern, Scenario B is evaluated. The results of both scenarios (A and B) are discussed in the following sections. In order to optimize crop pattern configuration, an economic analysis is employed considering deficit irrigation, and the results of a variation of crop mix are discussed.

### Results of Scenario A

The proposed model has been applied to the Varamin plain to determine the optimal pattern of dominant crops. An obtained optimal crop pattern of a base scenario is presented in Table 2. In this scenario, the coverage area of barley and cucumber, which have high yield with low water demand, has increased to improve the region income.

Components of the objective function including the benefit and cost corresponding to the optimal crop pattern are presented in Table 3. The maximum

**Table 2.** Components of objective function in Scenario A

Crops	Percent (%)	Benefit (Million \$)	Cost (Million \$)
<b>Wheat</b>	12	16.6	7.99
<b>Barley</b>	47	554	93.5
<b>Cucumber</b>	39	45.3	16.6
<b>Tomato</b>	2	2.53	1.36
<b>Maize</b>	0	0	0
<b>Total</b>	100	618.1	119.45

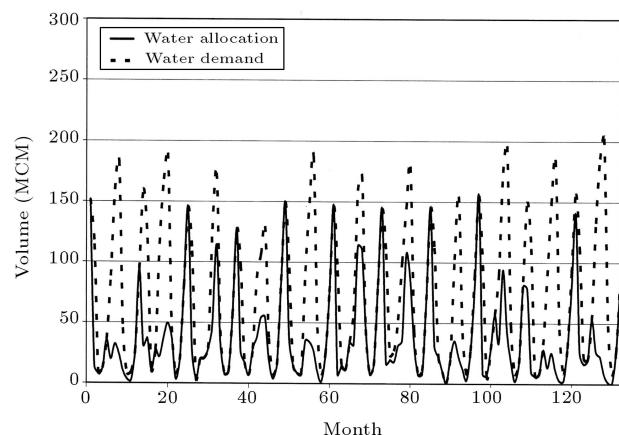
fraction of cost is obtained through wheat cultivation, out of optimal crop patterns. As shown in Table 3, cucumber is the most beneficial crop, although its cultivation has considerable cost. The total benefit of the optimal option is about (Million \$) 440, while the benefit of the existing condition is about (Million \$) 79.

Investigation of the optimal water allocation scheme, in comparison with water demand variation during eleven years of the study period (Figure 3), shows that in certain months, when surface water is more than water demand, the preference option in water allocation is surface water. However, in some months with low demand, for avoiding the water table increasing beyond the desired level, the total allocated water exceeds demand. The reliability, resiliency and vulnerability of supplying water demand are calculated as 50.0%, 36.4% and 24.1 MCM/month, respectively.

In practice, there are some strategic constraints in addition to economic considerations, which govern the practical optimal crop pattern. The effects of the considered constraints on optimal water allocation and crop pattern are discussed in the next sub-sections.

### Results of Scenario B

As mentioned in the base scenario analysis, if eco-social constraints are not considered in determining



**Figure 3.** Comparison of water demand and allocation in Scenario A.

**Table 3.** Crop pattern, net benefit and allocated surface and groundwater in observed condition and Scenarios A and B.

	<b>Actual Observed</b>	<b>Scenario A</b>	<b>Scenario B</b>
<b>Crop Pattern (%)</b>	<b>Wheat</b>	38	12
	<b>Barley</b>	29	47
	<b>Cucumber</b>	4.5	39
	<b>Tomato</b>	6.5	2
	<b>Maize</b>	22	0
<b>Net Benefit (Million Dollar)</b>	79	440	220
<b>Allocated Surface Water (MCM)</b>	399	228	222
<b>Allocated Groundwater (MCM)</b>	454	217	239

the optimum crop pattern, the optimization problem may result in non-practical solutions. For instance, as can be seen in the results of the base scenario (Table 2), strategic crop coverage, such as wheat, decreases significantly.

To achieve a practical solution, these restrictions are incorporated into the optimization problem through utilizing new constraints. In the second scenario, the minimum crop coverage area of wheat is set equal to 40%. In this scenario, extra constraint is added to the optimization model as follows:

$$\alpha_1 \geq 0.4, \quad (14)$$

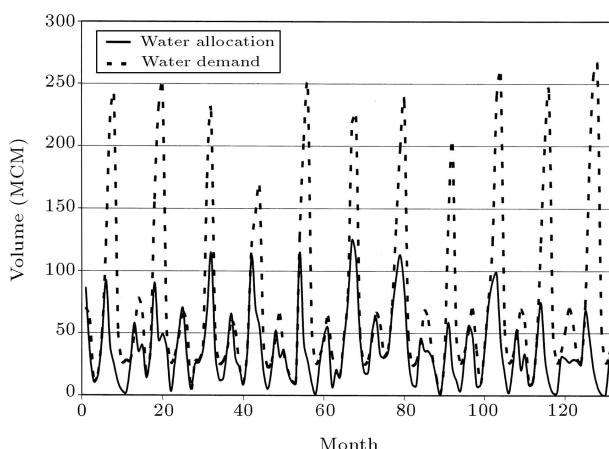
where  $\alpha_1$  is the percentage of crop 1 (wheat). The results of water allocation, cumulative and monthly variations of a water table for this scenario and the base scenario are shown in Figures 4 to 7. As can be seen in Figures 4 and 5, by imposing the wheat area to be more than 40 percent, maximum monthly water demand increases from 205 MCM to 260 MCM (about 25%) and the reliability of supplying water demand has decreased to 45% from about 50% in the base scenario. The resiliency and vulnerability of supplying water demand are calculated as 38.3% and

26 MCM/month, respectively. These results show that the performance of the model under Scenario B is not as good as Scenario A.

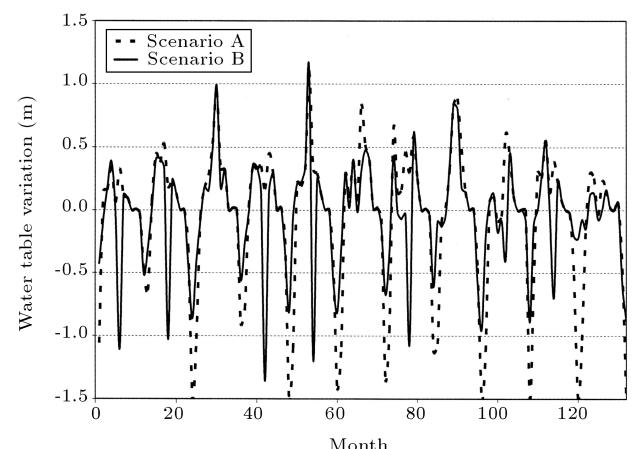
Regarding Figures 4 and 6, groundwater drawdown increases in this scenario, in comparison with Scenario A, and its cumulative variation are negative, with respect to the water table at the start of the operation (level zero). However, fluctuations of water table have the same behavior in both scenarios, because the objective function of the optimization model is economic-based and the groundwater table variations are considered as a constraint. Therefore, two scenarios have similar groundwater table variations to use total available water resources for achieving the maximum net benefit.

The optimal crop coverage for Scenario B and the base scenario are presented in Table 3. The net benefit of the optimal crop pattern in this scenario is about 220 Million Dollars, which is about 50% of the maximum possible benefit of Scenario A. It shows that governmental policies could significantly affect income and these policies should be established considering their eco-social results.

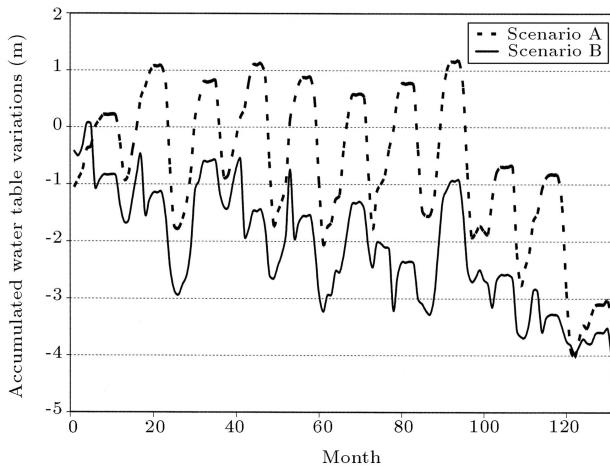
The different temporal distributions of water de-



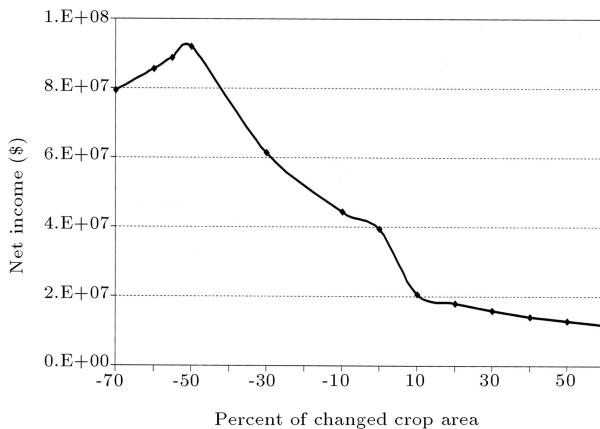
**Figure 4.** Comparison of water demand and allocation in Scenario B.



**Figure 5.** Comparison of monthly groundwater table variations in Scenarios A and B.



**Figure 6.** Comparison of cumulative groundwater table variations in Scenarios A and B.



**Figure 7.** Benefit variation versus crop coverage in Scenario A.

mand and surface water availability make the groundwater a major part of the water resources supplying the water demand. As can be seen in Table 3, the percentage of surface and groundwater for supplying the water demand is about 50%, which shows the significance of the conjunctive use of surface and groundwater in the study region.

The net benefit of Scenario B is about three times more than the net benefit of 11 years of cultivation in the study area (about \$79 Million). The annual allocated water to the agricultural area in Scenario B is about 461 MCM, compared with 853 MCM during the historical periods. Also, in order to increase the profit, barley and cucumber areas have been increased rather than the existing crop pattern, and maize is classified as a non-economical crop. This shows that the optimal crop pattern and water allocation obtained by the optimization model in Scenario B is more efficient than the existing operation scheme.

The proposed model could be expanded for multi-plain, multi-water resources and new crop pattern

configuration. In order to achieve a better management scheme for groundwater table variations, some adjustments on objective function and constraints related to the groundwater table variation are needed. Also, developing a groundwater simulation model for estimation of water table fluctuations could help verification of the results.

### Deficit Irrigation Potential

The physical environment can be a major limiting factor in the growth, productivity and survival of plants. Water stress is usually the main physical limitation to crop yield. The design of irrigation schemes does not address situations in which moisture availability is the major constraint on crop yield. However, in arid and semi-arid regions, increasing water demands are necessitating major changes in irrigation management and scheduling in order to increase the efficiency of water allocation in agriculture.

Therefore, innovations are needed to increase the efficiency of water use. An option is deficit irrigation with plants exposed to certain levels of water stress during either a particular growth period or throughout the whole growth season without significant reduction in yields. Deficit irrigation practices differ from traditional water supply practices. The manager needs to know the level of allowable transpiration deficiency without a significant reduction in crop yield. The main objective of deficit irrigation is to increase the water use efficiency of a crop by eliminating irrigation that has little impact on yield. The resulting yield reduction may be small compared with the benefits gained through diverting the saved water to irrigate other crops for which water would normally be insufficient under traditional irrigation practices.

Before implementing a deficit irrigation program, it is necessary to know crop yield responses to water stress, either during defined growth stages or throughout the whole season [31]. The crop yield response factor ( $K_y$  in Equation 8) varies depending on species, variety, irrigation method and management practices, and the growth stage when deficit evapotranspiration is imposed. The crop yield response factor gives an indication of whether the crop is tolerant to water stress. A response factor greater than unity indicates that the expected relative yield decrease for a given evapotranspiration deficit is proportionally greater than the relative decrease in evapotranspiration [32]. The most resistant plants to water stress, with a short critical growth stage and high yield potential under normal irrigation, such as tomato and barley, should be selected to exercise deficit irrigation schemes. Meteorological parameters, such as average variations of annual weather humidity, temperature and evaporation in water deficit scheduling should be considered.

In order to investigate the possibility of deficit irrigation in the Varamin plain, the optimal crop pattern obtained from Scenario A is considered for determining water demand. The benefit of the cultivation of each crop is estimated using the yield function presented in Equation 8. By assuming a fixed water allocation and crop pattern mix, the percentage of the cultivated area is changed to obtain the maximum income. The variation of net income vs. changes of cultivated area, rather than the existing condition, is presented in Figure 7. The results show that, if the existing crop area of about 58000 ha decreases by 50%, then the maximum benefit will be obtained. As can be seen in Figure 7, water stress under the existing condition is more than the threshold limit of the crops resulting in a 44% decrease in net income. Therefore, it is suggested to reduce the cultivated area for less water stress and increased income.

Although economically beneficial, this strategy may lead to adverse social impacts, such as the migration of locals due to less job opportunities. Therefore, further studies are needed for determination of the optimal cultivated area in the region considering social and cultural factors.

## SUMMARY AND CONCLUSION

In this study, an optimization model for determination of optimal crop patterns and water allocation has been developed. The objective function of this model is to maximize net income with a conjunctive use of surface and groundwater, considering the effects of a marginal water deficit in the reduction of crop production. The constraints include allowable monthly and cumulative water table variations and the irrigation land available for crop cultivation. Two scenarios are developed for the evaluation of regional policies on crop patterns in the study area. The scenarios are compared based on the system performances indices including reliability, resiliency and vulnerability. The results show that the model without any imposed minimum crop pattern limitation (Scenario A) provides more income, but social and economic aspects should be considered as constraints in suggesting crop pattern configuration (Scenario B). In this way, Scenario A provides more net benefits than the constrained model by up to 50%. In Scenario B, the areas of non-economical crops increase because of some socio-political considerations. Also, the possibility of deficit irrigation application in the study region is evaluated. The results show that because the region is under water stress under the existing condition, reducing crop coverage will increase net income. Although the economic analysis shows that reducing the cultivated area could boost net income, social and cultural adverse consequences could follow.

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