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Management of irrigation water for cropping pattern using a mathematical linear programming methodology / Case study

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Abstract: The main objective of the research is to study the efficiency of using the mathematical linear programming methodology in the management of irrigation water of the cropping pattern in Swaida Province, Syria, through a questionnaire targeting 106 irrigated vegetable farmers during 2021-2022. In the actual crop pattern, irrigation water was estimated at 5.9 million m^3, while the proposed cropping pattern model reduced it by 44.86 % where it was estimated at 3.25 million m^3. Each crop has obtained an irrigation water requirement according to the FAO CROPAT 8.0 program. The proposed linear programming model increased in the area of: peas, dry broad beans, parsley, beans, garlic, pepper, cabbage, squash, eggplant, cucumbers, cauliflower about 691.96 %, 656.21 %, 398.72 %, 277.98 %, 204.51 %, 175.44 %, 118.21 %, 88.43 %, 61.56 %, 32.43 %, 23.82 % respectively over the actual area and reducing the area of: okra, watermelon, Armenian cucumber , potatoes, melon, tomato, wheat, onions by 5.14 %, 12.08 %, 15.24 %, 18.54 %, 28.66 %, 83.75 %, 88.32 %, 90 %, respectively, of the actual area. The study recommends the necessity of interfering in preparing agricultural plans for cropping pattern by relying on correct scientific methodologies and away from randomness in a manner that serves the achievement of self -sufficiency and the preservation of available resources, and the sustainability of natural resources that are characterized by scarcity, especially water.

Key words: water needs, crop pattern, mathematical linear programming, and minimization.

Upravljanje namakanja pri kmetijski pridelavi z metodo linearnega programiranja. Vzorčna raziskava

Izvleček: Glavni namen raziskave je bil ugotoviti učinkovitost metode linearnega matematičnega programiranja pri upravljanju namakanja različnih kultur v provinci Swaida, Sirija. Vprašalnik je bil razdeljen med 106 kmetov, ki pri pridelavi zelenjave uporabljajo namakanje v rastnih sezonah 2021-2022. Pri dejanski pridelavi je količina vode za namakanje znašala 5,9 miliona m3, ki jo je predlagani model zmanjšal za 44,86 %, kar je bilo ocenjeno kot 3,25 miliona m3. Vsaka izmed poljščin je dosegla zahtevek po namakanju glede na FAO CROPAT 8.0 program. Predlagani linearni model je povečal pridelovalne površine glede na aktualno stanje za grah, bob za zrnje, peteršilj, fižol, česen, papriko, zelje, buče, jajčevce, kumare, cvetačo za približno 691,96 %, 656,21 %, 398,72 %, 277,98 %, 204,51 %, 175,44 %, 118,21 %, 88,43 %, 61,56 %, 32,43 %, 23,82 % in zmanjšal površine glede na sedanje stanje za bamijo (užitni oslez), lubenice, armenske kumare, krompir, dinje, paradižnik, pšenico in čebulo za 5,14 %, 12,08 %, 15,24 %, 18,54 %, 28,66 %, 83,75 %, 88,32 % in 90 %. Študija priporoča nujnost poseganja v pripravo kmetijskih načrtov za planiranje posevkov z uporabo znanstvene metodologije in opuščanje nestrokovnih pristopov. Na takšen način bo dosežena samooskrba in ohranjanje trajnosti in razpoložljivosti naravnih virov, še posebej tistih, za katere je značilno pomanjkanje, zlasti za vodo.

Ključne besede: potrebe po vodi, vzorec pridelka, matematično linearno programiranje, minimizacija

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1 INTRODUCTION

Syria is characterized by a high rate of population growth, limited natural resources and difficult climatic conditions. Thus, it is necessary that the use of available resources is accompanied by the principle of sustainability in order to achieve economic development, which requires the implementation of agricultural policies that depend on assessing the productivity of resources, especially the land and water to achieve maximum returns without draining those resources ((NAPC, 2002)).

Farm management controls all the factors of production, but it faces many challenges such as the application of modern scientific management principles and modern production and marketing technologies, especially in the traditional agricultural sectors or small farms (AOAD, 2007).

Water resources are the most important agricultural resources and play a basic role in agricultural development, and therefore managing these resources is important in terms of reducing the negatives resulting rain fluctuations in dry and semi -dry environments, as in Syria.

There are many modern methods of managing these resources, including Mathematical Linear Programming Methodology. Here are some studies that dealt with this methodology in planning a crop pattern.

In the study by Al-abdala et al. (2024), a cropping pattern was proposed using mathematical linear programming as an essential tool to examine various aspects of cropping systems, taking into account all production constraints, such as fluctuating weather conditions, water-related issues, and the economic circumstances in the Syrian Al- Swaida Governorate. The results indicated an 80 % increase in total net income compared to the existing cropping pattern, along with a reduction in water consumption 5.6 million m^3 versus a total of 5.9 million m^3 for the current pattern.

Sejati & Akbar (2024) in this study, optimization techniques employed to optimize the availability of irrigation water in order to achieve maximum agricultural production and profit, as well as more effective and efficient irrigation utilization. The optimization technique used in this crop pattern optimization study employs linear programming through the use of the POM QM application. This study plans for 3 alternatives involving 2 different crops, namely corn and peanuts. Alternative 1 implements the cropping pattern for MT I in November, alternative 2 for MT I in November II, and alternative 3 for MT I in December I. Among the planned alternatives, the cropping pattern that yields maximum profit is alternative 3, which results in a rice cultivation area of 634.15 hectares for MT I, 15.22 hectares for MT II, 3.1 hectares for corn, and 7.5 hectares for peanuts. The achieved profit in one year is Rp 11,553,320,000 for the cropping pattern with corn and Rp 11,566,000,000 for the cropping pattern with peanuts.

Imron & Murtiningrum (2021) aimed to obtain optimum cropping area and maximum benefits by optimizing the allocation of irrigation water based on the dependable discharge and existing area. The optimum cropping area was obtained by making several alternative cropping patterns. The linear programming was used to analyze the optimization of irrigation water allocation. The results showed that the irrigation water allocation with a dependable discharge of 80 % exhibited an optimum cropping area of 58,609 ha, cropping intensity of 271.36 % and maximum benefits of IDR 1,041,186,630,000.00. From the results of these studies, the cropping pattern that can be applied by considering the water availability and the existing area to obtain the optimum cropping area and maximum benefit per year is paddy-paddy-paddy/second crop.

A severe water shortage crisis has had a bad impact on the sustainable development in Minqin, Gansu Province, China. Therefore, a mathematical programming model for optimal allocation of irrigation water resources aimed at not only irrigation water optimization but also improving water use efficiency. The obtained results could be helpful for decision makers to make a decision on the optimal use of irrigation water resources under multiple uncertainties. (Ren et al., 2019)

The determinants of the crop pattern are agricultural land and water resources. Research results have proven that the constraints used in the linear programming model to achieve the goal function of reducing the amount of water included the crop area and the return net. The proposed model achieved an increase of 12.19 % in the total return and decrease of 13.45 % in the total amount of water compared to the actual cropping pattern (Mohamed et al., 2019).

A linear programming model is introduced in order to optimize water use through field experiments were conducted in Algeria. The idea behind this model is to assess the effectiveness or ineffectiveness of precipitation to determine the amount of irrigation water required to optimize water use. The model has proved satisfactory and a comparison between the model results and the field findings suggests that the model could reduce water consumption by 28.5 % (Difallah et al., 2017).a linear programming model is presented in order to optimize water use. The idea behind this model is to assess the effectiveness or ineffectiveness of precipitation to determine the amount of irrigation water required to optimize water use. To achieve this idea, the \"knapsack\" problem decisional form was used, and the combination of the linear programming and the above-mentioned form proved satisfactory. Field experiments were conducted in Algeria. Based on calculated budgets a model using linear programming was developed. A comparison between the model results and the field findings suggests that the model could reduce water consumption by 28.5% (Difallah et al., 2017).

The research problem is the continuous increase in demand for water resources in the agricultural sector as a result of the increase in water requirements necessary for the expansion of agricultural production, especially after the continuous introduction of new varieties of irrigated crops and vegetables and new agricultural technological needs. All of that are in order to achieve self-sufficiency at the local level or for external marketing. The problem, severity of which increased after successive droughts, the great depletion of groundwater, and the random expansion of irrigation wells in Swaida Province, Syria, negatively affected this resource, which necessitates a review of the use of irrigation water to achieve the optimal and appropriate use that achieves the best return. Thus, the importance of this study lies in the achievement of efficiency in the use of wells.

The main objective of the research is to study the efficiency of using the mathematical linear programming methodology in the management of irrigation water for the cropping pattern in the Swaida province/ Syria through the following sub-objectives:

– Studying the most important features of the irrigated crop pattern in the studying sample.
– Reaching the optimal cropping pattern that minimization of irrigation water consumption within the constraints of the available productive resources and ensuring that each crop obtains its water requirements using linear mathematical programming.

2 MATERIALS AND METHODS

2.1 THE STUDY AREA

The study was conducted in Swaida Province, southern Syria, Figure (1), where irrigated vegetable crops were cultivated during the 2021-2022 seasons. This governorate experiences a typical Mediterranean climate, characterized by wet, cold winters; dry, hot summers; and two brief transitional seasons. The average annual precipitation ranges from 210 to 430 mm, and the soils vary from clayey to heavy clay. Two distinct agricultural systems can be identified in the region. On the eastern mountainous slopes, conditions are favorable for the cultivation of fruit trees, particularly apples, grapevines, and almonds. In contrast, the western plains, both irrigated and non-irrigated, are dominated by field vegetable farming. This agricultural system has evolved due to an increasing number of wells and improved water management through drip irrigation, which has become the predominant irrigation method. Moreover, the high rate of water extraction from deep wells is a significant developmental factor that contributes to the lowering of water tables, despite the expansion of drip irrigation (Watnabbach, 2006).

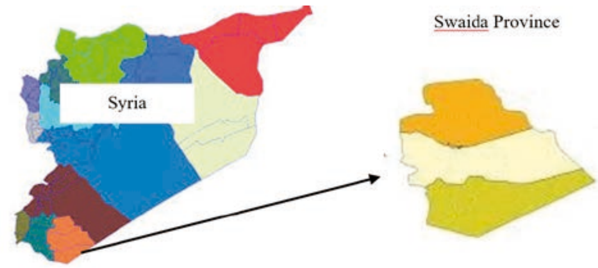

Figure 1: The location of Al-Swaida Province in the Syrian Arab Republic.

2.2 DATA AND SAMPLE SIZE

The study relied on primary data through a questionnaire targeting irrigated vegetable farmers, which included questions related to the cropping Pattern. It also relied on secondary data regarding the number of irrigation wells and climatic data. The target community was identified as owners of wells for irrigating crops for a period of not less than three consecutive years. The sample size was determined according to the formula: (Glenn, 1992), (Yamane, 1967):

$$n = \frac{N}{1 + N(e)^2}$$

Where: N: the studied community is 221 wells (Agricultural Extension Department, 2020). e: Precision ± 7 % level is adopted, n: sample size = 106 observations, representing 48.06 % of the studied statistical population.

2.3 STATISTICAL ANALYSIS SOFTWARE

2.3.1 The study utilized the following software tools.

a. IBM SPSS Statistic 28: for descriptive and quantitative data analysis.

b. Excel Solver: for solving optimization problems in single-objective mathematical programming.

c. FAO. CROPWAT 8.0: CROPWAT is a decision support tool developed by the land and water development division of FAO. CROPWAT 8.0 for Windows is a computer program for the calculation of optimal crop water requirements and irrigation requirements based on soil, climate and crop data.

2.4 ANALYSIS METHOD

The study relied on two main analytical approaches:

a. Descriptive analysis methods: Using descriptive statistical indicators including the arithmetic mean, relative importance, percentages, frequencies, as well as charts and tables to characterize the main economic features and study variables in the sample.

b. Linear programming methodology (LP): is a widely used (military, industrial, financial, marketing, accounting, and agricultural problems) mathematical modeling technique designed to help managers in planning and decision making relative to resource allocation and even though these applications are diverse, all LP problems have several properties and assumptions in common and all problems seek to maximize or minimize a quantitative objective (Render et al., 2012). It is a model, which is used for optimum allocation of scarce or limited resources to competing products or activities under such assumptions as certainty, linearity, fixed technology, and constant profit per unit (Murthy, 2007).

2.4.1 The Structure of the Model: has three major components: (Bronson & Govindasami, 1997)

a. Decision variables: are physical quantities controlled by the decision maker and represented by mathematical symbols.

b. Objective function: defines the criterion for evaluating the solution. It is a mathematical function of the decision variables that converts a solution into a numerical evaluation of that solution.

c. Constraints are a set of functional equalities or inequalities that represent physical, economic, technological, legal, ethical, or other restrictions on what numerical values can be assigned to the decision variables.

In this research, the mathematical formulation of the optimal crop pattern model that achieves the lowest amount of water needs takes the following form:

$$Min: Z = w1X1 + w2X2 + w3X3 + \cdots \ldots + wnXn$$

Subject to constraints:

$$a11\,X1 + a12\,x2 + a13\,X3 + \ldots \ldots + a1n\,Xn \le b1$$
$$a21\,X1 + a22\,X2 + a23\,X3 + \ldots \ldots + a2n\,Xn \le b2$$
$$a31\,X1 + a32\,X2 + a33\,X3 + \ldots \ldots + a3n\,Xn \le b3$$
$$am1\,X1 + am2\,X2 + am3\,X3 + \ldots \ldots + amn\,Xn \le bm$$
$$X1 \ge 0, X2 \ge 0, X3 \ge 0, \ldots \ldots, Xn \ge 0\ *$$

Where:

- Z: the objective function, which is the sum of the water needs of the cropping pattern (m^3).

- Min: minimize the objective function (z).

$X1, \ldots X_n$: are the variables of the linear program, and they represent the areas of crops that make up the cropping structure (dunums).

$w1, \ldots w_n$: the coefficients of the variables affecting the function, representing here the optimal water requirement for each crop in the cropping structure (m3/dunum), estimated by FAO Cropwat 8.0 program.

$a11, \ldots a_{mn}$: The coefficients of the decision variables and they are known.

$b1, \ldots b_m$: The available resources which are specific and positive.

* Non-negative constraints.

3 RESULTS AND DISCUSSION

3.1 IRRIGATION METHODS, WELLS, AND IRRIGATED AREAS IN THE SYRIAN GOVERNORATE OF AL- SWAIDA

a. Irrigated areas according to irrigation sources and methods: The average total irrigated area in Al-Swaida was approximately 4141.88 hectares, with lands

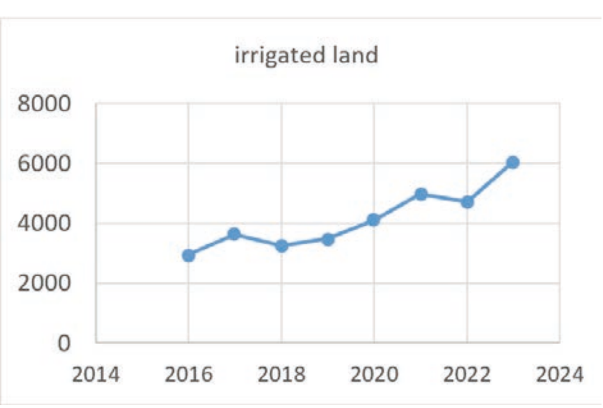

Figure 2: The irrigated area in Al-Swaida during the period 2016-2023.

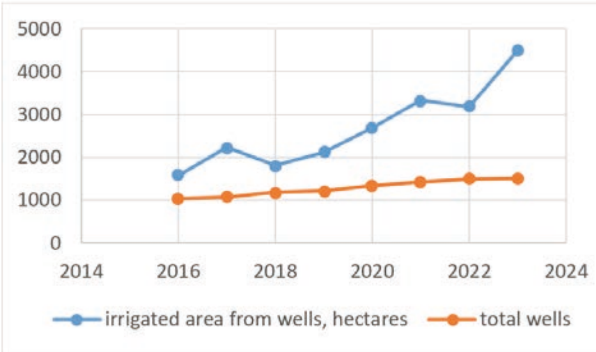

Figure 3: The number of irrigation wells and the irrigated areas in Al-Swaida during the period 2016-2023.

irrigated via wells making up 64.7 % and those irrigated through government irrigation projects constituting 35.3 %. In contrast, lands irrigated using modern methods (sprinkler and drip irrigation) represented about 92.3 % of the average total irrigated area in Al- Swaida during the period from 2016 to 2023. Generally, there has been an increase in irrigated land from 2950 hectares in 2016 to 6054 hectares in 2023, as shown in Figure (2) (Ministry of Agriculture Statistics, 2016-2023).

b. Wells and their irrigated areas: Figure (3) illustrates the increase in the irrigated area from wells from 1569 hectares in 2016 to 4497 hectares in 2023. The average irrigated area by wells in Al- Swaida was 2678 hectares, with an average total of 1281 wells. The number of wells rose from 1028 in 2016 to 1512 in 2023, while artesian wells constituted 19.8 % of the total on average, and surface wells made up 80.2 % during the period from 2016 to 2023 (Ministry of Agriculture Statistics, 2016-2023).

3.2 FEATURES OF THE ACTUAL IRRIGATED CROP PATTERN IN THE STUDY SAMPLE

3.2.1 Crop pattern components

The total area actually cultivated is estimated at 8116.3 dunums, consisting of 19 crops, 10 of which are summer and 9 are winter. Table (1).

Table 1: Components of the actual cropping pattern in the study sample.

Season	crop	number of farmers		Actual cultivated area/dunum		Actual amount of irrigation water m^3	
		frequency	%	value	%	value	%
Summer pattern	tomato (X1)	86	81	3541.4	43.63	3179823	53.86
	Eggplant (X2)	41	39	271.6	3.35	212554.2	3.6
	Pepper (X3)	29	27	160.5	1.98	125045.6	2.12
	Melon (X4)	37	35	1194.5	14.72	833999.9	14.13
	Watermelon (X5)	7	7	100.5	1.24	70169.1	1.19
	Cucumbers (X6)	35	33	196	2.41	95314.8	1.61
	Squash (X7)	19	18	77.4	0.95	39156.66	0.66
	Armenian cucumber (X8)	12	11	46	0.57	26891.6	0.46
	Okra (X9)	6	6	16	0.2	11961.6	0.2
	Beans (X10)	17	16	45	0.55	16321.5	0.28
Winter pattern	Potatoes (X11)	11	10	317	3.91	217430.3	3.68
	Onions (X12)	11	10	100	1.23	99200	1.68
	Garlic (X13)	11	10	28	0.34	5101.6	0.09
	Cabbage (X14)	15	14	160.1	1.97	93594.46	1.59
	Cauliflower (X15)	22	21	353.1	4.35	195617.4	3.31
	Peas (X16)	22	21	325.9	4.02	23790.7	0.4
	Dry broad beans(X17)	13	12	149.9	1.85	19472.01	0.33
	Parsley (X18)	9	8	23.5	0.29	9646.75	0.16
	Wheat (X19)	17	16	1009.9	12.44	629167.7	10.66
Total				8116.3	100	5904259	100

Source: Questionnaire 2021-2022.

Tomatoes, melon and eggplant are the most cultivated crops in the summer crop pattern with a rate of 43.63 %, 14.72 % and 3.35 %, respectively, of the total cultivated area and by the largest number of farmers of the study sample.

Wheat, cauliflower, and peas are the most common crops grown by the sample farmers in the winter pattern, with percentages of 112.44 %, 4.35 %, and 4.02 %, respectively of the total cultivated area.

3.2.2 Actual consumed irrigation water

It was estimated at 195,617.4 m^3 in the total sample. Tomatoes and watermelon consumed the largest amount of irrigation water by 53.86 % and 14.13 %, respectively, of the total irrigation water, while parsley and garlic consumed the least amount by 0.16 % and 0.09 %, respectively. Table (1).

3.3 THE OPTIMAL CROPPING PATTERN, WHICH MINIMIZES THE USE OF IRRIGATION WATER BY USING LINEAR PROGRAMMIN:

3.3.1 Basic criteria

In this paragraph, the crop pattern will be proposed to minimize the irrigation water using the linear programming model based on the following strategic criteria:

Strategic cultivated area criteria's**:** These criteria are related to agricultural planning and policies. Decision makers can, through flexible linear programming models, determine the areas that will be planted for each crop. In this proposed model, the minimum area for each crop is determined at least 10% of the total area of the crop grown during the season studied in the sample.

b. Strategic Water criteria's:

- The optimal water requirement: It has been calculated for each crop based on using the FAO CROPWAT 8.0 program, where the climatic data and physical soil specifications in the study area were determined and entered into the program. Based on the combined data, the optimal amount of water that should be provided for each crop is determined during the season.

- The amount of irrigation water does not exceed the actual amount available for each crop that was used by farmers.

3.3.2 Mathematical model

a: Objective function

Min z: minimization of the irrigation water (m3)

WI: optimal water requirements for each crop i.

Xi: crop I.

$$MIN\,W = \sum_{i=1}^{n} W_i x_i$$

b: Subject to constraints

$$\sum_{i=1}^{n} w_{ij} x_{ij} = SL_i + WL_i$$

- Area resources constraint**:** The total irrigated area is equal to the sum of the summer and winter area for the studied season = 8116.3 dunum.

- Organizational constraints for cultivated area (dunum): there are 19 constraints:

$$\sum_{i=1}^{n} a_{ij} x_{ij} \geq 0.1 \sum_{i=1}^{n} x_{ij}$$

The minimum area for each crop is not less than 10 % of the total area of the crop grown during the season in the study sample.

- Water resource constraints**:** there are 19 constraints:

$$\sum_{i=1}^{n} w_{ij} x_{ij} \leq \sum_{i=1}^{n} w_{ij} x_{ij}$$

The maximum water requirement for each crop does not exceed the amount of water available for each crop that was used by farmers.

- Non-negative constraints

$$x_{ij} \geq 0$$

3.3.3 Crops area according to the proposed model

After solving the mathematical model for the proposed cropping pattern, the estimation results showed that in order to minimize the irrigation water we need to increase the cultivated area of some crops and decrease other crops. According to Figure (3) the model suggested an increase in the area of : pea, dry broad beans, parsley, beans, garlic, pepper, cabbage, squash, eggplant, cucumber, cauliflower about 691.96 %, 656.21 %, 398.72 %, 277.98 %, 204.51 %, 175.44 %, 118.21 %, 88.43 %, 61.56 %, 32.43 %, 23.82 % respectively over the actual area, and decreasing the area of: okra, watermelon, Armenian cucumber, potatoes, melon, tomatoes, wheat, onions by 5.14 %, 12.08 %, 15.24 %, 18.54 %, 28.66 %, 83.75 %, 88.32 %, 90 %, respectively, of the actual area.

3.3.4 Saving the water requirement achieved for the proposed crop pattern

The proposed model reduced the amount of irrigation water by 44.86 % less than the actual irrigation water within the constraints on the availability of water and terrestrial resources in the study sample, as the total water requirement for the proposed crop pattern was about 3.25 million m^3 compared to 5.9 million m^3 of the actual pattern, Figure No. (4). The amount of irrigation water according to the optimal need for each crop increased in some crops and decreased in others compared to the actual crop pattern. The results showed an increase in the amount of irrigation water for each of: peas, dry broad beans, parsley, beans, garlic, peppers, cabbage, squash, eggplant, cucumber, and cauliflower by 691.96 %, 656.21 %, 398.72 %, 277.98 %, 204.51 %, 175.44 %, 118.21 %, 88.43 %, 61.56 %, 32.43 %, 23.82 % respectively, and it decreased in each of the crops: okra,

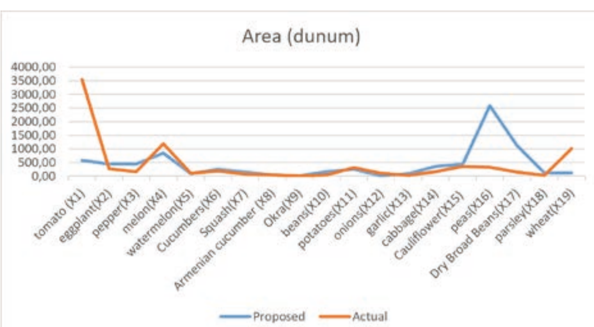

Figure 3: The difference in cultivated crop areas between the cropping pattern proposed by the programming model and the actual cropping pattern in Swaida.

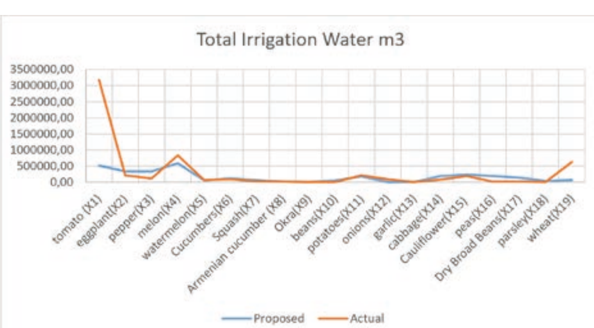

Figure 4: The difference in irrigation water requirements for crops between the cropping pattern proposed using the programming model and the actual cropping pattern in Swaida.

watermelon, Armenian cucumber , potato, melon, tomato, wheat, onion by 5.14 %, 12.08 %, 15.24 %, 18.54 %, 28.66 %, 83.75 %, 88.32 %, and 90 %, respectively.

3.4 DISCUSSION

Below is a detailed discussion of the scientific results achieved by the proposed mathematical linear programming model, from several key sides.

3.4.1 Reallocation of cultivated areas

a Adjusting cultivated areas

For certain crops (e.g., peas, dry broad beans, parsley, beans, garlic, peppers, cabbage, zucchini, eggplant, cucumber, and cauliflower), the proposed model recommends increasing their cultivated areas by percentages ranging from + 23.82 % to + 691.96 % compared to the current areas. Conversely, it is recommended that the cultivation areas for other crops (e.g., okra, melon, squash, potato, watermelon, tomato, wheat, and onion) be reduced by percentages varying from -5.14 % to -90 %.

Significance of the results

The crops for which an increase in area is advised either exhibit superior economic returns or possess high water productivity, allowing them to make optimal use of the available water while achieving better profitability under current water limitations. In contrast, a reduction in the area devoted to crops with high water consumption or lower economic returns can contribute to an overall decrease in water usage without impairing the production of staple crops. This strategy is rooted in the principles of improving resource utilization and achieving economic efficiency in resource-constrained environments.

3.4.2 Actualized water requirement for the proposed configuration

a. Overall water requirement reduction

For the proposed pattern, has been reduced by 44.86 % compared to the actual configuration (about 3.25 million m^3 versus 5.9 million m^3). This significant decrease represents considerable water savings a key indicator in regions facing challenging water conditions and constraints on water resources, such as the Swaida Governorate.

b Distribution of water requirements among crops

The results indicate that the water requirement for certain crops increases in line with the expansion of their cultivation areas under the optimal model, with water consumption growing proportionally (in some cases, up to +691.96 %). Conversely, crops with reduced cultivation areas exhibit a corresponding decline in water demand. This finding confirms that the model effectively integrates the relationship between cultivated area and water consumption, demonstrating that a multivariate analysis incorporating both water and land constraints can achieve an optimal balance between maintaining production levels and enhancing water use efficiency.

3.4.3 Economic and environmental dimensions

a. Economic impact

Optimizing the allocation of cultivated areas leads to a notable increase in net income, as the proposed configuration emphasizes crops that offer superior economic returns alongside higher water efficiency. This outcome is fundamental to enhancing the economic viability of agricultural resources**.**

b.Environmental sustainability

The substantial reduction in water demand—a saving of 44.86 %—serves as a positive indicator for sustainability, particularly in regions experiencing environmental pressures and limitations in natural resources such as water. Additionally, reallocating cultivated areas among various crops helps reduce inefficient water use, thereby contributing to the conservation of natural resources for future generations.

4 CONCLUSIONS

The use of linear programming technology as a decision-making tool is highly effective in managing and allocating economic resources in agricultural production, make sure optimal economic efficiency while preserving the allocated areas for cultivating essential crops such as wheat and tomatoes.

The application of the linear programming model has proved a significant reduction in the total amount of irrigation water required for the proposed cropping pattern, achieving a decrease of 44.86 % compared to the actual water consumption. The proposed model requires about 3.25 million m^3, whereas the actual cropping pattern demands 5.9 million m^3. This substantial reduction underscores the importance of decision-makers' intervention in recommending and implementing optimal cropping configurations that align with existing land and water constraints.

The involvement of relevant authorities in developing strategic agricultural plans for irrigated cropping patterns is crucial. Relying on sound scientific methodologies rather than arbitrary approaches can serve essential objectives, including achieving self-sufficiency, preserving available resources, and ensuring the sustainability of scarce natural resources, particularly land and water.

Despite the success of the proposed model in reducing irrigation water usage by 44.86 %, certain challenges and limitations remain, including the possible effects of climate variability and the practical difficulties of implementing the model across different agricultural environments.

Future research can further refine the model by integrating additional variables such as climate change impacts and improving the accuracy of water availability data. Expanding the study to encompass diverse regions with varying environmental conditions would enhance the model's applicability and provide broader agricultural and economic benefits.

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