Acta Sci. Pol.
Formatio Circumiectus 23 (4) 2024, 61–76
ENVIRONMENTAL PROCESSES

www.acta.urk.edu.pl ISSN 1644-0765 DOI: http://dx.doi.org/10.15576/ASP.FC/193864

ORIGINAL PAPER Accepted: 28.09.2024

MITIGATING WATER SHORTAGES AND ENHANCING FOOD SECURITY THROUGH CROP OPTIMIZATION: INSIGHTS FROM THE EASTERN NILE DELTA

Heba F. Abdelwahab[1], Abdelazim M. Negm[1], Elsayed M. Ramadan[1],
Alban Kuriqi[2, 3]✉ 0000-0001-7464-8377, Ismail Abd-Elaty[1]

[1] Department of Water and Water Structures Engineering, Faculty of Engineering, Zagazig University, 44519 Zagazig, Egypt
[2] CERIS, Department of Civil Engineering, Architecture and Georesources, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais 1, 1049-001 Lisboa, Portugal
[3] Civil Engineering Department, University for Business and Technology (UBT), 10000 Pristina, Kosovo

ABSTRACT

Aim of the study
The scarcity of water resources is a global problem, particularly acute in arid and semi-arid regions. As a semi-arid country, Egypt faces significant challenges due to its limited water resources. This study aimed to provide insight into the current and future water situation in the East Nile Delta in Egypt. It sought to illuminate the policies and strategies used to reduce water consumption and increase water supply. Additionally, the study aimed to identify gaps in knowledge that require further research and to illustrate the different types of models used to optimize water resources management and maintain food security.

Material and methods
The study analyzed the status of water resources availability, water demand, and other influencing factors in the East Nile Delta. To address water scarcity, the study employed optimization models, specifically using linear optimization programming. This model was applied to the Eastern Delta area, focusing on the region supplied by the Ismailia Canal. The model aimed to balance the limited supply of freshwater with the increasing demand by proposing changes in cropping patterns.

Results and conclusions
The study found that the best way to secure water supply and minimize water scarcity is by using optimization models. In the Eastern Delta, the area supplied by the Ismailia Canal had a water deficit of about 789.81 MCM. By changing the cropping patterns, the water deficit could be reduced. The results indicated a decrease in the cultivation of non-strategic crops such as onions, garlic, fruit trees, peanuts, sesame, and soybeans. Conversely, there was an increase in the cultivation of strategic crops such as wheat, cotton, maize, and corn, as well as crops with high net yields like tomatoes and potatoes. These changes would help balance water demand and supply, ensuring a more sustainable water management strategy for the future.

Keywords: crop pattern, Ismailia Canal, optimization, East Delta, strategic crops

✉e-mail: alban.kuriqi@tecnico.ulisboa.pt

INTRODUCTION

Anthropogenic factors such as over-pumping and natural events such as earthquakes impact coastal aquifers by reducing freshwater recharge, aquifer water budgets, and increasing saltwater intrusion (Kuriqi and Abd-Elaty, 2024). The optimization of cropping patterns has a positive effect on the preservation of the environment and economic growth in agriculture, which contributes to the long-term development of agriculture. Cropping pattern optimization is the process of adjusting cropping patterns to achieve certain goals, such as achieving economic benefits, reducing the consumption of water resources, and improving water use efficiency, taking into account all real-life situations (Li et al., 2020a, 2020b). Modern irrigation systems are valuable for managing agricultural water resources, particularly in arid and semi-arid regions. Still, they also affect the degree of groundwater salinity for drinking and irrigation purposes (Abd-Elaty et al., 2024a).

Optimization models for cropping patterns are often categorized as single-objective programming or multi-objective programming models, depending on their optimization objectives. (Jain et al., 2021). Single-objective programming models consider the impact of cropping pattern changes on purpose, and previous research has shown that the economic benefit was the primary consideration (He et al., 2021). However, the single-objective programming model focuses only on one purpose and neglects the trade-off between the environmental impacts, economic benefits, and associated social impacts of cropping pattern changes. Therefore, multi-objective programming was successively used for the optimization of cropping patterns, considering contradictions between the coordination of multi-objectives and trade-offs between these objectives in order to make all objectives as optimal as possible.

A multi-criteria crop planning model was developed to optimize cropping patterns in the Indian state of Telangana (Jain et al., 2021). The multi-objective heuristic algorithms SPEA2 and NSGA-III were used in a multi-reservoir and multi-objective system problem to predict short-term optimal crop patterns in Iran's Karun basin. The results show that NSGA-III performs better than SPEA2.

In the eastern Iranian province of Lorestan, a multi-criteria programming model was used to select a cropping pattern to evaluate the reduction of water consumption, the possibility of increasing net profit, and the reduction of environmental impact simultaneously in a life cycle assessment (Nikouei et al., 2022). The results showed that the multi-center cropping pattern reduced environmental indicators such as non-renewable energy use by 14%, water use by 1% and global warming potential by 14%. At the same time, farmers' net profit remained unchanged compared to the region's current pattern. The cropping pattern that farmers currently use is only focused on achieving short-term profit targets. A novel approach to land allocation was important to achieve harvests with the use of non-renewable energy, lower water consumption, and lower greenhouse gas emissions in the region. This proposed planning model could serve as a basis for long-term cropping plans in other irrigated and rain-fed agricultural systems around the world.

The Economic-Ecological Synergistic Optimization for Climate Change and Cropping Patterns model was developed in Fujin City, Heilongjiang Province JXID, for the optimization of cropping patterns (Chen et al., 2022). By combining multi-objective programming, an input and output model for a model of one-dimensional water quality, non-point source pollution, and Bayesian with interval multi-linear regression was used. Cropping patterns for different regions are optimized under different climate change scenarios, and conflicts between increased economic benefits and reduced ecological pollution (i.e., in surface runoff and subsurface infiltration) were balanced. The results showed that the best acreage for reducing ecological pollution tended to decrease, with a reduction of 3% for soybean and 24.7% for maize. In contrast, the acreage for rice hardly changed compared to the existing condition.

A dynamic model was developed to simulate the factual situation in the Iranian Kermanshah plain in order to determine the best cropping pattern for this region (Barati et al., 2020). The simulation model was used stochastically with the time series method to predict the future values of climate parameters. After ensuring the performance of the time series and dynamic models, the cropping pattern was optimized using the current optimization software in addition to the multi-objective mathematical programming approach. The results showed that the ratio between the benefits gained, and the amount of water extracted from the wells was always greater under improved conditions than under the existing conditions.

A surrogate-based optimization framework for high-resolution, large-scale landscape management optimization using irrigated corn cropping systems was developed in eastern Colorado, USA (Nguyen et al., 2019). A surrogate simulation model and a biogeochemical model were employed using a synthetic neural network. The results showed that, for our analysis, the surrogate was 6.2 million times faster than the DayCent model and captured more than 99% of the variation in DayCent's simulated results. Compared to a 'business-as-usual' scenario, farm-level optimization increased farm income by 83%–150%, grain yield by 10.1–11.3%, SOC by 16%–53%, and GHG emissions by 19%–55%.

On the other side, a multi-criteria optimization model was presented by Dhanraj et al. (2021) to build regional biomass-to-energy systems that take these considerations into account. The goal is to create a bioenergy system that is constrained by the availability of regional water, the availability of land at the county level, and the demand for competing water. The results showed that there is a major trade-off between the cost of ethanol and the demand for irrigation water. The model selected wheat, cotton, and sorghum as the most important crops in different regions.

In order to increase the efficiency of irrigation water use and regulate soil salinity, an optimization model for irrigation and drainage was developed in Hetao in northwest China (Li et al., 2020c). The model was built by combining simulations with field water-salt physical equilibrium adjustment processes and a genetic algorithm optimization model. The results showed that the developed model could provide appropriate field irrigation monthly and drainage decisions by considering field hydrology, especially the contribution of groundwater to crop water demand and the effects of groundwater on soil salinity. Abd-Elaty et al. (2024b) studied the impact of sea level rise and SLR and Grand Ethiopian Renaissance Dam (GERD) reservoir filling with increasing pumping rates, especially during the filling periods on water resources management in the Nile Delta, Egypt. The GERD reservoir filling could alter the freshwater, in which the aquifer groundwater resources decreased, and the salinity increased by nearly 4.5%, 11.5%, and 30% for the three scenarios, respectively.

The approach of imprecise interval programming, which was also used in a case study in the Jinghui irrigation region in Shaanxi Province, China, was further developed for the optimization of irrigation water resources (Gong et al., 2020). The greatest economic gain was achieved when effective precipitation, scheduling objectives, and crop evapotranspiration were considered, which had a significant impact on the best water resources for irrigation allocation. According to the results, the scarcity of water resources was serious and had a significant negative impact on the development of the Jinghuiqu irrigation region. In addition, by including effective precipitation in the model, a considerable amount of water could be saved, such as 47.36% of the total water consumption of corn when P = 25%.

The main objectives of this study are to:

1. Evaluate the status of water resources availability and demand in the East Nile Delta, focusing on the impact of water scarcity in the region.
2. Develop and apply optimization models using linear programming to propose improved cropping patterns that reduce water consumption while maintaining or enhancing crop yield.
3. Identify crop patterns that contribute to food security by prioritizing the cultivation of strategic crops with high net yields, ensuring a sustainable approach to water resources management.
4. Use mathematical models to predict future water deficits in the Eastern Nile Delta and propose measures to maintain long-term food security in the region.
5. Finally, propose strategies to balance the limited freshwater supply with the increasing water demand in arid and semi-arid regions, specifically in areas fed by the Ismailia Canal.

MATERIALS AND METHOD

Study area

The study area is in the region of the eastern Nile Delta and stretches along the length of the Ismailia Canal, which flows from the Nile to Port Said (Figure 1a). It lies between longitudes 31° 15' 0'' and 32° 15' 0'' E and latitudes 30° 15' 0'' and 31° 0' 0'' N, surrounded to the west by the Nile and the Damietta Arm and to the south by structural ridges, desert plateaus and foothills (Figure 1b).

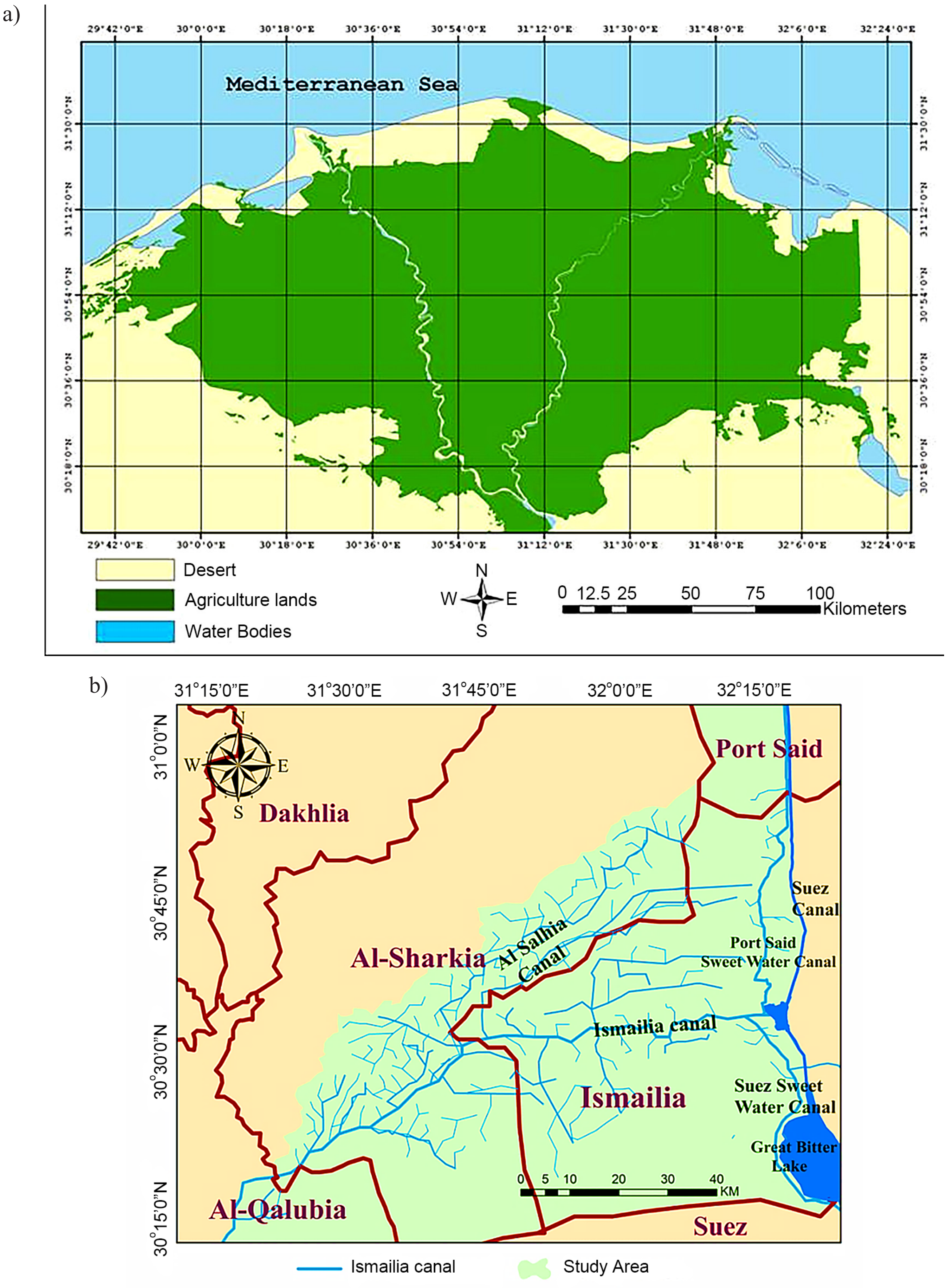

Fig. 1. Study area a) Land use (source: after Sakr, 2005); b) irrigation canal distribution (source: Ramadan et al., 2021)

Freshwater boundary changes accelerate coastal areas due to over-pumping and decreasing aquifer recharge and sea-level rise (Abd-Elaty et al., 2021; El Shinawi et al., 2022). The eastern part of the Nile Delta has incredible importance as one of the most important areas recently developed in Egypt, as many industrial projects and land developments are being carried out there. It is considered an important center of progress for the densely populated regions of the Delta and the Nile Valley (Arnous and Green, 2015).

CLIMATE

Rainfall

Egypt lies in a semi-arid zone where the average annual rainfall ranges from 0 mm per year in the desert to more than 360 mm per year in the northern regions. In comparison, the average rainfall in the Nile Delta ranges from 26 mm per year in the south and part of the center to more than 200 mm per year on the north coast (Nashwan et al., 2019). Precipitation increases in the north and west and decreases in the south and east as drought increases in the summer season, and precipitation peaks in winter, where the average rainfall is about 14 mm per year and does not exceed 220 mm (El-Nahry and Doluschitz, 2010).

The study area is characterized by a short rainy season, with most of the precipitation falling between November and March, while the rest of the area is almost dry. The average annual rainfall is between 20 mm at Shubra al Khaymah and about 220 mm at Port Said. Currently, there is a plan to utilize rainfall for agricultural purposes, where the total amount of rainfall is estimated at 1.3 billion m^3 $year^{-1}$, divided as shown in Table 1.

Table 1. Rainwater quantities that could be used in various parts of Egypt (source: after Abdel-Shafy et al., 2010)

Purpose of use	Rainwater quantities Billion m^3 $year^{-1}$
As a supplement to the Nile Delta's irrigation system	0.38
In Sinai	0.45
On the coast of the Red Sea	0.20
In Marsa-Matrouh and Alexandria	0.27
Total amount of rainwater	1.30

Evaporation and evapotranspiration

Agriculture consumes water through infiltration and evapotranspiration. The losses due to the transfer from the canals are estimated at around 2.0 billion $m^3 year^{-1}$ for the entire country. Evapotranspiration is dependent on cropping patterns. Cropping patterns are an important factor in the management of water resources, especially in the context of a market-based policy. The best estimate of the cropping pattern is used to predict future water demand. The combined effects of rapid population growth and rising living standards have increased the demand for food (Al-naggar, 2003).

Evaporation rates in Egypt range from 7 mm per day in the south to about 4 mm per day on the Mediterranean coast in the north. Table 2 shows the monthly average annual potential evapotranspiration in eight Egyptian regions, as reported by the Water Management Research Institute of the National Water Research Center in 2002 (Gado and El-Agha, 2021).

Table 2. Monthly average annual potential evapotranspiration in Egypt (source: Gado and El-Agha, 2021).

Regions	Mean annual ETo (mm/year)
South Upper Egypt	1722
North Upper Egypt	1610
Middle Egypt	1531
South Delta	1485
East Delta	1522
West Delta	1457
Middle Delta	1417
North Delta	1266

A temperature increase of 1°C can increase evapotranspiration by (4–5) %, while a temperature increase of 3°C can increase evapotranspiration by 15%. This means that if the Egyptian agricultural sector consumes 41 billion cubic meters, an increase of 1°C would require an additional amount of about 2 billion cubic meters to maintain the same production level (Gado and El-Agha, 2021).

Crop and agriculture

The canal currently irrigates about 588,638 feddan (1 Feddan = 0.42 Hectare) (400,468 feddan are irrigated by traditional surface irrigation and 118,170 feddan by modern irrigation systems), which is about 9% of Egypt's agricultural land (Aboel Ghar et al., 2004; AfDb, 2016). The types of crops irrigated by the Ismailia Canal:

1. Winter crops: barley, winter vegetables (i.e., strawberries, greens, tomatoes, melons, lettuce, cucumbers, and zucchinis), wheat, sugar beet, flax, domestic beans, onions, garlic, and clover.
2. Summer crops: yellow corn, sugar cane, sesame seeds, vegetables (i.e., green beans and green peas), onions, rice, watermelon, peanuts, and cotton.

The model was fed with data after CAPMAS (2017) such as the water demand in Table 3, the current cropping pattern and the cultivated area in Figure 2. The total net yield was about 3626.47 million L.E. for winter crops, 4649.61 million L.E. for summer crops, and Nili crops for the current cropping pattern (CAPMAS, 2017; Osama et al., 2017). Cotton, rice, wheat, and maize are among the strategic crops that have remained relatively stable or increased in meeting the actual food demand.

Table 3. Water requirements for winter, summer, and Nili crops in Egypt (source: after CAPMAS, 2017)

Crops	Water requirement (m^3 feddan^{-1})	Crops	Water requirement (m^3 feddan^{-1})	Crops	Water requirement (m^3 feddan^{-1})
Summer crops	Winter crops	Nili crops			
Clover	1920	Maize	3908	Maize	3122
Barley	1835	Rice	6972	Tomatoes	3127
Alfalfa	2747	Corn	2705	Other vegetables	3127
Lupine	1646	Peanuts	3559	Other crops	2606
Orchards	1920	Sesame	3554		
Onions	2592	Soybeans	4198		
Sugar beat	3959	Onions	4005		
Tomatoes	1713	Potatoes	2581		
Tahreesh	1920	Tomatoes	2581		
Wheat	2153	Cotton	3908		
Broad beans	1475	Other vegetables	2581		
Fenugreek	1646	Other crops	2705		
Garlic	2592	Sugar cane	8189		
Potatoes	1713				
Palms	1920				
Wood trees	1920				
Other crops	1920				
Other vegetables	1713				

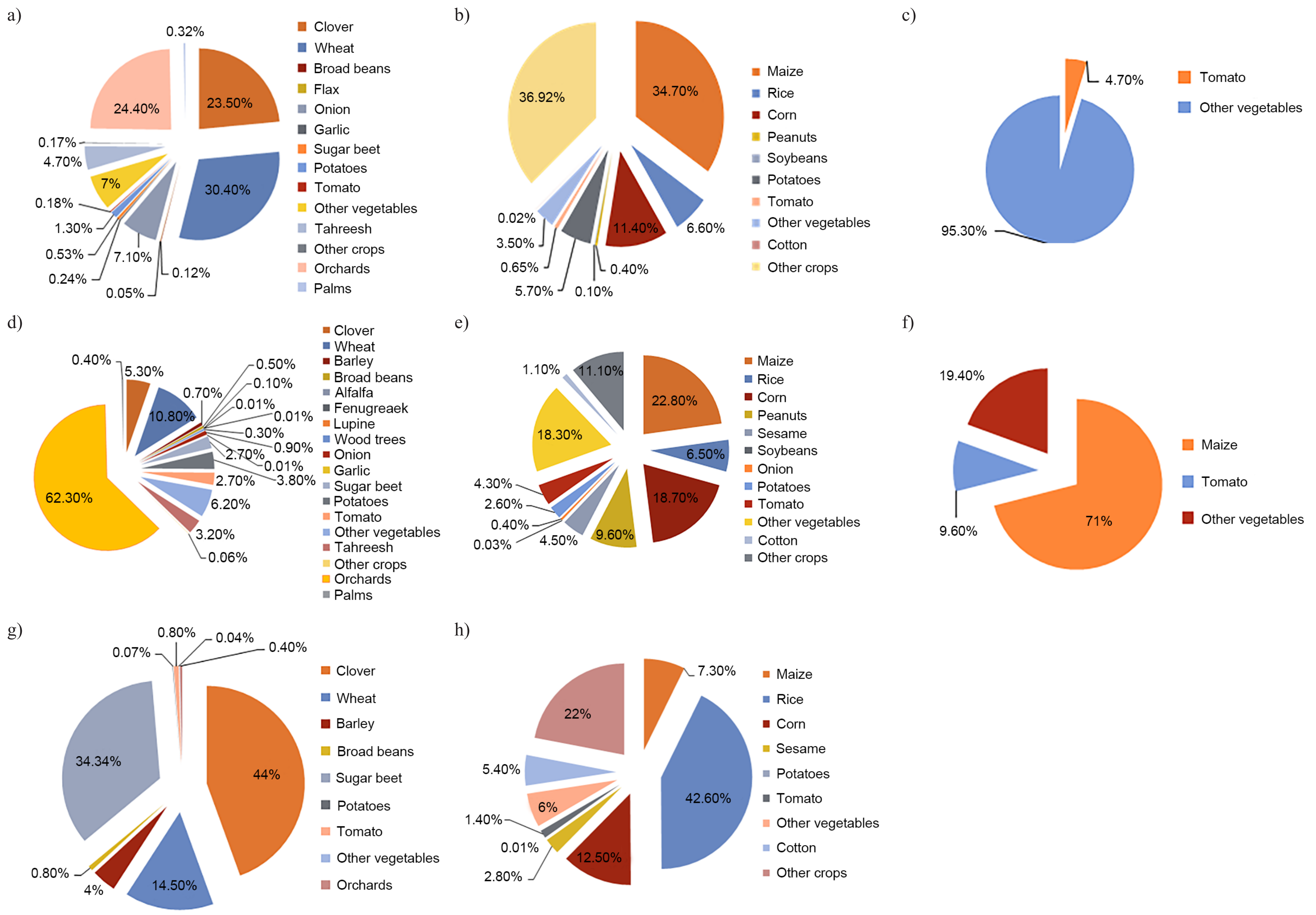

Fig. 2. Crop pattern and the cultivated area for a) Al-Qalyoubia, winter crop pattern; b) Al-Qalyoubia, summer crop pattern; c) Al-Qalyoubia, Nili crop pattern; d) Ismailia, winter crop pattern; e) Ismailia, summer crop pattern; f) Ismailia, Nili crop pattern; g) Port-Said, winter crop pattern; h) Port-Said, summer crop pattern (source: after CAPMAS, 2017)

METHODOLOGY

Objective functions

The objective function of the cropping pattern model of optimization is to maximize the total net profit by determining and selecting the optimal cropping pattern. In a theoretical result, the objective of the model is to maximize the profit from each crop in different seasons, Eq. 1 (Osama et al., 2017).

$$\text{Maximize } Z_t = \text{Max}\left[\Sigma X_W NR_W + \Sigma X_S NR_S + \Sigma X_N NR_N\right] \tag{1}$$

where:

Z_t – the net benefit from the winter, summer, and Nili crops in Egyptian pound (L.E.),

NR_W, NR_S, and NR_N – the net benefit from Winter, Summer, and Nili crops (L.E./Fed.) representatively,

X_W, X_S, and X_N – the areas of winter, summer, and Nili crops (Fed.) representatively.

Model constraints

1. **Water availability**: this restriction reduces irrigated water use. Water supply: For different crops, the total water consumption should be less or equal to the total available water in the field during the year.

$$\Sigma\left(WR_W\right)X_W \le \Sigma\left(W_W\right)_T \tag{2}$$

$$\Sigma\left(WR_S\right)X_S \le \Sigma\left(W_S\right)_T \tag{3}$$

$$\Sigma\left(WR_N\right)X_N \le \Sigma\left(W_N\right)_T \tag{4}$$

where:

ΣWR_W, ΣWR_S and ΣWR_N – the ratio of the requirement of water for Winter, Nili, and Summer crops in (m^3/ fed) representatively,

$\Sigma(W_W)_T$, $\Sigma(W_S)_T$ and $\Sigma(W_N)_T$ – the total water demand for irrigation for Winter, Summer, and Nili crops m^3.

2. **Land area limits** in agriculture during different seasons: During the season, the total area assigned to the plant must be equal to or less than the total area cultivated.

$$\Sigma X_W \le Aw_{WT} \tag{5}$$

$$\Sigma X_S \le A_{ST} \tag{6}$$

$$\Sigma X_N \le A_{NT} \tag{7}$$

where:

A_{WT}, A_{ST} and A_{NT} – the total cultivation areas for winter, summer and Nili crops in Feddan.

3. **Area of crops**: This requirement is to restrict the crop's growing area from being too large or too small to meet the food needs of the study population.

$$A_{WMin} \le \Sigma X_W\ \Sigma \le A_{WMax} \tag{8}$$

$$A_{SMin} \le \Sigma X_S \le A_{SMax} \tag{9}$$

$$A_{NMin} \le \Sigma X_N \le A_{NMax} \tag{10}$$

where:

A_{WMin}, A_{SMin} and A_{NMin} – the minimum areas of winter, summer, and Nili crops in feddan representatively,

A_{WMax}, A_{SMax} and A_{NMax} – the maximum areas of winter, summer, and Nili crops in Feddan representatively.

Model development

With the help of the LINDO software and by maximizing the total net yield, the linear planning model for these acreages is developed, and the optimal operating pattern is calculated until 2017. The application of the Linear Programming (LP) model resulted in an optimal cropping pattern. The model was compared with the current case. The increase and decrease in acreage are the up and down arrows (Table 4) (CAPMAS, 2017).

Table 4. Name and area served of each agriculture demand node (source: CAPMAS, 2017)

Demand area	Area served (Feddan)
Al-Qalyoubia governorate	61367
Ismailia governorate	382271
Port Said governorate	85000
Total	588638

RESULTS AND DISCUSSION

The analysis of the model was carried out; the net yield is 5011.42 million L.U. for winter crops, 4775.13 million L.U. for summer crops and Nili crops after optimization, and is not comparable with the existing cropping pattern. The water shortage of the current cropping pattern is 789.81 MCM (Ramadan et al., 2021), but by changing the cropping pattern, the total unmet demand is 549.52 MCM.

Optimization of winter crops

The wheat harvest changed from 18655.6 feddan to 19882.9 feddan, an increase of 7%, the onion harvest from 4357.1 feddan to 3129.7 feddan, a decrease of 4%, garlic from 147.3 feddan to 128.87 feddan, a decrease of 14%, the sugar beet harvest from 325.25 feddan to 257.7 feddan, potatoes from 797.8 feddan to 1297.8 feddan, representing an increase of 62%, tomatoes from 110.46 feddan to 926.64 feddan, representing an increase of 39%, and orchards from 14973.6 feddan to 13746.2 feddan, representing a decrease of 9%, as shown in Figure 3a, Al-Qalyoubia Governorate.

Sugar beet changed from 10321.3 feddan to 9365.6 feddan, potatoes from 14526.3 feddan to 19113.6 feddan, an increase of 31.6%, tomatoes from 10321.3 feddan to 33410.5 feddan and orchards from 238154.8 feddan to 207420.3 feddan, a decrease of 15%, as shown in Figure 3b for Ismailia governorate. Barley changed from 3400 feddan to 2082.5 feddan, potatoes from 59.5 feddan to 192329 feddan, tomatoes from 680 feddan to 3280 feddan, and sugar beet from 29189 feddan to 25687 feddan, a decrease of 13.6%, as shown in Figure 3c, and for Port Said governorate.

Tables 5–6 show the optimization of winter cropping patterns (feddan) in the study area for cities in three governorates.

The finding agrees with Khare et al. (2007), who used LINDO 6.1, an optimization package for the potential and feasibility of conjunctive use planning for one of the proposed link canals, Krishna (Nagarjunasagar)-Pennar (Somasila) canal under Peninsular rivers development as a part of India's ambitious river linking program. The results showed that the conjunctive use planning is beneficial and feasible for the proposed canal command. Hove-Musekwab (2013) developed an LP model that helped to determine the optimal cropping pattern for an irrigation scheme in Masvingo, Zimbabwe. As a result of the optimal solution, a farmer's income could be increased by 87%. Osama et al. (2017), who used a linear optimization model, was developed to maximize the net annual return from the three old regions of Egypt. The results showed that the developed model proposes a change in the cropping pattern in the old lands of Egypt to increase the gross net return without adding any further expenses. Abd-Elaty et al. (2023a) studied the optimal location of rice cultivation in the Nile Delta, Egypt, based on the groundwater recharge. The finding showed that placing rice cultivation in the northern region resulted in the highest reduction of salt volume (19%) compared with 0.50% and 15% in the central and southern regions, which produced a 15% increase. Wael et al. (2024) indicated that water-efficient irrigation techniques result in reduced recharge intensity, which consequently leads to a decline in groundwater levels. Specifically, the groundwater table was observed to decrease by between 10 and 50 cm.

Optimization of summer and Nili Crops

Corn from 6995.8 Feddan to 5707.2 Feddan (–23%), peanuts from 245.5 Feddan to 61.4 Feddan (–25%), soybeans from 61.37 Feddan to 36.82 Feddan (–67%), potatoes from 3497.92 Feddan to 4461.4 Feddan (+27.5%), tomatoes from 398.8 Feddan to 1245.8 Feddan, Other vegetables from 2147.9 Feddan to 3129.7 Feddan, an increase of 45.7%, and Other crops from 22656.7 Feddan to 213616 Feddan and Nili crops; Tomatoes from 2884.3 Feddan to 4228.2 Feddan and Other vegetables from 58482.6 Feddan to 57138.8 Feddan, as shown in Figure 4a, and Al-Qalyoubia Governorate.

In addition, peanuts fell from 36698 Feddan to 31384.5 Feddan, a decrease of 17%, sesame from 9250.7 Feddan to 5875.4 Feddan, a decrease of 36.5%, onions from 1529.1 Feddan to 1146.8 Feddan, an increase of 33%, potatoes from 9939.1 Feddan to 13914.7 Feddan, a rise of 40%, tomato from 16437.7 Feddan to 22133.5 Feddan, an increase of 34.7%, and cotton from 4205 Feddan to 6269.3 Feddan, a rise of 49%. Nili Crops: Maize from 271412.4 Feddan

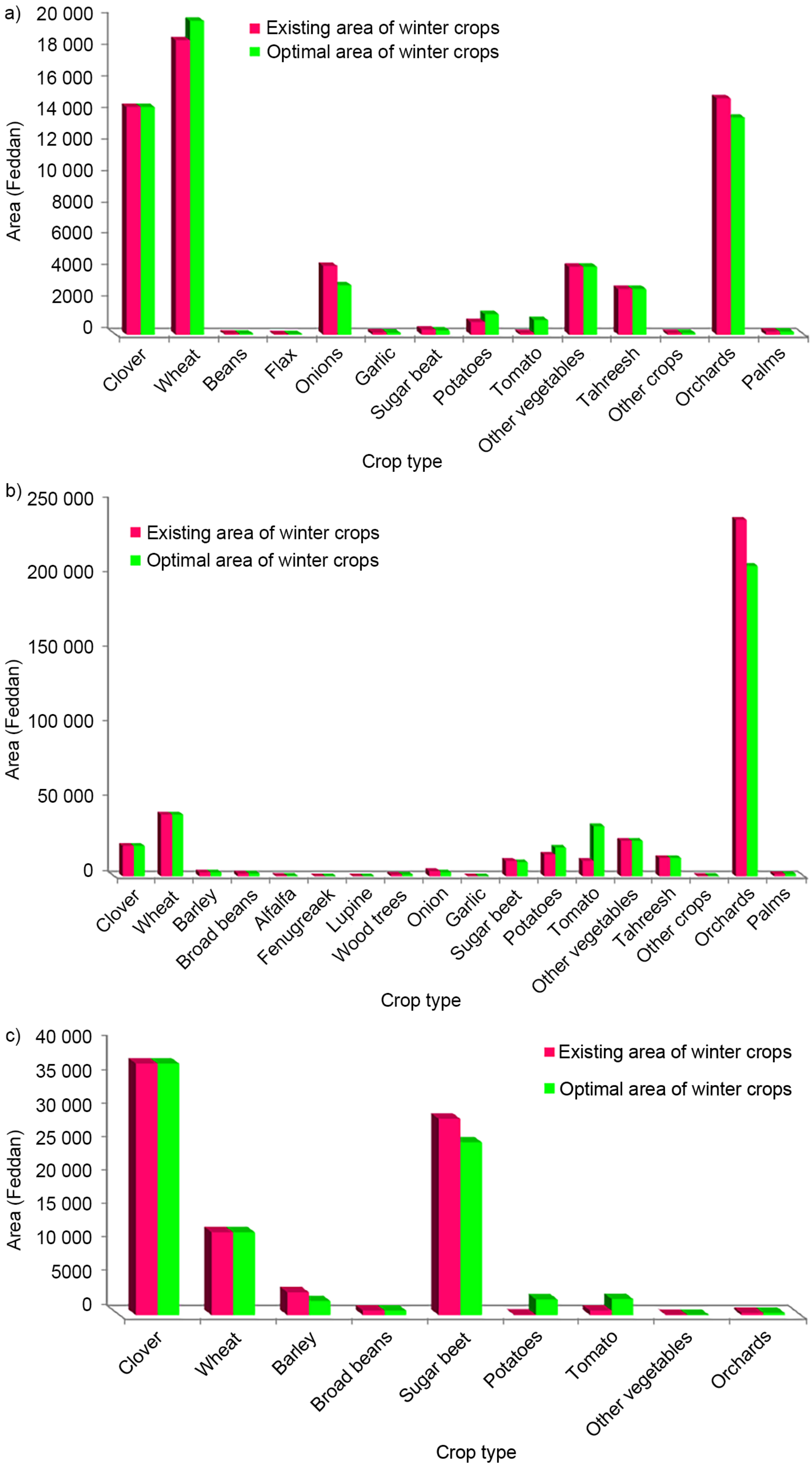

Fig. 3. Optimization of winter crops of Governorate a) Al-Qalyoubia, b) Ismailia, and c) Port Said (source: Authors' own elaboration)

Table 5. Optimization of winter Crops in the study area (Feddan) (source: Authors' own elaboration)

Al-Qalyoubia Governorate			Ismailia Governorate			Port Said Governorate		
Crops	Existing area	Optimal area	Crops	Existing area	Optimal area	Crops	Existing area	Optimal area
Clover	14421.25	14421.25	Clover	20260.36	20260.36	Clover	37400	37400
Wheat	18655.57	19882.91	Wheat	41285.27	41285.27	Wheat	12325	12325
Beans	73.64	73.64	Barley	2675.9	2675.9	Barley	3400	2082.5
Flax	30.68	30.68	Broad beans	1911.36	1911.36	Broad beans	680	680
Onions	4357.06	3129.72	Alfalfa	382.27	382.27	Sugar beet	29189	29189
Garlic	147.28	128.87	Fenugreek	38.23	38.23	Potatoes	59.5	2329
Sugar beat	325.25	325.25	Lupine	38.23	38.23	Tomato	680	2380
Potatoes	797.77	1294.84	Wood trees	1146.81	1146.81	Other vegetables	34	34
Tomato	110.46	926.64	Onion	3440.44	2675.9	Orchards	340	340
Other vegetables	4295.69	4295.69	Garlic	38.23	38.23			
Tahreesh	2884.25	2884.25	Sugar beet	10321.32	10321.32			
Other crops	104.32	104.32	Potatoes	14526.3	19113.55			
Orchards	14973.55	13746.21	Tomato	10321.32	33410.49			
Palms	190.24	190.24	Other vegetables	23700.8	23700.8			
			Tahreesh	12232.67	12232.67			
			Other crops	229.36	229.36			
			Orchards	238154.83	207420.24			
			Palms	1529.08	1529.08			

to 279057.8 Feddan, Tomatoes from 36698 Feddan to 32875.3 Feddan, and other vegetables from 74160.6 Feddan to 70337.9 Feddan, as shown in Figure 4b. For the Governorate of Ismailia, as shown in Figure 4, and for the Governorate of Ismailia sesame varies from 2380 Feddan to 1402.5 Feddan, decreasing by 40%, and potatoes from 8.5 Feddan to 986 Feddan, as shown in Figure 4c for Port Said Governorate.

The optimization of summer cropping patterns (feddan) in the study area for cities in three governorates is presented in Table 6.

Moreover, Divakar et al. (2011) developed a model for optimal bulk allocations of limited available water based on an economic criterion to competing use sectors such as agriculture, domestic, industry, and hydropower in the Chao Phraya River Basin, Thailand. The results indicated that the water allocation module can improve net economic returns compared to the current water allocation practices. Molinos-Senante et al. (2014) used an optimization model to maximize the value of water use. The model considered the water distribution efficiency and the physical connections between water supply and demand points. Subsequent empirical testing using data from a Spanish Mediterranean river basin demonstrated the usefulness of the global optimization model in solving existing water imbalances at the river basin level.

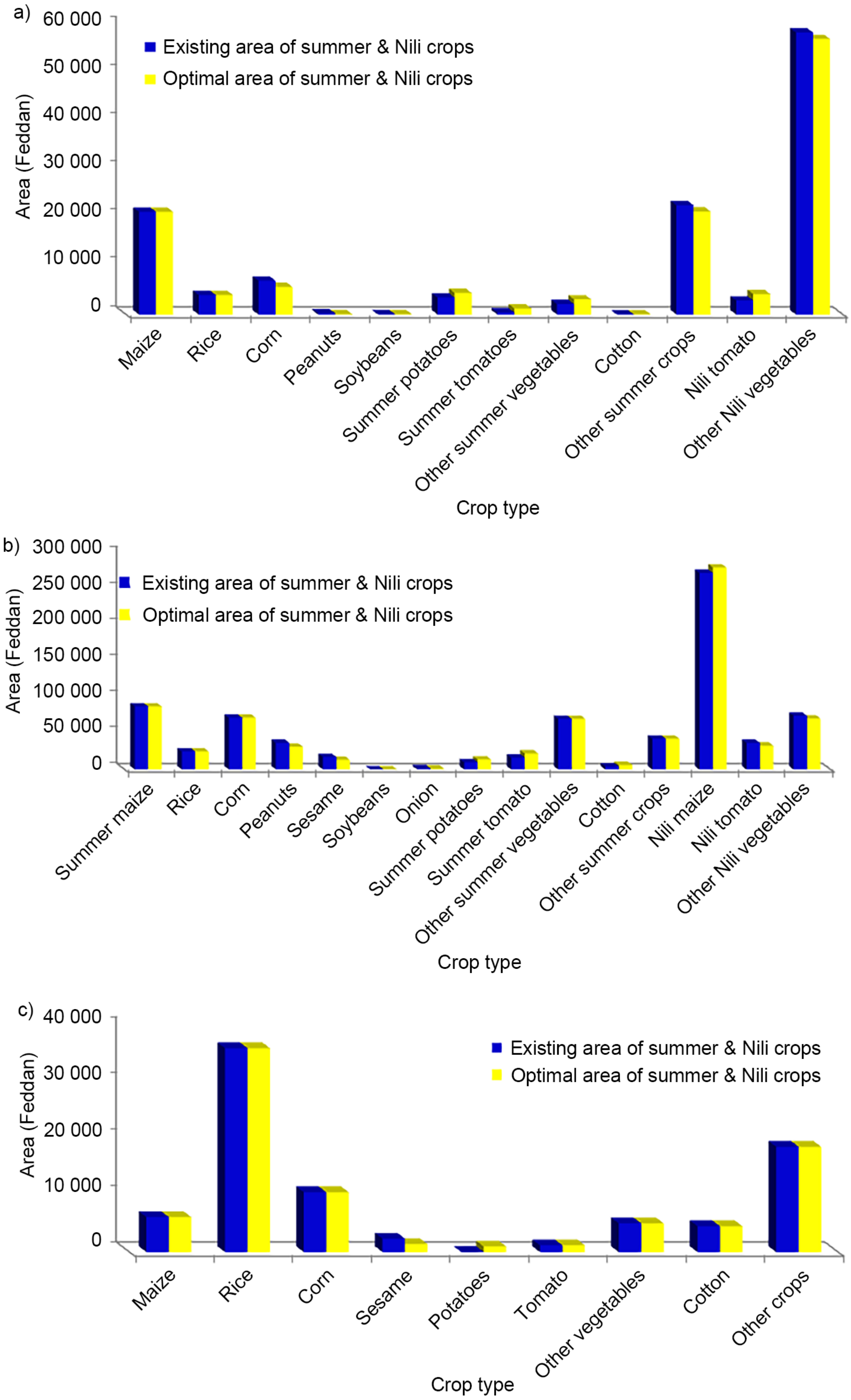

Fig. 4. Optimization of summer and Nili crops of governorate a) Al-Qalyoubia, b) Ismailia, and c) Port Said (source: Authors' own elaboration)

Table 6. Optimization of summer crops and Nili crops in the study area (Feddan) (source: Authors' own elaboration)

	Al-Qalyoubia Governorate			Ismailia Governorate			Port Said Governorate		
	Crops	Existing area	Optimal area	Crops	Existing area	Optimal area	Crops	Existing area	Optimal area
	Maize	21294.35	21294.35	Maize	87157.79	87157.79	Maize	6205	6205
Summer	Rice	4050.22	4050.22	Rice	24847.62	24847.62	Rice	36210	36210
	Corn	6995.84	6995.84	Corn	71484.68	71484.68	Corn	10625	10625
	Peanuts	245.47	61.37	Peanuts	36698.02	31384.45	Sesame	2380	1402.5
	Soybeans	61.37	36.82	Sesame	17202.2	13226.58	Potatoes	8.5	986
	Potatoes	3497.92	4461.38	Soybeans	114.68	114.68	Tomato	1190	1190
	Tomatoes	398.89	1245.75	Onion	1529.08	1146.81	Other vegetables	5100	5100
	Other vegetables	2147.85	3129.72	Potatoes	9939.05	13914.66	Cotton	4590	4590
	Cotton	12.27	12.27	Tomato	16437.65	22133.49	Other crops	18700	18700
	Other crops	22656.7	21361.85	Other vegetables	69955.59	69955.59			
	Maize	21294.35	21294.35	Cotton	4204.98	6269.24			
				Other crops	42432.08	42432.08			
Nili	Tomato	2884.25	4228.19	Maize	271412.41	279057.83			
	Other vegetables	58482.75	57138.81	Tomato	36698.02	32875.31			
				Other vegetables	74160.57	70337.86			

Abd-Elaty et al. (2023b) showed that changing the irrigation method has increased the groundwater drawdowns of 2.60 m, 4.20 m, and 6.50 m using sprinkle, sub-surface, and drip irrigation, respectively. At the same time, the maximum land subsidence reached 26 cm, 44 cm, and 65 cm. Abd-Elaty et al. (2024b) investigated the replacement of traditional surface irrigation methods with modern irrigation systems (MIS), including horizontal sprinkler, central pivot, surface drip, and subsurface drip aimed at improving water efficiency in the Nile Delta, Egypt. LINDO software was employed to optimize land allocation for each irrigation method. The transition from traditional surface irrigation to MIS resulted in significant water savings, reaching 2.15 × 10^9 m³. However, groundwater modeling indicated a decrease in groundwater levels, leading to an 8% increase in aquifer salinity due to reduced infiltration of recharge water. Gabr et al. (2024) investigated irrigation water management strategies in a water-scarce environment under the influence of climate change. The study recommended the use of crop patterns involving wheat, barley, potato, and sugar beet to conserve irrigation water. Overall, the findings from this study have far-reaching implications for water management in agricultural regions reliant on irrigation. As demonstrated by the significant reductions in water shortage through optimized cropping patterns, there is a clear need to shift towards more sustainable crop planning models. This is particularly important for areas like the Ismailia Canal system, where water resources are already stretched. As indicated by Wael et al. (2024), water-efficient irrigation techniques must be complemented by optimized cropping patterns to mitigate declining groundwater levels and other water-related challenges.

CONCLUSIONS

The results of this study highlight the significant impact of optimizing cropping patterns on both water demand and agricultural productivity. By altering the cropping structure in the study area, particularly for winter, summer, and Nili crops, the net water yield and overall crop output have improved. Specifically, after optimization, the net yield increased to 5011.42 million L.U. for winter crops and 4775.13 million L.U. for summer and Nili crops, which represents a noticeable increase compared to the existing cropping pattern. Different constraints represent the availability of water, which reduces irrigated water consumption, and land area constraints in the various growing seasons; during each growing season, the total area allocated to the crop must be less than or equal to the sum of the area cultivated and the area of the crops. This requirement is intended to limit the area under cultivation so that it is not too large or too small to meet the food needs of the population in the study area. Wheat, rice, maize, and clover, which are considered the strategic crops in Egypt, occupy most of the available area according to the data collected.

In contrast, non-strategic crops such as onions, garlic, fruit trees, peanuts, sesame, and soybeans occupy limited areas and have a low net yield compared to other crops. Most irrigation water is needed for sugar cane and rice. The results of the optimization model have shown that it is possible to increase the net yield of crops by reducing the cultivation of onions, garlic, fruit trees, peanuts, sesame, and soybeans, increasing the cultivation of wheat, cotton, maize, and corn to achieve self-sufficiency and increasing the cultivation of tomatoes. The total net yield was increased by 38% for winter crops and by 2.7% for summer and Nili crops. While this study has made substantial progress in optimizing water use and crop yield, it is important to note that short-term predictions regarding water demand and cropping success remain complex due to the variability in climatic and environmental factors. Future research could benefit from the integration of machine learning models to further enhance prediction accuracy and create adaptive cropping strategies based on real-time data.

ACKNOWLEDGMENTS

The authors thank the Department of Water and Water Structures Engineering, Faculty of Engineering, Zagazig University, Zagazig 44519, Egypt, for constant support during the study. Alban Kuriqi is grateful for the Foundation for Science and Technology's support through funding UIDB/04625/2020 from the research unit CERIS (DOI: 10.54499/UIDB/04625/2020).

REFERENCES

Abd-Elaty, I., Straface, S., Kuriqi, A. (2021). Sustainable saltwater intrusion management in coastal aquifers under climatic changes for humid and hyper-arid regions. Ecological Engineering, 171, 106382. DOI: 10.1016/j.ecoleng.2021.106382

Abd-Elaty, I., Sallam, G.A.H., Pugliese, L., Negm, A.M., Straface, S., Scozzari, A., Ahmed, A. (2023a). Managing coastal aquifer salinity under sea level rise using rice cultivation recharge for sustainable land cover. Journal of Hydrology: Regional Studies, 48, 101466.https://doi.org/10.1016/j.ejrh.2023.101466

Abd-Elaty, I., Fathy, I., Kuriqi, A., John, A.P., Straface, S., Ramadan, E.M. (2023b). Impact of modern irrigation methods on groundwater storage and land subsidence in high-water stress regions. Water Resources Management, 37, 1827–1840. DOI: 10.1007/s11269-023-03457-5

Abd-Elaty, I., Ramadan, E.M., Elbagory, I.A., Nosair, A.M., Kuriqi, A., Garrote L., Ahmed, A.A. (2024a). Optimizing irrigation systems for water efficiency and groundwater sustainability in the coastal Nile Delta. Agricultural Water Management, 304, 109064. DOI: 10.1016/j.agwat.2024.109064

Abd-Elaty, I., Kuriqi, A., Ramadan, E.M., Ahmed, A.A. (2024b). Hazards of sea level rise and dams built on the River Nile on water budget and salinity of the Nile Delta aquifer. Journal of Hydrology: Regional Studies, 51, 101600. DOI: 10.1016/j.ejrh.2023.101600

Abdel-Shafy, H.I., El-Saharty, A.A., Regelsberger, M., Platzer, C. (2010). Rainwater in Egypt: Quantity, distribution and harvesting. Mediterranean Marine Science, 11, 245–258. DOI: 10.12681/mms.75

Aboel Ghar, M., Shalaby, A., Tateishi, R. (2004). Agricultural land monitoring in the Egyptian Nile delta using Landsat data. International Journal of Environmental Studies, 61, 651–657. DOI: 10.1080/0020723042000253866

AfDb ADBG (2016). Egypt-integrated water resources management of the Nubaria and Ismailia Canals: Summary ESIA, environmental and social impact assessment, May 2016. Project code: P-EG-AAC-024.

Alnaggar, D. (2003). Water resources management and policies for Egypt. In: Policies and strategic options for water management in the Islamic countries. Paris: UNESCO, 55–69.

Arnous, M.O., Green, D.R. (2015). Monitoring and assessing waterlogged and salt-affected areas in the Eastern Nile Delta region, Egypt, using remotely sensed multi-temporal data and GIS. Journal of Coastal Conservation, 19, 369–391. DOI: 10.1007/s11852-015-0397-5

Barati, K., Abedi Koupai, J., Darvishi, E., Arzani, A., Yousefi, A. (2020). Crop pattern optimization using system dynamics approach and multi-objective mathematical programming. Journal of Agricultural Science and Technology, 22, 1397–1412.

CAPMAS (2017). Annual Bulletin of Irrigation and Water Resources for Central Agency for Public Mobilization and Statistics. https://www.capmas.gov.eg/

Chen, Y., Zhou, Y., Fang, S., Li, M., Wang, Y., Cao, K. (2022). Crop pattern optimization for the coordination between economy and environment considering hydrological uncertainty. Science of The Total Environment, 809, 151152. DOI: 10.1016/j.scitotenv.2021.151152

Dhanraj, R., Punnathanam, V., Shastri, Y. (2021). Multi objective optimization of ethanol production based on regional resource availability. Sustainable Production and Consumption, 27, 1124–1137. DOI: 10.1016/j.spc.2021.02.021

Divakar, L., Babel, M.S., Perret, S.R., Gupta, A.D. (2011). Optimal allocation of bulk water supplies to competing use sectors based on economic criterion – An application to the Chao Phraya River Basin, Thailand. Journal of Hydrology, 401, 22–35. DOI: 10.1016/j.jhydrol.2011.02.003

El-Nahry, A.H., Doluschitz, R. (2010). Climate change and its impacts on the coastal zone of the Nile Delta, Egypt. Environmental Earth Sciences, 59, 1497–1506. DOI: 10.1007/s12665-009-0135-0

El Shinawi, A., Kuriqi, A., Zelenakova, M., Vranayova, Z., Abd-Elaty, I. (2022). Land subsidence and environmental threats in coastal aquifers under sea level rise and over-pumping stress. Journal of Hydrology, 608, 127607. DOI: 10.1016/j.jhydrol.2022.127607

Gado, T.A., El-Agha, D.E. (2021). Climate change impacts on water balance in Egypt and opportunities for adaptations. In: M. Abu-hashim, F. Khebour Allouche, A. Negm (Eds.), Agro-Environmental Sustainability in MENA Regions. Cham.: Springer International Publishing, 13–47.

Gabr, M.E., Awad, A., Farres, H.N. (2024). Irrigation water management in a water-scarce environment in the context of climate change. Water, Air, & Soil Pollution, 235, 127. DOI: 10.1007/s11270-024-06934-8

Gong, X., Zhang, H., Ren, C., Sun, D., Yang, J. (2020). Optimization allocation of irrigation water resources based on crop water requirement under considering effective precipitation and uncertainty. Agricultural Water Management, 239, 106264. DOI: 10.1016/j.agwat.2020.106264

Hove-Musekwab, D. (2013). Use of linear programming model to determine the optimum cropping pattern for an irrigation scheme in Masvingo, Zimbabwe. Journal of Management and Science, 1, 450–452. DOI: 10.26524/jms.2013.56

He, L., Du, Y, Wu, S., Zhang, Z. (2021). Evaluation of the agricultural water resource carrying capacity and optimization of a planting-raising structure. Agricultural Water Management, 243, 106456. DOI: 10.1016/j.agwat.2020.106456

Jain, S., Ramesh, D., Bhattacharya, D. (2021). A multi-objective algorithm for crop pattern optimization in agriculture. Applied Soft Computing, 112, 107772. DOI: 10.1016/j.asoc.2021.107772

Khare, D., Jat, M., Sunder, J.D. (2007). Assessment of water resources allocation options: Conjunctive use planning in a link canal command. Resources, Conservation and Recycling, 51, 487–506. DOI: 10.1016/j.resconrec.2006.09.011

Kuriqi, A., Abd-Elaty, I. (2024). Groundwater salinization risk in coastal regions triggered by earthquake-induced saltwater intrusion. Stochastic Environmental Research and Risk Assessment, 38, 3093–3108. DOI: 10.1007/s00477-024-02734-y

Li, F., Zhang, M., Zhao, Y., Jiang, R. (2020a). Multi-target planting structure adjustment under different hydrologic years using AquaCrop model. Theoretical and Applied Climatology, 142, 1343–1357. DOI: 10.1007/s00704-020-03381-3

Li, J., Jiao, X., Jiang, H., Song, J., Chen, L. (2020b). Optimization of irrigation scheduling for maize in an arid oasis based on simulation–optimization model, 10, 935. DOI: 10.3390/agronomy10070935

Li, X., Zhang, C., Huo, Z. (2020c). Optimizing irrigation and drainage by considering agricultural hydrological process in arid farmland with shallow groundwater. Journal of Hydrology, 585, 124785. DOI: 10.1016/j.jhydrol.2020.124785

Molinos-Senante, M., Hernández-Sancho, F., Mocholí-Arce, M., Sala-Garrido, R.A. (2014). Management and optimisation model for water supply planning in water deficit areas. Journal of Hydrology, 515, 139–146. DOI: 10.1016/j.jhydrol.2014.04.054

Nashwan, M.S., Shahid, S., Wang, X. (2019). Assessment of Satellite-Based Precipitation Measurement Products over the Hot Desert Climate of Egypt. Remote Sensing, 11, 555. DOI: 10.3390/rs11050555

Nguyen, T.H., Nong, D., Paustian, K. (2019). Surrogate-based multi-objective optimization of management options for agricultural landscapes using artificial neural networks. Ecological Modelling, 400, 1–13. DOI: 10.1016/j.ecolmodel.2019.02.018

Nikouei, A., Asgharipour, M.R., Marzban, Z. (2022). Modeling land allocation to produce crops under economic and environmental goals in Iran: A multi-objective programming approach. Ecological Modelling, 471, 110062. DOI: 10.1016/j.ecolmodel.2022.110062

Osama, S., Elkholy, M., Kansoh, R.M. (2017). Optimization of the cropping pattern in Egypt. Alexandria Engineering Journal, 56, 557–566. DOI: DOI: 10.1016/j.aej.2017.04.015

Ramadan, E.M., Abdelwahab, H.F., Vranayova, Z., Zelenakova, M., Negm, A.M. (2021). Optimization-based proposed solution for water shortage problems: A case study in the Ismailia Canal, East Nile Delta, Egypt. Water, 13 (18), 2481. DOI: 10.3390/w13182481

Sakr, S. (2005). Impact of the possible sea level rise on the Nile delta aquifer. In: A study for Lake Nasser flood drought control project, Planning Sector, Ministry of Water Resources Irrigation, Cairo, Egypt.

Wael, M., Riad, P., Hassan, N.A., Nofal, E.R. (2024). Assessment of modern irrigation versus flood irrigation on groundwater potentiality in old clayey lands. Ain Shams Engineering Journal, 15, 102776. DOI: 10.1016/j.asej.2024.102776

ŁAGODZENIE PROBLEMU NIEDOBORU WODY ORAZ ZWIĘKSZENIE BEZPIECZEŃSTWA ŻYWNOŚCIOWEGO POPRZEZ OPTYMALIZACJĘ UPRAW: WNIOSKI Z BADAŃ WE WSCHODNIEJ DELCIE NILU

ABSTRAKT

Cel pracy
Niedobór wody to palący problem na skalę globalną, szczególnie w regionach pustynnych i półpustynnych. Egipt – kraj klasyfikowany jako półpustynny – zmaga się ze znacznymi ograniczeniami w dostępie do zasobów wodnych. Niniejsze badanie dotyczy obecnych i prognozowanych warunków wodnych w egipskiej wschodniej delcie Nilu oraz ma na celu wyjaśnienie obecnej polityki i strategii dotyczących oszczędzania wody i zwiększania jej podaży. Ponadto badanie ma pozwolić na zidentyfikowanie zagadnień, które wymagają dalszych badań, oraz na przedstawienie przeglądu różnych modeli stosowanych w celu optymalizacji zarządzania zasobami wodnymi i ochrony bezpieczeństwa żywnościowego.

Materiał i metody
W badaniu przeanalizowano stan dostępności zasobów wodnych, zapotrzebowanie na wodę i inne czynniki istotne na obszarze wschodniej delty Nilu. Aby rozwiązać problem niedoboru wody, w pracy zbadano różne modele optymalizacji, w szczególności programowanie liniowe. Model ten zastosowano w obszarze wschodniej delty, skupiając się na regionie zaopatrywanym przez Kanał Ismailijski. Model miał na celu zrównoważenie ograniczonej podaży wody pitnej ze wzrastającym zapotrzebowaniem, umożliwiając wprowadzenie zmian w schematach upraw.

Wyniki i wnioski
W badaniu ustalono, że najlepszym sposobem na zabezpieczenie dostaw wody i zminimalizowanie jej niedoboru jest zastosowanie modeli optymalizacji. Niedobór wody w obszarze zaopatrywanym przez Kanał Ismailijski we wschodniej delcie wynosił około 789,81 MCM. Zmieniając schematy upraw, można było zmniejszyć niedobór wody. Wyniki sugerowały ograniczenie uprawy roślin niestrategicznych, takich jak: cebula, czosnek, drzewa owocowe, orzeszki ziemne, sezam i soja. Równocześnie intensyfikację upraw strategicznych, takich jak: pszenica, bawełna, kukurydza i zboża, a także upraw o wysokich plonach netto, np. pomidory i ziemniaki. Zmiany te pomogą zrównoważyć popyt i podaż wody, zapewniając bardziej zrównoważoną strategię zarządzania nią w przyszłości.

Słowa kluczowe: schematy upraw, Kanał Ismailijski, optymalizacja, wschodnia delta Nilu, uprawy strategiczne