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A decision tool for optimal irrigated crop planning and water resources sustainability

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Abstract In the present study, the conjunctive use policies of surface and ground water resources are developed for minimizing water shortage in an irrigation district subject to constraints on groundwater withdrawals and crop planning capacities. An integrated soil water balance algorithm is coupled to a non-linear optimization model in order to carry out water allocation planning in complex deficit agricultural water resources systems based on an economic efficiency criterion. Various options of conjunctive use water resources along with current and proposed cropping patterns have been explored by Koohdasht Irrigation District (KID), a semi-arid region in I.R. Iran. The analysis provides various scenarios, which can help managers in decision-making for the optimum allocation plans of water resources within the irrigation area. The results reveal that the proposed model, as a decision tool for optimal irrigated crop planning and water resources sustainability, may be used for maximizing the overall net benefits and global water productivity of an irrigation district considering an allowable annual recharge of groundwater. Findings indicate the importance of the conjunctive water management modeling, which can be easily implemented and would enhance the overall benefits from cropping activities in the study area.

Keywords Conjunctive use modeling · Cropping pattern · Irrigation district · Water resources management

1 Introduction

Agricultural systems need to consider production, environmental, and societal issues for the sustainability of agriculture. Numerous interacting factors involving soil, water, plant, climate, and management components must be taken into account. Because of the complex nature of these systems, modeling is a key tool that aids in understanding the intricacies

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of the interactions and delivers a myriad of potential outcomes to users world-wide. In the last decade, new modeling technologies and algorithmic advances, as well as hardware and software improvements, have provided an excellent framework on which to build optimization-based decision support systems, as well as multidiscipline design tools [10,11]. Some of these optimization models and algorithms were applied in specific areas of the agricultural water management.

Water resources sustainability in arid and semi-arid regions with low precipitation and high potential evapotranspiration is a great challenge for managers and decision makers. Conjunctive use of water can be considered as one of the approaches of addressing sustainable water resource management issues in these regions, so as to minimize shortages of water in dry seasons.

There is a large amount of literature on the benefits of conjunctive use of surface water and groundwater [5,17]. A variety of simulation, optimization and linked simulation-optimization models have been applied widely to find operating strategies for conjunctive use [1–3,6,9,12,16,17]. Such models typically use linear (still popular and effective tools to investigate a variety of water allocation problems), non-linear, or dynamic techniques with a dynamic balance of relevant quantities, appropriate constraints and a single or a multiple objective. Artificial neural network models as a simulator of surface water and groundwater interaction with an optimization model were also used for conjunctive use of surface water and groundwater on a basin-wide scale [14].

Groundwater plays a crucial role in the water management of Koohdasht Irrigation District (KID), a semi-arid region in I.R. Iran. Despite its crucial role, several areas of the district do not have a comprehensive program for managing and regulating groundwater. Much of groundwater production is self-supplied, and is not accurately managed or quantified by local agencies. Hence, developing a conjunctive water use model and operating all manageable water resources in the region can increase the yield, efficiency, supply reliability, and cost effectiveness of the KID. The main objective of the present study is to explore the potential use of groundwater in the conjunctive use scenario, and to arrive at an optimal use of water resources by maximizing the net benefits and global water productivity, and minimizing the mining allowance of groundwater factors under various physical and economic constraints in KID. For that, a set of integrated constraints (i.e., soil water balance) in optimization of irrigation water allocation for multi-cropping patterns was enhanced and a mathematical programming model to determine a stable conjunctive use policy for irrigation in a reservoir–aquifer system was proposed.

2 Material and methods

2.1 Mathematical programming

The objective function for optimum allocation of a limited water supply for a single crop may be assumed as follows:

$$\frac{Y_a}{Y_p} = \prod_{i=1}^{n} \left[1 - k_{yi} \left(1 - \frac{W_{ai}}{W_{pi}} \right) \right] \tag{1}$$

where Y_a and Y_p are actual and potential yields, respectively, K_{yi} is yield response factor to deficit irrigation, and W_{ai} and W_{pi} are water used and potential water demand, respectively. Symbols of i and n show the growth stage and total number of crop growth stages, respectively.

Here, the specified K_y coefficients in the study area by Montazar [8] were used. Agro-Ecological Zone Method–AEZM [4] is also used to determine potential crop yields, employing radiation data along with corrections for the climate and for the crop.

The objective function is one of the most popular functions proposed by Stewart and Hagan [15]. It was also used by other researchers including Reca et al. [13] and Montazar et al. [9]. Maximization of the Y_a/Y_p ratio in Eq. 1 would be an objective function for one crop cultivation pattern. A set of constraints may be considered based on the definition of relative yield. The constraint equations are simple and can be defined as follows:

$$0 \leq W_{ai} \leq W_{pi}, \quad \sum_{i=1}^{n} W_{ai} \leq \sum_{i=1}^{n} W_{pi} \tag{2}$$

For a real condition, the needed constraint functions are more complex and may be defined as soil water balance and crop evapotranspiration constraints [9].

The non-linear programming technique has been used to formulate the conjunctive use optimization model, to arrive at the optimal allocation of surface and ground water, and to maximize the benefits within the framework of given constraints and proposed cropping pattern. The LINGO 10.0 package was used to optimize the objective functions [7]. The objective function has been formulated for maximizing the net benefits resulting from the cropping pattern in the irrigation command area. The costs of surface water and groundwater were considered 0.006 and 0.01 USD/m^3, respectively [8]. Other costs, including labor and cultivation costs, in the study were also considered based on the local prices [8]. The unit cost of surface water has been considered the same for all the months during which the surface water is available. The objective function is formulated considering benefits and unit costs of providing water, which can be expressed as:

$$\text{Maximize net annual benefits } (Z) = \sum_{l=1}^{z}\sum_{j=1}^{c} A_{lj} \times Y_{aj} \times P_j$$
$$- \left\{ \sum_{l=1}^{z}\sum_{j=1}^{c} A_{lj} \times C_j - \sum_{l=1}^{z}\sum_{m=1}^{12} \mathrm{CT}_{\mathrm{sw}(l)} \times \mathrm{SW}_{lm} - \sum_{l=1}^{z}\sum_{m=1}^{12} \mathrm{CT}_{\mathrm{gw}(l)} \times \mathrm{GW}_{lm} \right\} \tag{3}$$

where l is the number of zones of the irrigation district ($l = 1, 2, \ldots, z$), j is the number of crops ($j = 1, 2, \ldots, c$), m is the number of months ($m = 1, 2, \ldots, 12$), A_{lj} is the area under jth crop in lth zone (ha), Y_{aj} is the actual yield of jth crop (kg ha^{-1}), P_j is the price of jth crop (USD/kg), C_j is labor costs and all other cultivation costs including land, planting, growing, and harvesting for jth crop, $\mathrm{CT}_{\mathrm{sw}(l)}$ is the total unit cost of surface water for lth zone (USD/m^3), SW_{lm} is the surface water allocation for lth zone during mth time interval (MCM), $\mathrm{CT}_{\mathrm{gw}}(l)$ is the total unit cost of groundwater for lth zone (USD/m^3), and GW_{lm} is the groundwater allocation for lth zone during mth time period (MCM).

In the optimization of the above equation, the decision variables are SW_{lm} and GW_{lm}. In order to maximize the objective function (Eq. 3), the following constraints had to be taken into account:

– Constraints for water requirement of the cropping pattern as follows:

$$\sum_{j=1}^{c} W_{a(jm)} \times A_{lj} \leq \sum_{l=1}^{z} (\mathrm{SW}_{lm} + \mathrm{GW}_{lm}) \quad \forall m \tag{4}$$

where $W_{a(jm)}$ is the water requirement of jth crop for mth time period (m), A_{lj} is the area of jth crop for lth zone (ha).

– In the study area, there are three cropping seasons, i.e., wet season (W), first dry season (D1) and second dry season (D2). Hence, for each season one constraint is sufficient and which can be assumed as:

$$A_j \geq 0 \quad \forall l \qquad \text{for each season (W, D1, and D2)} \tag{5}$$

$$\sum_{j=1}^{c} p_{lj(S1)} \times \mathrm{CA}_l \leq \mathrm{CA}_l \quad \forall l \qquad \text{for W} \tag{6}$$

$$\sum_{j=1}^{c} p_{lj(S2)} \times \mathrm{CA}_l \leq \mathrm{CA}_l \quad \forall l \qquad \text{for D1} \tag{7}$$

$$\sum_{j=1}^{c} p_{lj(S3)} \times \mathrm{CA}_l \leq \mathrm{CA}_l \quad \forall l \qquad \text{for D2} \tag{8}$$

where p_{lj} is the percentage of jth crop in lth zone with respect to culturable commanded area (CA) of lth zone and CA_l is the culturable command area for lth zone (ha). The p_{lj} value is considered different during each season (W, D1, and D2).

– The constraints on groundwater availability for all the zones of the irrigation district may be shown as follows:

$$\sum_{l=1}^{z} \sum_{m=1}^{12} \mathrm{GW}_{lm} \leq \mu \times \mathrm{GWA} \tag{9}$$

where GW_{lm} is the groundwater allocation for lth zone during mth time interval (MCM), μ is the mining allowance of the groundwater resource factor (=1 when no mining is allowed), and GWA is the annual groundwater recharge.

– The surface water availability constraint may be considered as follows:

$$\sum_{l=1}^{z} \sum_{m=1}^{12} \frac{\mathrm{SW}_{lm}}{e_{cd(l)}} \leq \sum_{m=1}^{12} \mathrm{SWA}_m \quad \forall m \tag{10}$$

where SW_{lm} is the surface water allocation for lth zone during mth time interval (MCM), $e_{cd(l)}$ is the conveyance and delivery efficiency of canal for lth zone, SWA is the surface water available at the head of canal for mth time interval (MCM).

2.2 Study area description

The Koohdasht Irrigation District lies in 33°25′N–33°45′N latitude and 47°25′E–47°50′E longitude. The average annual precipitation is only 413.6 mm, which corresponds to semi-arid conditions. The mean annual temperature is 13.8°C. Geographically, the irrigation area is located in the Lorestan province in the West of Iran. Location of KID is showed in Fig. 1. It serves an estimated gross irrigated area of 40,000 ha. The needed water is supplied from the Madian River, as well as 396 wells and 8 springs scattered along the irrigation district. Surface water supplies are inadequate to meet irrigation needs of crops. Consequently, groundwater is being heavily exploited through the wells. Hence, the uncontrolled heavy pumping of groundwater has caused over-exploitation in the irrigation area. Also, around 95,000 ha of KID is managed as a rain-fed agricultural system, which is not considered in this study.

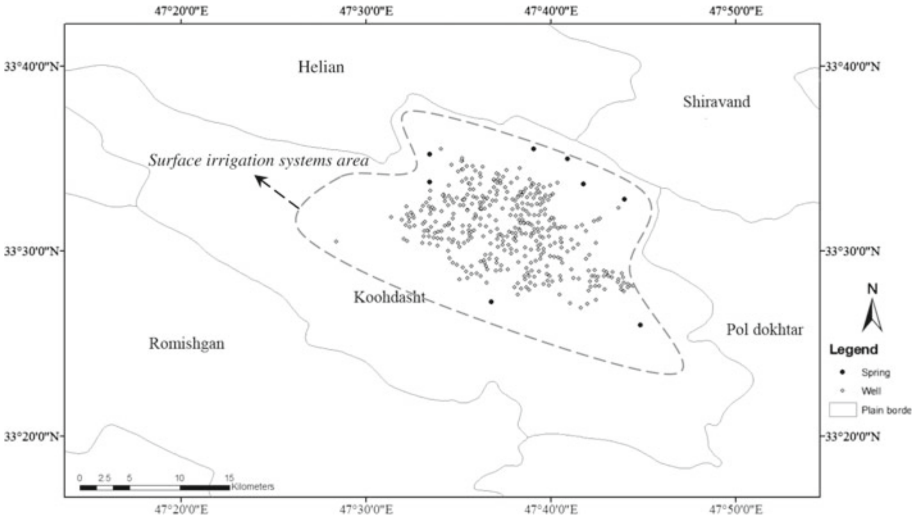

Fig. 1 Location of KID, wells and springs scattered along the surface irrigation systems area

In the past decade, a new challenge in water resources management has been created due to a historical low rainfall combined with a growing demand for water. In view of these changes, farmers have been forced to find strategies to cope with water scarcity. The used strategies are mainly increasing groundwater use and adapting the production strategies. If the present increasing trend of groundwater abstraction continues, it may further lead to a decline in the groundwater table. The groundwater level variations in the study area from 1997 to 2003 are given in Fig. 2. The water table varies about 5 m during 6 years. In the past decade, the groundwater level dropped at an average of 75 cm per year. In these situations, both sources of water should be managed conjunctively so as to minimize fluctuations in total water supply caused by variations in rainfall patterns. Hence, ideally in a controlled and well managed conjunctive water use system, an increase in groundwater withdrawals occurs in times of drought and permits temporary mining of the aquifer to reduce surface supplies. In times of abundant surface water supplies, a greater than normal application of surface water would enable aquifers to replenish their supplies.

Based on existing technical information pertaining to the study area, the mean specific yield and transmissivity of the aquifer are 0.031 and 380 m^2/day, respectively. The water level varies from 10 to 85 m below the ground level. The recharge to the aquifer consists of the recharge due to rainfall (10% as percolation of precipitation), canal seepage and the deep percolation from the root zone of the crop grown which is estimated at 30% of the total allocated water in KID [8].

The available surface water is considered 39.270 MCM (Table 1), which supplies at 31.744 MCM during the 6 months of March to August, i.e., at 80% of annual water delivered. During August to December, the available surface water decreases to 7.526 MCM, and during January, there is no available surface water.

There are three main cropping seasons in the KID that include a rainy season from November to March, a first dry season from April to June, and a second dry season from July to October. The major crops of the rainy season are wheat, barley, and colza. Major crops during the first dry season are wheat, barley, colza, maize (and corn), sugar beet, tomato, bean, cucumber, summer crops (includes melon, watermelon, gourd and cantaloupe), and

Fig. 2 Monthly drop of groundwater level of study area from 1997 to 2003

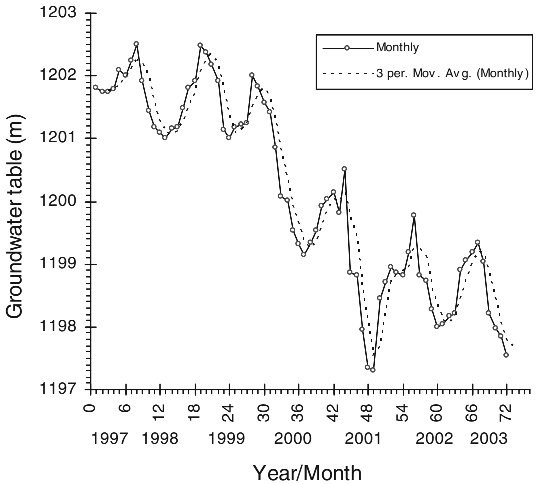

Table 1 Volume of available surface water in the different months (MCM)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Volume of available surface water	0.000	1.041	3.413	4.640	6.033	6.695	5.851	5.112	3.628	0.300	1.781	0.776

rice, whereas during the second dry season are maize (and corn), sugar beet, tomato, bean, cucumber, summer crops (includes melon, water melon, gourd and cantaloupe), and rice.

In the present study, in order to utilize the water resources reasonably, to match water supply and requirement and reach a satisfied economic benefit, ten proposed cropping patterns were decided considering the socio-economic requirements like food self-sufficiency, employment and prevailing agricultural/irrigation practices in the irrigation district. Also, eight existing cropping patterns related to 2001–2009 growing seasons were considered. The cultivated area of different crops for the existing and proposed cropping patterns has been given in Table 2. Existing and proposed cropping pattern scenarios are indicated as E1–E8, and P1–P10, respectively. Five deficit irrigation practices, the application of 10–50% deficit irrigation, were also investigated. The deficit irrigation practices were accomplished for all of the proposed and existing cropping patterns.

3 Results

The conjunctive water use model was applied to evaluate the different water allocation options. The model was run for eight existing cropping patterns (8 growing seasons of 2001–2009) and ten proposed cropping patterns with different scenarios of surface and ground water utilization.

3.1 Conjunctive water use options

To investigate conjunctive use options, all scenarios of surface and ground water allocation and cropping patterns were evaluated. For each scenario, optimal allocations of surface and

Table 2 Cultivated areas of different crops in the 8 existing and 10 proposed cropping patterns (ha)

Crop	Scenario no.																	
	E1	E2	E3	E4	E5	E6	E7	E8	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Wheat	8,183	10,841	10,813	13,198	8,087	18,195	9,461	5,536	10,000	11,500	14,000	14,800	15,000	17,000	18,000	18,500	19,000	1,8195
Barley	605	497	641	42	374	240	0	1,206	300	350	450	500	500	500	800	1,200	1,500	1,206
Maize	4,076	3,206	3,510	0	5,296	5,068	4,570	3,679	4,500	4,700	5,300	5,400	5,500	6,000	6,000	7,000	7,800	5,296
Rice	152	184	43	152	0	104	0	0	0	25	60	75	75	0	50	50	80	152
Tomato	740	12	130	23	53	283	21	60	50	60	85	100	100	100	160	200	250	283
Cucumber	0	2,645	605	545	972	1,201	954	86	900	1,000	1,100	1,100	1,200	1,000	1,000	1,200	1,350	2,645
Colza		0	5	0	0	16	705	20	0	0	0	0	0	150	250	0	0	858
Sugar beet	0	0	0	0	0	0	1,179	39	0	0	0	0	0	0	50	100	100	1,179
Bean		102	8	0	23	4	0	9	0	0	10	30	40	40	60	60	60	104
Summer crops	2,193	4,998	2,159	701	1,696	1,349	2,676	890	1,300	1,500	2,000	2,100	2,200	2,000	1,750	2,500	2,500	3,828
Orchards	1,250																	
Total	16,086	22,255	18,010	16,929	16,602	27,041	18,910	12,354	17,350	19,495	23,475	24,615	25,115	27,290	29,120	31,810	33,940	36,142

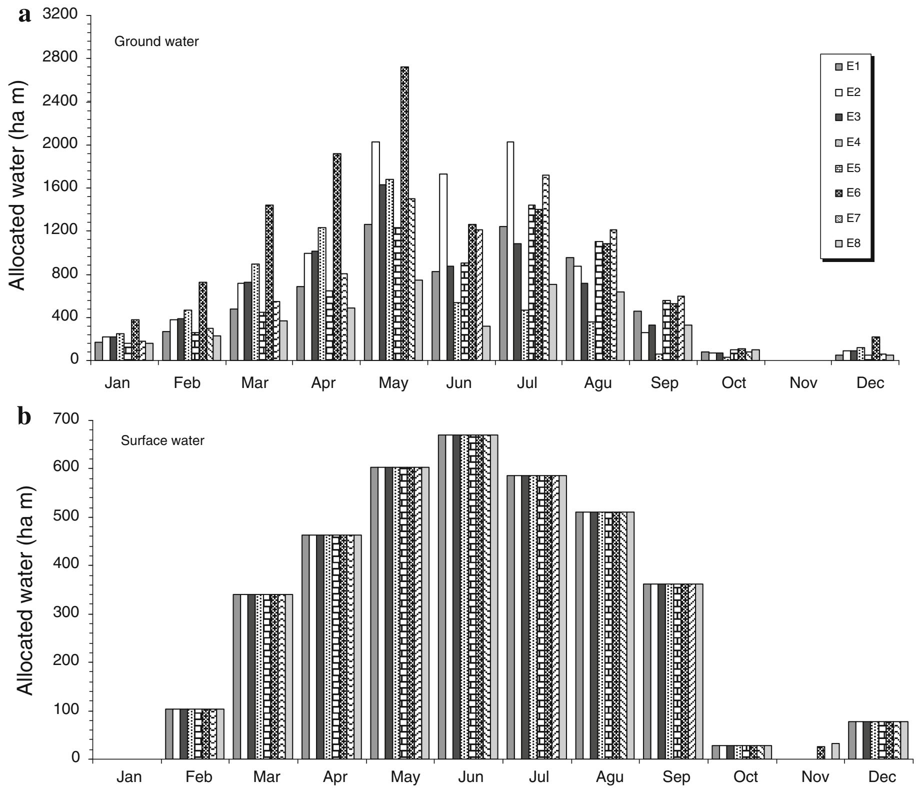

Fig. 3 Optimal monthly allocation of **a** surface water and **b** ground water for the 8 existing cropping patterns

ground water were obtained considering the cropping pattern for the maximum benefit by relaxing the individual crop area constraint. The monthly optimal water allocation plans (from surface and ground water resources) for the scenarios is presented in Figs. 3 and 4. The total allocated water (TAW) and the ratio of total allocated groundwater (GW) to TAW for the study scenarios are also showed in Table 3.

In the scenario E6, a net benefit of 74.300 million USD (Fig. 5a) was obtained from the 22,255 ha area using 37.718 and 117.951 MCM utilization of surface and ground water, respectively (Table 3). The maximum net benefit, among the current cropping patterns, is obtained in this case but the mining allowance of groundwater factor (μ) and global water productivity (GWP) may not be considered in the desired status (Fig. 5b, c). The GWP and μ of the irrigation district were determined to be 0.477 USD/m^3 and 1.045, respectively. Hence, groundwater withdrawal is restricted to the recharge to maintain the river-aquifer equilibrium. In this case, 64.3% of the area is considered under wheat in the wet and first dry season, while 17.9% of the area under maize in the first and second dry seasons. In the other cases except E2, the μ ranged between 0.366 and 0.729, and the net benefit and GWP are lower than 61.688 million USD and 0.555 USD/m^3, respectively. Also, the net benefit of scenario E2 (72.139 million USD) is lower than scenario E6 but it's GWP is about 111% of E2 (0.531 USD/m^3).

The results show that scenarios P1 and P10 have the lowest and greatest net benefit value among the proposed cropping patterns, respectively. In scenario P1, a net benefit of 57.960

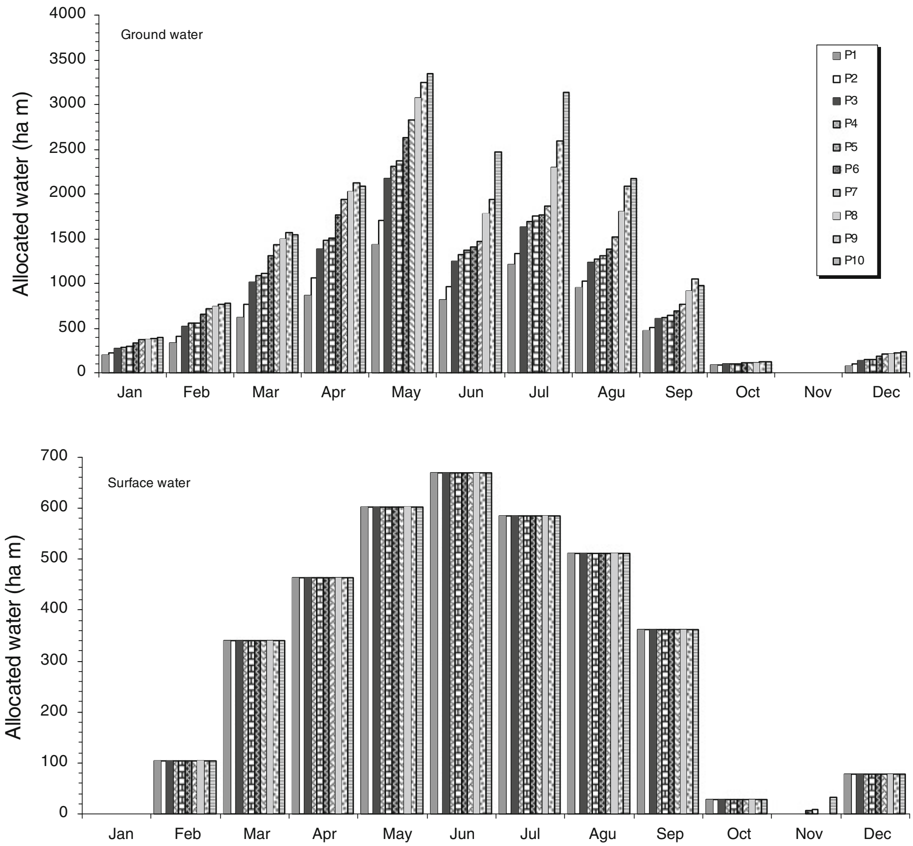

Fig. 4 Optimal monthly allocation of surface and ground water for the 10 proposed cropping patterns

million USD was obtained along with 37.450 and 70.544 MCM utilization of surface and ground water, respectively. Net benefit rose almost 205% in case P10 as compared to the benefit of case P1. The GWP and μ value for case P1 and P10 were obtained: 0.518 USD/m^3 and 0.625, and 0.547 USD/m^3 and 1.529, respectively. In scenario P10, groundwater utilization is strongly increased, which is due to an increase in cultivated area and water requirement as compared to other cases. The cultivated area (37,392 ha) is about 100% more in this case as compared to the P1 condition. In this case, 52% of the area is considered under wheat and barley in the wet and first dry season, while 20.6% of the area under maize (and corn) in the first and second dry seasons.

3.2 Water allocation in deficit irrigation practices

The interval for computing the deficit ratio was taken as 0.1 and the deficit ratio ranged from 0.5 to 1. A deficit ratio equal to 0.5 indicates a 50% deficit irrigation and equal to 1 means irrigation is applied to bring moisture in the root zone to field capacity (full irrigation). Here, the deficit irrigation practices are presented for scenarios E2, as E2-D, E8, as E8-D, P2, as P2-D, P4, as P4-D, and P10, as P10-D practice. No deficit irrigation was run for orchard crops. Cropping area was considered 23,505, 13,604, 20,745, 25,865, and 37,392 ha for all

Table 3 Total allocated water (TAW) and GW/TAW values of each study scenario

Scenario no.	Total allocated water-TAW (MCM)	(GW/TAW) × 100
E1	102.252	63.4
E2	131.113	71.5
E3	109.201	65.6
E4	88.342	61.9
E5	106.358	64.8
E6	156.360	75.8
E7	119.724	68.7
E8	79.072	52.2
P1	107.992	65.3
P2	119.150	68.6
P3	140.197	73.3
P4	146.193	74.4
P5	149.524	74.8
P6	159.812	76.5
P7	169.616	77.8
P8	185.671	79.8
P9	198.527	81.1
P10	201.334	82.1

deficit irrigation practices in the cases E2-D to P10-D, respectively. The monthly optimal water allocation plan (conjunctive water use) for each of the scenarios was derived by the model. As an example, Fig. 6 shows the monthly optimal water allocation plan for the deficit irrigation practice of 30%.

A comparative statement of results of all the scenarios is also given in Fig. 7. The results indicate that appropriate and timely planning and decision-making for revisions and changes in cropping pattern policies will enhance the system productivity and additionally make it possible to exercise a demand-based water management with due consideration for impacts on water resources. For example, in the scenario P4-D with 30% of deficit irrigation, a cultivated area of 62% under wheat and barley, a net benefit of 58.673 million USD may be obtained from the 25,865 ha area with 37.470 and 68.073 MCM utilization of surface and ground water, respectively. The mining allowance of the groundwater factor (μ) is considered 0.601 and the GWP of command area is 0.554 USD/m^3. Hence, groundwater withdrawal is restricted to almost 60.1% of the recharge to the aquifer, while an index of 96.4% was obtained for the full irrigation practice of the case. The net benefit of the P4-D is almost equal in the E7 option, with a saving of 14.185 MCM groundwater supplies compare to the case E7. The global water productivity of KID may also rise about 12% compared to the E7 case. However, we can save a significant quantity of groundwater which can be used in other needy areas where even groundwater is not available. Such practices may be spatially recommended in dry condition and also avoid some environmental problems like depletion of groundwater and disturbance of stream aquifer equilibrium.

4 Discussion

Figure 5b, c show the GWP and μ for the cropping pattern scenarios. As an example, the total water pumped annually from the groundwater resources exceeds the annual recharge by 53% for case P10. For this case, the GWP and GW/TAW are 0.547 USD/m^3 and 0.821 (i.e., 82.1% of the needed water of KID is allocated from groundwater resources), respectively.

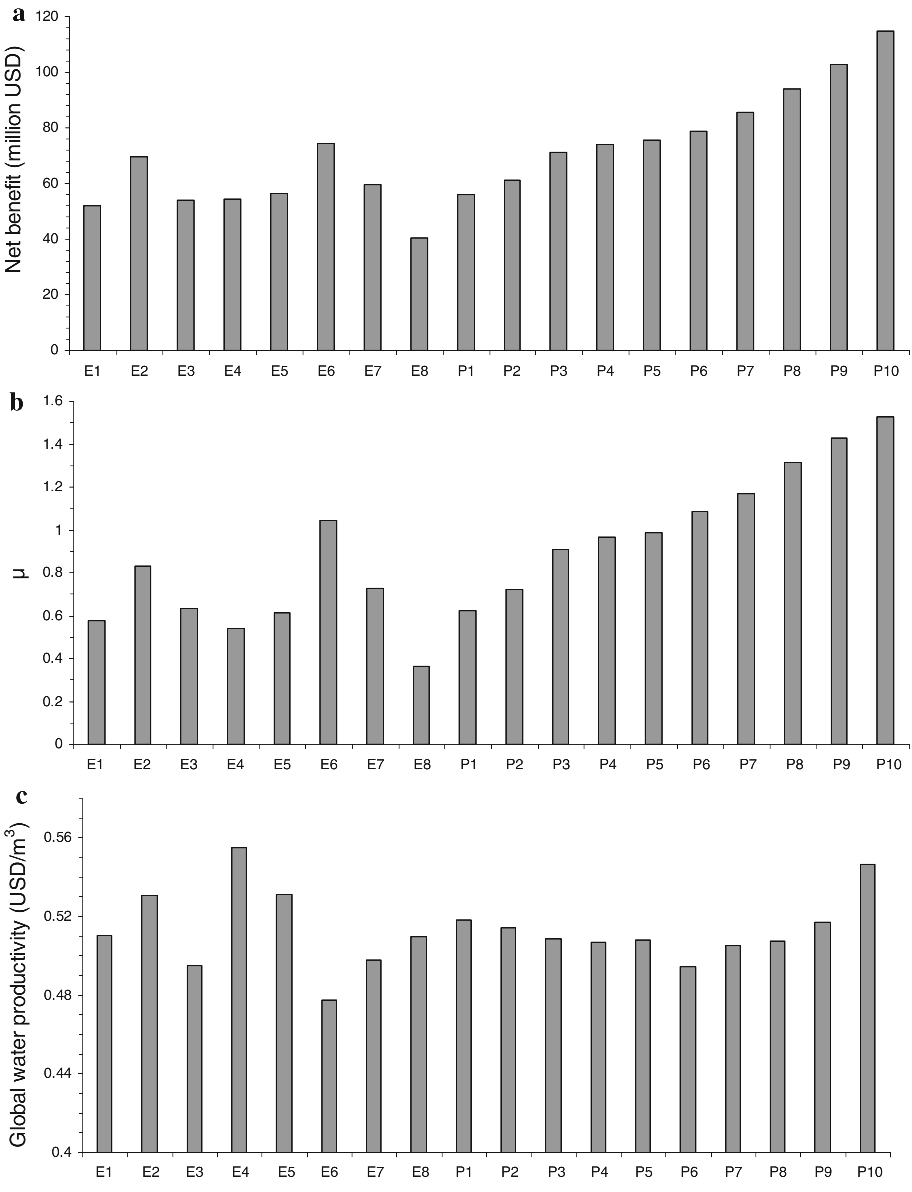

Fig. 5 Maximum net benefit (**a**), GWP (**b**) and μ (**c**) indices values of the study scenarios

In the 30% deficit irrigation practice of P10-D (Fig. 7), the μ values is satisfied (around 1.0) and the global water productivity value is severely increased because of low water allocation, in spite of lower farm income (0.573 USD/m^3). As can be seen in Fig. 7, up until the level of 20–30% of deficit irrigation based on the cropping pattern, the reduction in irrigation area income and GWP may be favourable. The findings indicate that the sensitivity of GWP to deficit irrigation practices in KID is more than other assessment indices.

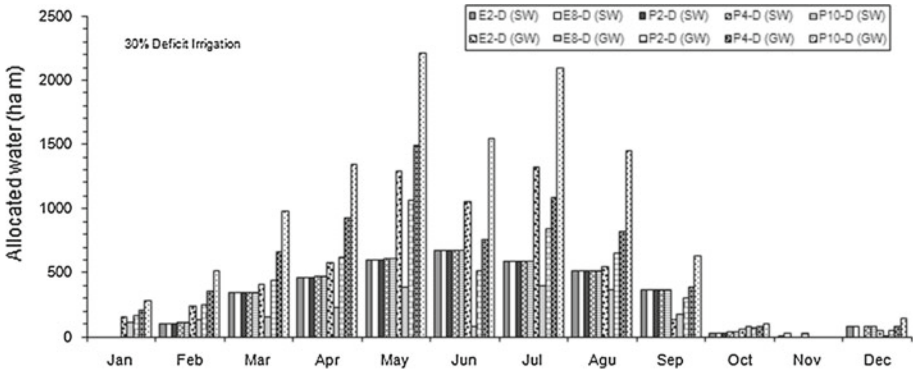

Fig. 6 Optimal monthly allocation of surface and ground water for the deficit irrigation practice of 30%

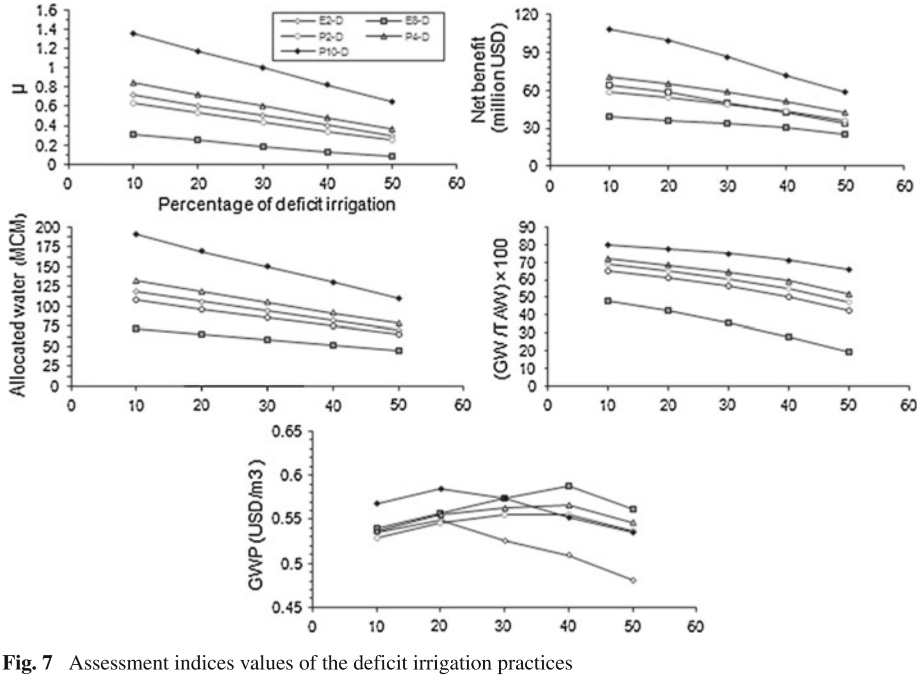

Fig. 7 Assessment indices values of the deficit irrigation practices

The analysis demonstrates that the appropriated crop planning option could be significantly affected by the main objective of the decision-making process. In other words, to increase the profit, one must consider multi-product cropping patterns with emphasis on high produce and price in the decision-making process, even though these decisions may result in decreasing irrigation efficiency, uncontrolled water pumping from wells, and lack of sustainability in groundwater conditions. Limiting the harvesting land of crops with a high requirement of water (sugar beet, maize-corn and cucumber) and increasing the harvesting land for wheat and barley, in addition to applying a deficit irrigation strategy can solve the problem to some extent. As a result, the cases P10, E4, and E8 have the most appropriate status of net benefit (115 million USD), GWP (0.555 USD/m^3), and μ (0.366), respectively.

Also, the total water and groundwater utilized may be considered the best one in case E8 (79.072, and 41.275 MCM, respectively). However, the desired option can be recommended with a mean status of all the indices. Here, case P3 may be considered as the appropriate one with a net benefit, GWP, and μ of 71.347 million USD, 0.509 USD/m^3, and 0.911, respectively. For this case, the total water and groundwater utilized were 140.197 and 102.764 MCM, respectively. The results may slightly change considering other aspects which are not included in the present analysis, like uncertainties of rainfall and consequent effect on groundwater recharge and surface water, surface and ground water interaction, variation in prices, temporal variability of various hydrologic and pricing phenomena.

Investigations reveal that deficit irrigation could be recommended as an efficient management practice to enhance conjunctive use option for maximizing the overall net benefits considering an allowable annual recharge of groundwater in the study region. Therefore, extensive options are recommended to determine appropriate deficit irrigation management scenarios and to identify the reactions by strategic crops to the different management scenarios adopted. A change in the cropping pattern of the study area to a low-consumption pattern, which decreases irrigation requirement and groundwater extraction, may be another approach but it may not be a lucrative choice for the farmers. Conjunctive use and suitable cropping patterns have evolved to meet present and future requirements in the study area. Using the surface and groundwater conjunctively, reliability of the irrigation can be increased, which reduces the losses due to uncertainty in rainfall and insufficient surface supplies. However, farmers can be motivated easily towards conjunctive use options with a deficit irrigation practice, as it increases their income, provides security against meteorological uncertainties and flexibility in cropping pattern. The evaluations indicate that conjunctive use options are feasible and can be implemented in the KID.

5 Conclusions

An optimization model with various hydrological and managing constraints was developed for generating optimal crop planning and water allocation policies. The model finds the optimal set of areas allocated to each crop, calculates water demands for the plain, and allocates surface and ground water to the demands. Various scenarios of conjunctive use of surface and ground water along with current and proposed cropping patterns of KID were explored. Some deficit irrigation practices were also investigated. The results illustrate that the proposed conjunctive use policies can control the monthly and cumulative groundwater level variations during the planning horizon. The optimal water allocation policies can significantly increase the total agricultural benefit and global water productivity in the study area.

The analysis demonstrates that the appropriated crop planning option could be significantly affected by the main objective of the decision-making process. In other words, to increase the profit, one must consider multi-product cropping patterns with emphasis on high produce and price in the decision-making process, even though these decisions may result in decreasing irrigation efficiency, uncontrolled water pumping from wells, and lack of sustainability in groundwater conditions. Investigations reveal that deficit irrigation could be recommended as an efficient management practice to enhance at conjunctive use option for maximizing the overall net benefits considering an allowable annual recharge of groundwater in the study region. The optimization model developed has the flexibility to model different conditions and assumptions and can be used for planning the land and water resources management of irrigation districts.

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