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Optimal Cultivation Pattern to Increase Revenue and Reduce Water Use: Application of Linear Programming to Arjan Plain in Fars Province

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Abstract: Because the available water resources of the Arjan plain region in Iran do not fully meet the watering requirements for plants in farmlands, the crops suffer from water stress, a situation that causes them to wilt. The aim of this study is to develop a water resources planning model that helps decision-makers determine an appropriate cultivation pattern, optimize the exploitation from surface water resources, and specify the method of allocating water across different farm crops to minimize the detrimental effects of water shortage. Through investigating various models of water resources planning and properties along with the governing conditions for each of these models, the linear programming model was selected as a suitable option due to its simplicity and practical applicability to water resource allocation planning. The model was run for a five-year period by considering gradual variations through the determination of the most appropriate exploitation pattern from the available water resources (surface and groundwater). Results reveal that the negative water balance can be improved gradually as positive, where it will reach +20 million m^3 per year in 2040 from the current deficit of 236 million m^3 with an 8% increased net profit.

Keywords: optimization; water resources; cultivation pattern; groundwater

1. Introduction

For many decades, the scarcity of water resources has become a serious problem due to the rapid population growth and shift in economic development. As a result, this has become a pressing issue in formulating sustainable development policies [1–3]. In many countries, agriculture requires the largest amount of water, which places even more importance on agricultural water management. For example, agricultural water use accounts for 63.6% of the national total water use in China [4]. Crop area is considered as an important reference data for agricultural water management and plays an increasingly significant role in the sustainable development of agriculture [5–10]. The most common technique used for cropping pattern optimization (CPO) is linear programming (LP). Efficient optimization methods for crop area planning are desired and beneficial to agricultural water management as they can decide how much water should be allocated to different cropped areas in order to obtain certain goals, such as maximizing benefit and minimizing water-use of an irrigation system [11–14].

The proposed goal is to find a way to maximize the profit or minimize the cost; to this end, cases where available resources must be combined are analyzed. Via mathematical programming, an optimal way of combining scarce resources can be quantified.

From an engineering perspective, planning irrigation with a deficit is very complex, because the production functions need to be reliable [15]. Any uncertainity in those functions will spoil the precise production prediction as well as the determination of the most economical water level [16]; however, deficit irrigation is a concept that can be applied with great success. Many farmers who experience a shortage of available water resources can practice deficit irrigation, aiming to maximize profit by many times in an empirical way. Achieving a proper cultivation pattern with the aim of water resources management is a complex problem, which is dependent upon various factors. In this regard, an LP model was used for optimization of cultivation patterns in the Arjan plain.

Examination of resources indicates that models have been used for optimization in various areas including management of water resources and determination of optimal cultivation pattern. Zhou et al. [17] investigated the theory and application of the fuzzy ideal linear programming model for a plain in a sub-region of Haraz. They concluded that by establishing flexibility in the ideals in a fuzzy model, the resources can be allocated in a better way for the developed area under cultivation. Shang and Mao [18] proposed an optimization model for irrigation under the conditions of limited availability of water.

Theocharis et al. [19] presented a simplified non-linear programming method for selecting the best diameters for pipes used for irrigation. Previously, many real-life case studies about crop area optimization have been addressed during the last three decades. López-Baldovin et al. [20] developed a multicriteria objective function for the Guadalquivir Valley. In this model, cluster analysis was employed to divide the irrigated area into homogeneous types of farming. The results showed that the crops' evolution over time was significantly related to the political environment regarding the Common Agricultural Policy (CAP).

Accordingly, the objective of this study is to develop a water resources programming model for determination of a proper cultivation pattern; to optimize exploitation from surface and groundwater resources; and to specify the way water can be allocated among agricultural crops in the Arjan plain in Fars Province.

Case Study

The Arjan plain is located in the southwestern part of Iran in the Fars province. This is a protected area of about 60,000 ha, with an average annual rainfall of 430 mm (16.92 inches). This area is located between two wetlands, Arjan wetland from the east and Parishan wetland from the west, in addition to being located between two major cities, Shiraz and Kazeroon. These two wetlands create a beautiful area. Furthermore, the demands of these nearby two major demands for agriculture has resulted in local people beginning to invest in agriculture in this area, which considered as the most important economic role. Figure 1 presents the Arjan plain location in Iran and the Arjan and Parishan wetlands [21,22].

About 60% of this area is bounded by Zagros Mountain, and the climate of the wetlands is more similar to the city of Kazeroon, with the International Wetland of Parishan located 12 km from Kazeroon. The Arjan plain elevation is almost 1500 m above the sea level, the Arjan wetland elevation is 2015 m and the Parishan elevation is 820 m above the sea surface level. According to the cultural background of the Arjan plain, local people utilized remedial plants to cure their illness in the past in addition to demanding food crops from the major cities, such as watermelon, apple, eggplants and so on. Therefore, the biodiversity of plants in this area will be critical regarding the demands for food and vegetables from the major neighboring cities in addition to the local economy. The Arjan and Parishan wetlands as well as the plain are considered as protected areas by the International Union for Conservation of Nature (IUCN) list.

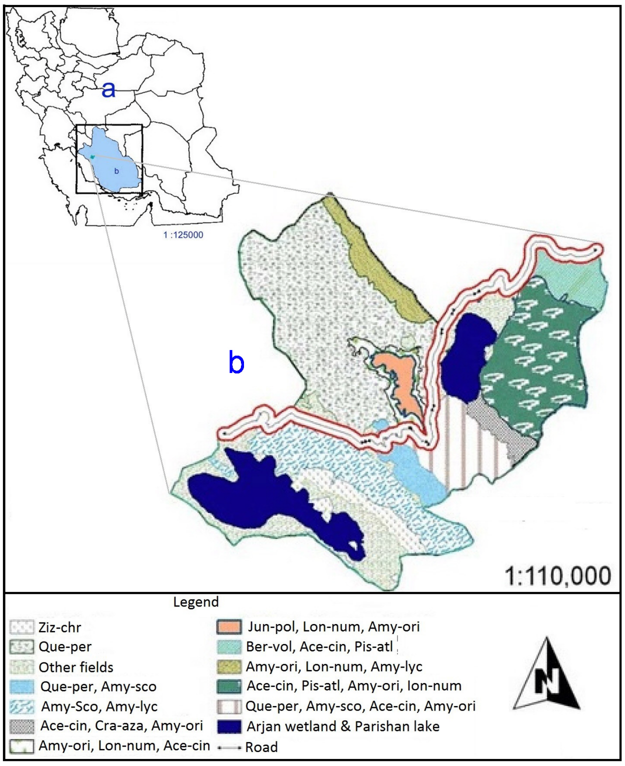

Figure 1. Location of study area: (**a**) Iran; (**b**) Fars Province and the Arjan–Parishan wetlands.

2. Materials and Methods

2.1. Optimization

Optimization is a method through which the best possible solution for a problem is determined based on the specified target and the existing constraints. All of these values are determined by mathematical functions and relations. The optimized problem has one target function and related constraint conditions encompassing the properties of the system of interest.

The common methods of mathematical programming for optimization include linear programming, non-linear programming, dynamic programming, integer programming, binary programming, the critical path method, and the allocation method.

2.2. Optimization of Cultivation Pattern

The water resources available in the region of interest do not fully meet the agronomic water need for crops in agricultural lands. Consequently, the plants face water stress and in turn, this results in yield reduction. As a result, the way resources are exploited and water is allocated across different crops should be optimized in order to minimize the detrimental effects of water shortage.

Through investigation of various models of water resource programming and properties along with the conditions governing each of these models, linear programming was chosen as the best model for this case of study.

2.3. Linear Programming (LP)

Linear programming is one of the simplest and most practical models of optimization. To develop a linear programming model, the steps below are followed:

1. Development of target function
2. Development of a set of equations and inequalities (constraints)

3. The no-negative condition

This model deals with the solution of the type of problems in which the relations between the variables are linear for both the target function and constraints. This simplifies the problem, although this also imposes more constraints.

This type of programming in water resources can be applied in problems with simple relations, such as direct allocation of resources. Furthermore, it can be applied even to complex problems of exploitation and management.

The general model of linear programming is as defined by Equation (1):

$$\begin{gathered} Max\ Z = C^2 \times X \\ S \times T : AX \leq b\ ; X \geq 0 \end{gathered} \tag{1}$$

where C is the n-dimensional coefficient vector of the target function; X is the n-dimensional vector of the decision variables; b is the m-dimensional vector of constants indicating available resources; A is the m by n matrix of the coefficients of constraints; and T is the matrix transpose operator.

Under logical and specific assumptions, non-linear problems can also be converted into LP problems. They then need repetition or approximation methods to be solved. The advantages of LP are as follows [23]:

1. the possibility of solving problems for a large number of decision variables;
2. no requirement of initial values;
3. quick calculation of the global optimal solution;
4. availability of the related software programs.

The target function of the proposed optimization model is formulated as Equation (2):

$$Max \sum_c A_c \left[B_c \left(Y_a \middle/ Y_p \right) - C_c \right] \tag{2}$$

where A_c is the cultivation area of Product c (ha); B_c and C_c are the revenue and the cost of Product c per ha, respectively per area unit (Iranian Rials per ha); Y_a and Y_p are the actual and potential products, respectively (kg/ha); Y_p/Y_a are the relative produced product (the function of producing a product out of water-dimensionless).

In Equation (2), Y_a is the only unknown variable and other variables are either measurable (A_c, B_c, and C_c) or calculable (Y_p). In contrast to the various functions of producing a crop out of water, Equation (3) was used in this study:

$$Y_a \middle/ Y_p = 1 - Ky_c \left(1 - \frac{ETa_c}{ETp_c} \right) \tag{3}$$

where ETa_c and ETp_c are the actual and potential evapo-transpiration (PET) of the plant, respectively, during the growth season (mm); $\mathrm{Ky_c}$ is the coefficient of plant sensitivity to water, which is the correlation between the related productivity loss and the related evapotranspiration reduction.

In Equation (3), if the actual evapo-transpiration (ETa) is equal to the potential evapo-transpiration for Product c (e.g., ETa_c/ETp_c = 1); thus, Y_a/Y_p is also equal to 1. However, if ETa is lower than the ETp (e.g., ETa_c/ETp_c < 1), then Y_a/Y_p < 1. Essentially, in this case, its value changes in relation to ETa_c/ETp_c in a linear fashion (with its slope in proportion with Ky_c). In order to employ Equation (3) in the model, the value of ETa_c/ETp_c is considered equivalent to the ratio of the actual to potential irrigation water, where the amount of potential irrigation water can be calculated with Equation (4):

$$IRp_{c,t} = K_{lf}(ETp_{c,t}) \middle/ E_f \tag{4}$$

where $IRp_{c,t}$ is the potential irrigation water allocated to each plant in every month t (mm); $ETp_{c,t}$ is the potential evapo-transpiration of the plant in every month t (mm); K_{lf} is the leaching coefficient assumed as 1.1 in this study; E_f is the irrigation efficiency.

After the target function, constraints are the next to be calculated in the formula. The area under cultivation is the first constraint, with the total cultivation area equal to the total area of each plain as in Equation (5), and the area under cultivation for each crop can only vary by 20% when considering the social conditions, with the aim of gradual changes in the region's cultivation combination according to Equation (6):

$$\sum_c A_c = A_t \tag{5}$$

$$0.9Ap_c \leq A_c \leq 1.1Ap_c \tag{6}$$

where A_t is the total area of each plain (ha); Ap_c is the cultivation area of Crop C under the existing conditions (ha).

Irrigation water is the second constraint. The maximum limit for the actual irrigation water in each month is equal to the potential irrigation water, which is calculated in Equation (7):

$$IRa_{c,t} \leq IRp_{c,t} \tag{7}$$

The total irrigation water during the growth season is equal to the total irrigation water in each month, which is calculated according to Equations (8) and (9):

$$IRa_{c,g} = \sum_c IRa_{c,t} \tag{8}$$

$$IRp_{c,g} = \sum_c IRp_{c,t} \tag{9}$$

where $IRa_{c,t}$ and $IRp_{c,t}$ are the actual and potential irrigation water in each month t (mm); $IRa_{c,g}$ and $IRp_{c,g}$ are the actual and potential irrigation water in the growth season (mm).

Water harvest is the third constraint. Harvesting surface water is conducted completely. However, harvesting groundwater is limited to the maximum allowable limit of groundwater resources in the target year, which is calculated in Equation (10):

$$GR \leq GR_{max} \tag{10}$$

The total irrigation water is equal to the sum of the harvested water from the surface and groundwater, which is calculated in Equation (11):

$$SU + GR = IR \tag{11}$$

where GR is the groundwater harvesting (million m^3); GR_{max} is the maximum allowable limit to harvest groundwater resources in the target year (million m^3); SU is the surface water harvesting (million m^3); IR is the total irrigation water (million m^3).

The allocation of water to plants is the fourth constraint. The total water allocated to plants (IRR_t) should be fully divided between downstream agricultural plants as calculated by Equation (12):

$$IRR_t = \sum_c IRa_{c,t} \times A_c \tag{12}$$

The model inputs include the following two parameter groups.

1. The parameters related to economic calculations, extracted from reports of basic studies (agricultural and socioeconomic) [23], include

   - the product efficiency in each plain;

- the unit price of each product in the region, which is the average of reference-year and the final year with inflation effects of 11.9% [24];
- price per ha of each product in the region.

2. The parameters related to calculations of irrigation water include

- the total irrigation efficiency of each plain in different years;
- the net monthly irrigation requirement of each product;
- the coefficient of plant sensitivity to water;
- the maximum allowable withdrawal from groundwater in different years.

Due to the great significance of these parameters, the required constant and coefficient values for the LP model are presented in Tables 1–3.

Table 1. The total efficiency of irrigation of the Arjan plain for the target years (%).

Base Year	Target Years				
2015 (Current Status)	2020	2025	2030	2035	2040
52.2	55.7	57.8	59.3	64.1	67.0

Table 2. The maximum allowable groundwater withdrawal from the Arjan plain for the target years (unit: Million Cubic Metres, MCM).

Base Year	Target Years				
2015 (Current Status)	2020	2025	2030	2035	2040
659	473	465	437	428	392

Table 3. The net monthly irrigation requirement (IR), revenue (B), cost (C), and Ky of agricultural products of the Arjan plain.

Month	IR for Each Month (mm)												B	C	Ky [25]
Crop Type	1	2	3	4	5	6	7	8	9	10	11	12	Sum	($k in ha)		
Wheat	81	159	119	-	-	-	-	48	8	3	9	25	452	654	348	1.10
Barley	81	154	62	-	-	-	-	48	9	4	10	25	393	57	21	1.10
Fig	48	51	149	280	282	201	101	25	-	-	-	-	1137	2897	1106	0.80
Watermelon	55	103	202	250	61	-	-	-	-	-	-	-	671	1387	642	1.10
Melon	55	103	202	244	60	-	-	-	-	-	-	-	664	1276	611	1.10
Hay	53	110	156	194	185	135	82	41	22	5	10	19	1012	55	35	0.90
Green beans	-	-	-	65	103	162	100	25	-	-	-	-	455	1848	939	0.90
Potato	51	57	199	287	273	177	61	-	-	-	-	-	455	408	185	1.10
Onion	71	116	202	261	230	-	-	-	-	-	-	-	1105	274	80	1.05
Apple	13	79	193	256	243	166	30	-	-	-	-	-	980	2084	737	1.05
Pear	20	117	194	256	243	152	-	-	-	-	-	-	982	2529	988	0.95
Peach	23	114	184	242	228	142	-	-	-	-	-	-	933	3222	1328	0.65
Eggplant	53	110	156	194	185	135	82	41	22	5	10	19	1012	1953	728	0.70
Walnut	-	68	188	294	279	169	-	-	-	-	-	-	998	7759	2303	0.75
Grapes	-	47	163	226	213	81	-	-	-	-	-	-	730	1933	802	0.85
Lentil	52	90	220	273	40	-	-	-	-	-	-	-	675	1211	255	1.25
Chickpea	52	90	220	271	40	-	-	-	-	-	-	-	673	378	137	1.15
Rapeseed	81	154	62	-	-	-	-	48	9	4	10	25	393	477	182	1.20

The total efficiency of irrigation of the Arjan plain was 52.2% in 2015; however, after managing the irrigation system and water allocation, in the target years of 2020, 2025, 2030, 2035, and 2040, the total efficiency should increase. Total changes in efficiency are expected to amount to a 15% increase, which is significant in the Arjan plain project.

Based on the long-term governmental plan of surface and ground water harvest, regardless of the climate changing situation and precipitation, surface water harvest is always 9 Million Cubic Metres (MCM), but the governmental long-term plan for groundwater harvest will change every five years, decreasing from 659 MCM in 2015 to 392 MCM in 2040, which is a 267 MCM decrease over a period of 25 years.

It can be claimed that the crops with a Ky smaller than 1 tolerate the lack of water to a greater extent and could be exposed to a water deficit. On the other hand, crops with a Ky greater than 1 show a yield decrease that is more than proportional to the applied evapotranspiration decrease [26]. Benefit-to-cost (B/C) calculation shows that the highest rate of B/C is for lentils with 4.76; moreover, for onions and walnuts, the B/C ratio is almost 3.4, which is significant. Other crops have a B/C ratio between 2 and 3, except wheat, hay, and green beans for which the B/C ratio is less than 2. Different B/C ratios cause different results in terms of irrigation water allocation and cultivation area.

3. Results and Discussion

The LP model applied to the study region was developed using in LINGO 8.0 [27]. The LP model is used for the determination of the optimal cultivation combination, of the most suitable exploitation pattern regarding the available resources, of the optimal allocation of this pattern between different plants, and eventually of the profit to be made from the agriculture. The results of the study are described as follows.

3.1. The Optimal Cultivation Pattern

The results of the model, run over many years, are provided in Table 4 for the Arjan plain. The results reveal that the variations in the cultivation pattern over different years is expected to result in an increasing trend in the net gained profit from $223 million in 2020 to $245 million in 2040, despite reduced withdrawal from groundwater resources. The net profit is calculated based on all revenue and the cost of all products in each year, including land rent costs, capital, tax, labor force costs, and all other costs. This is calculated as follows (Thompson, 1978):

Step (1) Sales revenue = price of product (B_c) × quantity sold;
Step (2) Gross profit = sales revenue − cost of sales and other direct costs;
Step (3) Operating profit = gross profit − overheads and other indirect costs;
Step (4) Pretax profit (earnings before taxes) = operating profit − interest payable;
Step (5) Net profit (B_c-C_c) = Pre-tax profit – tax.

In Table 4, the total cultivation area is 50,701 ha and the net profit is 697 billion IR Rials, which is equal to 18.6 million US Dollars (USD) in 2015 as a reference year. Net profit is expected to continuously increase with changes in cultivation area. Furthermore, the area utilization is expected to decrease, which is in the interest of local farmers. The harvest of surface water is limited to its maximum allowable amount of 9 MCM each year and the groundwater harvest decreases by time due to improvement of irrigation efficiency. In 2020, the total cultivation area will decrease by around 20%, the net profit will increase by about 0.5%, and there will be a decrease of 31% in irrigation water use. The lack of water in the southern part of Iran is critical and very serious. Therefore, the most important aspects of this optimization are the declining use of irrigation water and increasing net profit. In the target year of 2040, net profit will increase by around 8%, which is quite important for local farmers, and water demand will decline by around 42% compared to the reference year. All crops in Table 4 cab be classified into four different classes based on changes in cultivation area as follows.

Class 1 includes the crops whose cultivation area is to stay stable from 2015 to 2040 period after optimization (Figure 2a). The crops in Class 1 are eggplant, onion, peach, and walnut. These crops will be optimally cultivated and that there is no need to change the cultivation area in the Arjan wetland area.

Table 4. Optimization results of cultivation area, net profit, and water harvests for the Arjan Plain.

Variables		Target Years					
		2015	**2020**	**2025**	**2030**	**2035**	**2040**
Cultivation area by crops (ha)	Wheat	33,488	22,607	21,804	20,858	19,857	18,778
	Barley	5121	4630	4515	3724	3236	3102
	Fig	3966	3880	3557	3201	2910	2619
	Watermelon	88	97	107	117	129	116
	Melon	5403	4863	4376	3939	3545	3190
	Hay	679	747	822	904	994	1094
	Green beans	211	232	255	281	309	340
	Potato	814	895	985	1083	1192	1311
	Onion	34	37	41	45	50	55
	Apple	300	330	363	399	439	439
	Pear	85	94	103	113	124	124
	Peach	23	23	23	24	24	24
	Eggplant	270	270	270	271	271	271
	Walnut	5	6	6	7	7	7
	Grapes	214	235	259	285	313	313
	Lentil	0	366	732	1097	1463	1829
	Chickpea	0	617	1234	1851	2286	2743
	Rapeseed	0	425	931	1137	1842	2328
Sum of cultivation area (ha)		50,701	40,354	40,383	39,336	38,991	38,683
Net profit	10^9 IR Rials	697	702	714	724	738	752
	10^6 USD	18.6	18.7	19.0	19.3	19.7	20.1
Water harvest (MCM)	Surface water	9	9	9	9	9	9
	Ground water	657	452	440	424	403	379
Total irrigation water (MCM)		666	461	449	433	412	388

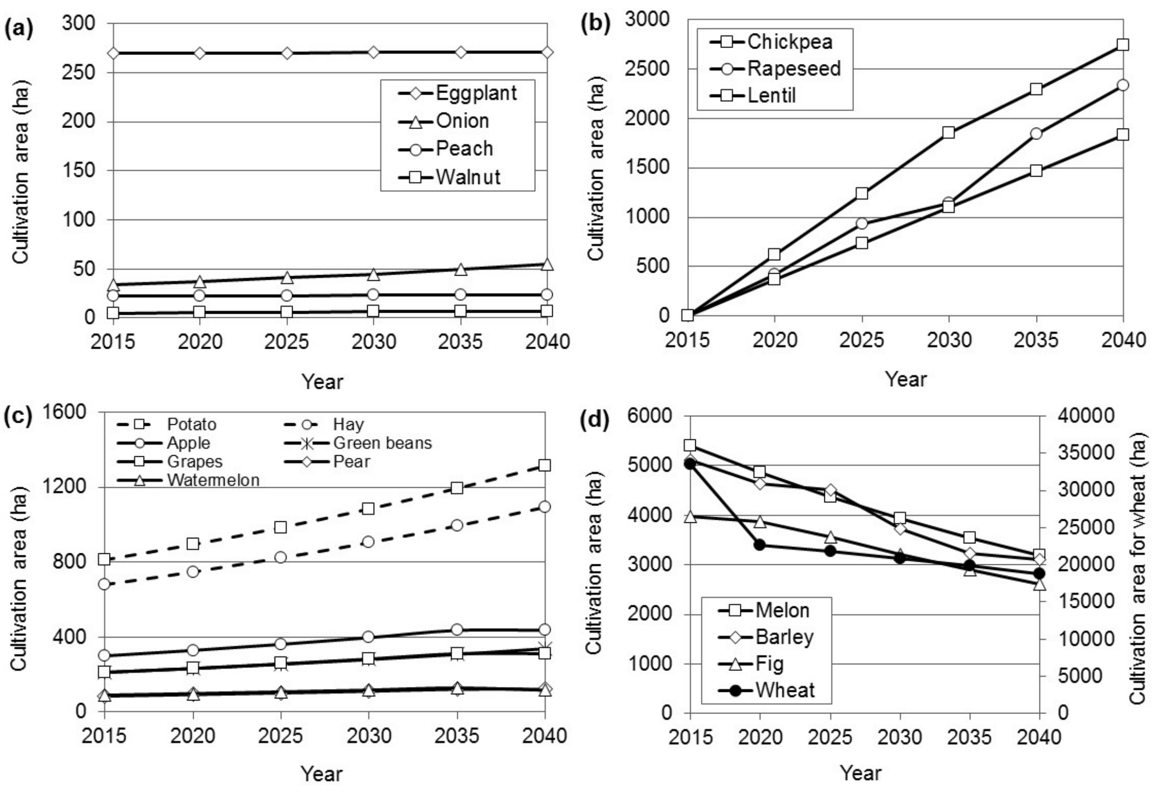

Figure 2. Cultivation area changes for (**a**) Class 1; (**b**) Class 2; (**c**) Class 3; and (**d**) Class 4.

Class 2 includes the crops that will not be cultivated but will be suitable for the Arjan wetland area regarding the weather situation and condition, and they will increase the benefit and decrease the water demand (Figure 2b). These crops are chickpea, rapeseed, and lentil that were not cultivated until 2015 even though their B/C values are higher than other crops. Based on optimization results, their cultivation area can increase significantly by 2040 with an average rate of about 100 ha per year to generate new revenue for future.

Class 3 includes the crops that will experience increases in cultivation area after optimization in the 2015–2040 period (Figure 2c). These crops are grape, pear, apple, watermelon, potato, greenbeans, and hay. Their increasing rate ranges from 2 to 19 ha/year during the period of 2015 to 2040. The long-term perspective for the Arjan wetland should consider this suggestion to increase the revenue continusouly.

Finally, Class 4 includes the crops that are expected to experience declines in cultivation area after optimization in the 2015–2040 period (Figure 2d). These crops are melon, barley, and fig. Note that wheat is presented in the right axis. Unfortunately, these four crops are cultivated on a large scale in the study region relative to other crops, showing 95% of the total area as of 2015. Optimizaiton results, however, show that this occupancy gradulally reduces to 72% by 2040, while the total revenue increases. This implies that these crops are not suitable for the Arjan wetland area considering their water use pattern and B/C. Regarding the precipitation rate, water demand, and the geographical situation of the study region, these crops are not suitable for cultivation in large scale and should be replace by other crops such as Class 2 or 3 in the long term.

3.2. Plain Balance

Through determination of the most appropriate exploitation pattern from the available resources (surface and groundwater), the negative balance of the plain was modified by the model and becomes gradually positive, having developed from −216 to +20 in 2040. The changes in the plain balance are presented in Figure 3 during different years.

It is important to note that the changes in the plain balance from 2015 to 2020 has been large; however, these changes occur at a slower rate over the following years. This can be due to the changes in the current cultivation pattern to the optimal pattern where the annual optimal cultivation becomes the basis for the following year.

Figure 3 shows that the current balance in 2015 is −216, which will jump to −53.1 after 5 years. This is considered as the most important jump among all the years. Cultivation management will have decreased the negative balance and after 20 years, there will be a positive balance of +2. The highest balance of 20 MCM occurs in 2040, although the highest change occurs in 2020, with a decrease of 75.5% to 53.1 MCM.

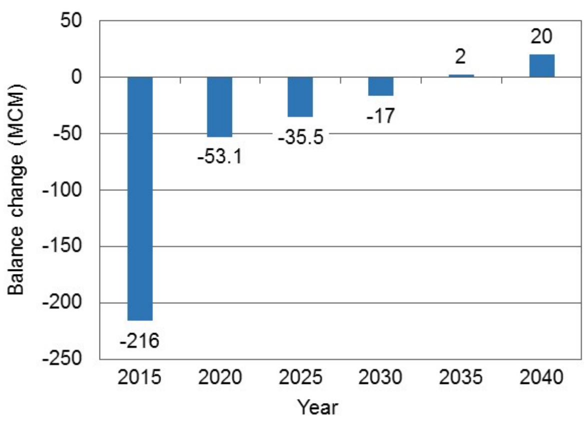

Figure 3. The changes in the Arjan plain water balance (MCM).

4. Conclusions

The Arjan plain is one of the most important plains in the southwestern part of Iran. The southern part of Iran is faced with several issues regarding lack of water and decreasing groundwater level. Groundwater is one of the most important resources for irrigation worldwide and especially in semi-arid areas, such as the Arjan plain. Therefore, the cultivation management and modeling is one of the most important topics for the Arjan plain.

After considering all limitations, inputs and calculated variables in our target model, the cultivation area and irrigation water was optimized based on the different vegetables and crops. The limitations of this study were the maximum allowable limit to harvest groundwater and surface water resources in the target years, the maximum limit for the actual irrigation water in each month, and the boundary condition of cultivation area of each crop. The target of the model saw the cultivation area and irrigation water requirement decrease, but the net profit of local farmers increased. These changes in irrigation water harvest resulted in a substantial positive shift in the Arjan plain water balance. The presented results are merely preliminary, intended to show model capabilities, and all of the results are based on published data and conditions currently available. The reference year in this paper is 2015, and target years were set for every 5 years from 2020 until 2040 to determine cultivation area optimization and possibilities for revenue maximization; therefore, there is no validation for results regarding the 2020–2040 period.

The final net profit was shown to change from $18.6 million USD in 2015 to $20.1 million USD in 2040 according to our calculations, which is an increase of 8% compared to the reference year. The surface water harvest was the same regarding the local limitations, but the groundwater harvest changed from 657 MCM for 50,702 ha (12,953 m^3/ ha) to 379 MCM for 38,683 ha (9796 m^3/ha), which is a decrease of 42.3% in groundwater demand in the Arjan plain.

Considering the water resource shortages in most of the plains in the country, and since the highest water consumption occurs in the agricultural sector, viewpoint changes in the pattern of cultivation of agricultural crops and in the allocation of water to this sector are inevitable. Optimization models can be employed as a desirable tool for the determination of optimal cultivation patterns in order to reduce water consumption and increase production in total plans of water resource management.

Author Contributions: Amin Daghighi conceived and designed; Ungtae Kim advised formulation; Amin Daghighi and Ali Nahvi wrote the paper initially and performed numerical simulations; all authors equally analyzed the data and contributed to manuscript revisions.

Conflicts of Interest: The authors declare no conflict of interest.

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