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Optimization-Based Proposed Solution for Water Shortage Problems: A Case Study in the Ismailia Canal, East Nile Delta, Egypt

Elsayed M. Ramadan [1], Heba F. Abdelwahab [1], Zuzana Vranayova [2,*], Martina Zelenakova [2] and Abdelazim M. Negm [1]

[1] Water and Water Structures Engineering Department, Faculty of Engineering, Zagazig University, Zagazig 44519, Egypt; smokhtar@zu.edu.eg (E.M.R.); hebafathy@zu.edu.eg (H.F.A.); amnegm@zu.edu.eg or amnegm85@yahoo.com (A.M.N.)
[2] Faculty of Civil Engineering, Technical University of Kosice, 04200 Kosice, Slovakia; martina.zelenakova@tuke.sk (M.Z.)
* Correspondence: zuzana.vranayova@tuke.sk; Tel.: +421-907-178-151

Abstract: Water conflicts in transboundary watersheds are significantly exacerbated by insufficient freshwater sources and high water demands. Due to its increasing population and various development projects, as well as current and potential water shortages, Egypt is one of the most populated and impacted countries in Africa and the Middle East in terms of water scarcity. With good future planning, modeling will help to solve water scarcity problems in the Ismailia canal, which is one of the most significant branches of the Nile River. Many previous studies of the Nile river basin depended on quality modeling and hydro-economic models which had policy or system control constraints. To overcome this deficit position and number, the East Nile Delta area was investigated using LINDO (linear interactive, and discrete optimizer) software; a mathematical model with physical constraints (mass balances); and ArcGIS software for canals and water demands from the agriculture sector, which is expected to face a water shortage. Using the total capital (Ismailia canal, groundwater, and water reuse) and total demand for water from different industries, the software measures the shortage area and redistributes the water according to demand node preferences (irrigation, domestic, and industrial water demands). At the irrigation network's end, a water deficit of 789.81 MCM/year was estimated at Al-Salhiya, Ismailia, El Qantara West, Fayed, and Port Said. The model was then run through three scenarios: (1) the Ismailia Canal Lining's effect, (2) surface water's impact, and (3) groundwater's impact. Water scarcity was proportional to lining four sections at a length of 61.0 km, which is considered to be optimal—based on the simulation which predicts that the Ismailia canal head flow will rise by 15%, according to scenarios—and the most effective way to reduce water scarcity in the face of climate change and limited resources as a result of the increasing population and built-in industrial projects in Egypt.

Keywords: water scarcity; Nile River; groundwater; water reuse; shortage; climate change; optimization; Ismailia canal; East Delta; LINDO

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1. Introduction

In many countries around the world, water shortage is one of the most serious issues. About 1.2 billion people, or nearly one-fifth of the world's population, live in water-scarce regions, and 500 million more people are living in regions that are on the verge of becoming water-scarce [1,2]. Water shortage problems, negative effects of climate change, and growing populations lead to conflicts around transboundary surface and groundwater resources between two or more countries, such as in the Euphrates-Tigris (ET) basin [3–5].

Egypt is one of the countries facing significant challenges as a result of its restricted water supplies, which are primarily a result of its fixed share of Nile River water, its general aridity [6], and its dependence on agriculture, which provides a living for 55 percent of the population and accounts for about 15 percent of the country's Gross Domestic Product (GDP), amounting to US$232 billion and nearly one-third of total jobs [7].

With a rising population, dependence on agriculture, and new industrial ventures, modeling may help to solve the problem of water scarcity by accounting for all important components that make up a river basin and addressing various planning and management priorities and activities, in order to assist planners in evaluating and selecting the most appropriate activity guidelines for the local situations and objectives.

Since 1923, several studies have been conducted using various models to monitor water shortages around the world. The first optimization model for flood control and water supply was created in 1923 [8]. The optimization model was designed for supplying sources (conventional and non-conventional) when taking into account water quality, water distribution capability, and current relations between water supply and water demands. The model was then applied to a basin of the Spanish Mediterranean River that was experiencing water shortages. The findings revealed that the model is a useful method for investigating water allocation and enhancing water supply management in water-scarce areas [9].

In the Zohreh River Basin in Iran, a hydro-economic optimization model was used to build the irrigation systems of the Chamshir Dam, which was fed with water from rainfall and reservoir inflow, while taking into account crop yield, production costs, and crop price. In addition to sets and indices such as irrigation areas and reservoir capacity sizing, optimum reservoir activity policies and irrigation management techniques were calculated, and various scenarios for the baseline, risk situations, climate change effects, and upstream conditions were evaluated. As a result of using various influential variables, the results demonstrated how to reduce the design parameter values and reservoir capability in order to prevent stress [10].

It should come as no surprise that ensuring the water security of the Nile River basin has been a common and significant goal for hydro-economic studies. The impact of the long cascade of hydroelectric dams on water economics in Sudan and Egypt, as well as the Ethiopian Blue Nile, was assessed using a linear optimization model. The key goals of this optimization model were to increase the hydropower output as well as the downstream agricultural water supply in Egypt, Sudan, and Ethiopia [11].

The Nile Economic Optimization Model (NEOM), a more recent basin-wide hydro-economic optimization model, was presented using GAMS software to determine the economic consequences of various infrastructural developments within the basin and outline the aims of optimizing basin-wide economic benefits of irrigation and hydropower output. According to the findings, the combined economic benefits more than doubled the realized total gain, from USD 4.1 billion in the status quo scenario to more than USD 9 billion when all countries cooperated entirely [12], Under normal operating conditions, a stochastic hydro-economic model was then used to analyze the middle to long term activity of infrastructures, specifically focusing on the four USBR proposed reservoirs in Ethiopia and the AHD in Egypt. The optimization was completed using Stochastic Dual Dynamic Programming (SDDP). Flow data were used to estimate the parameters of the built-in multi-site periodic autoregressive hydrological model. The flood peak level in the Blue Nile will be reduced as a result of flow control caused by the new dams' operation, according to the report [13].

A hydro-economic model was developed using the same SDDP model to determine the positive and negative effects of GERD on Sudan and Egypt [14]. Similar to the findings, GERD would provide significant irrigation and hydropower benefits to Ethiopia if the system operated cooperatively. Although the model did not manage the flow's inter-annual variability, the results showed that GERD would play a significant role in eliminating hydrological uncertainty during the low flow time. The analysis also failed to account for the expected negative externalities of GERD, such as the effects on flood plain (recession) agriculture. The sedimentation of reservoirs was once again ignored [13]. Using optimal control theory and dynamic programming, an economic assessment of cooperative and non-cooperative sediment management between upstream and downstream Eastern Nile basins for sediment control at AHD was conducted (DP) [15].

The effect of flood downstream of the Aswan High Dam, which is situated between Assiut and Delta barrages, was addressed due to rehabilitation, high releases, and the impact of floods. Using HEC-RAS, the results showed that 200–220 to 250–300 and 350 Mm^3/day were categorized as strong floods (one dimension model) [16]. The groundwater management was studied using the OPDM (Operational and Planning Distribution Model) model in Bahr Mashtoul, Egypt. Changes in the quantity of groundwater used in irrigation, from −50 percent to 50 percent, as well as changes in groundwater salinity, from −50 percent to 50 percent, were studied and the effects on crop incomes were seen [17].

On the other hand, among the available sources of reused wastewater, surface water, groundwater, and desalinated water, a cost management model was used to decide the most suitable water source/supply alternative [18]. For the city of Riyadh, Saudi Arabia, a multi-objective target programming methodology was used to model water delivery from multiple sources to multiple users over 35 years [19] and evolved an optimization-based method for designing water desalination and distribution networks to meet the needs of various water-using industries [20].

In the Nile Delta, Sinai Peninsula, Nile Valley, and Western Desert Oases, GIS and remote sensing were commonly used in groundwater mapping and were considered to be the key tools for improving groundwater resources [21], contributing to the management of water quality in the Ismailia canal by detecting changes in land cover and usage and applying statistical correlations between water quality parameters. The best spectral-domain displayed a significant relationship with eight water quality tests, according to the findings. A linear model was used to predict information about important water quality parameters along the Ismailia Canal and this model provided a set of solid decision-making mechanisms with statistical tools to provide detailed and views of surface water quality information under the same conditions [22]. In Wadi Dahab, Egypt, GIS, RS, and watershed modeling (WM) were used to determine the best locations for Water Harvesting (WH) Zones. The results revealed that runoff water harvesting maps could divide the basin into five parts, ranging from very high to very low, with the majority of Wadi Dahab classified as very high and high (15.56 percent and 58.27 percent, respectively) for runoff water harvesting (RWH) [23].

In the Kushabhadra-Bhargavi River Delta of Eastern India, a linear program was used to optimize the interaction between groundwater and surface water, as well as to calculate the overall net returns in the year from crop yields by locating crop patterns free of seawater intrusion. The findings revealed that rice cultivation should be reduced, and crop diversification increased, to improve farmers' livelihoods [24].

Optimization under uncertainty (OUU) is defined as using the linear program problem implied in nitrate concentration in surface water and groundwater in combination with chance constraints (following a stated level of risk) and is referred to as chance-constrained linear programming (CCLP). By changing the constraint value to account for a user-specified degree of risk, CCLP produces an optimal spatial distribution of nitrate loading change that implicitly accounts for uncertainty constraints resulting from the uncertainty parameters [25].

In terms of the study area, Ismailia Canal is the major multipurpose canal in the East Nile Delta. This canal serves approximately one-third of the East Nile Delta population. It provides water for agriculture, industry, and domestic uses. It connects directly with the Suez Canal and is divided at its end into two branch canals: the Suez and Port Said Canals. These branch canals carry water to the Fayed, El Qantara West, and Port Said regions.

All of these canals have agricultural land expansion plans that require additional water duties higher than the budget of the Ismailia Canal. Additional water resources are being investigated to rectify the available demand gap [26].

Most of the previous research that studied the Ismailia canal in Egypt concentrated on economic or water quality modeling [27–29]. Ismailia canal has been evaluated using water quality indexes for agriculture, manufacturing, drinking water, and aquatic life [27], was all of which contributed to a mathematical model for integrating complex data to produce a score that informs the public and the policymakers about the state of water quality. Water quality index (WQI) can also be used to compare the quality of different water sources and to monitor improvements in water quality over time [28]. The mathematical optimization model was used to increase the yearly return in Egypt from three regions by selecting the best land locations for various crops and imposing various constraints on the model, such as land availability in various seasons, water availability, crop effective areas, and sufficiency ratios. From 2008 to 2012, researchers collected data on 28 crops and built a model that included irrigation water requirements, spatial crop variations, crop yields, and food requirements. The findings revealed that by increasing tomato production, the annual return from crops could increase. Furthermore, by restricting non-strategic crop areas while preserving strategic crop areas, the principles of self-sufficiency could be met [29].

We focused in this study on offering a feasible solution to the water scarcity/shortage issue in the area of the Ismailia canal. This could be done efficiently by applying a mathematical optimization model which is capable of analyzing various organizational guidelines. The selected optimization model is uses LINDO (linear interactive, and discrete optimizer) software which is a convenient and powerful tool for solving linear, integer, and quadratic programming problems. These problems occur in the areas of business, industry, research, and government. Specific application areas in which LINDO has proven to be of great use includes water distribution and inventory management. The model optimizes the physical system and desired operation rules as a collection of the constraints embedded in the model, resulting in the best feasible solution for water delivery with a low deficit in order to achieve the best solution to the water scarcity problem [30].

2. Physical Conditions for the Study Area

The study area is the East Delta zone, which is bounded and dissected by several canals, drains, and lakes and contains four major governorates (Al-Qalubia, Al-Sharkia, Ismailia, and Port Said). Figure 1 depicts the Irrigation canals in the East Delta, including the Ismailia Canal. Such fresh surface water bodies as the Ismailia Canal and its branches, as well as the Suez Canal, will be studied for simplicity, as will the regions that stretch along the length of Ismailia Canal and benefit from its fresh surface water. As shown in Figure 2, the canal covers a latitude range of 30°15′0″ to 31°0′0″ N and a longitudinal range of 31°15′0″ to 32°15′0″ E. Ismailia Canal is one of Egypt's most significant branches of the Nile River, providing surface water for four governorates in the East Nile delta. Its length is 128 km, with a depth of 1–3 m and a width of 30–70 m [31]. The area irrigated by the Ismailia Canal has a population of 4,869,573 people [32]. The canal irrigates approximately 778,656 feddan in the current case, or about 9% of Egypt's agricultural land [33–36].

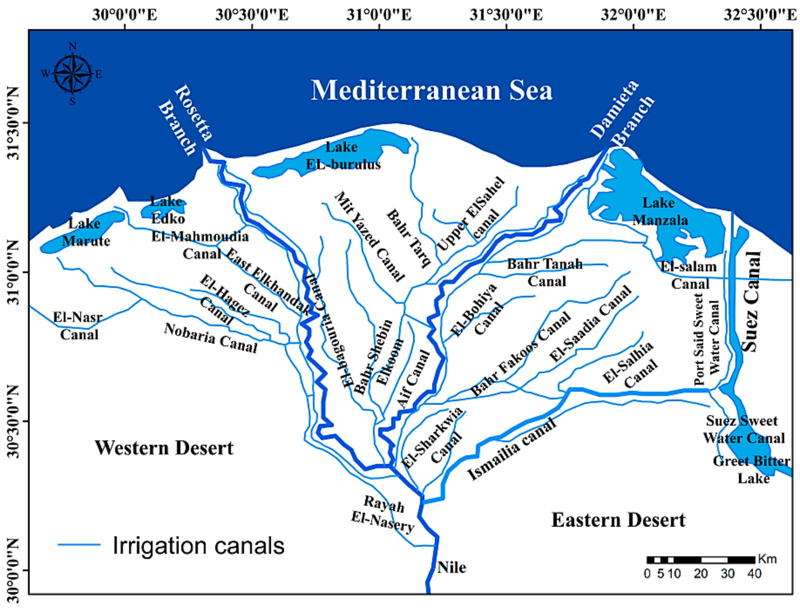

Figure 1. Irrigation canal networks in the Nile Delta [37].

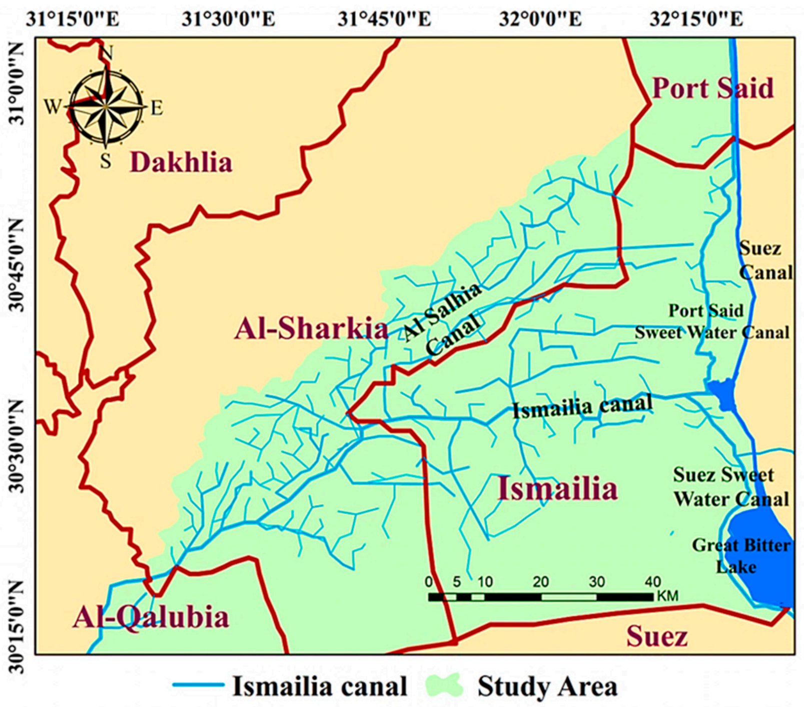

Figure 2. GIS map showing the study area.

3. Materials and Methods

Figure 3 shows the flow chart of the optimization model applied in this research, where a mathematical model with physical constraints (mass balance) was developed using LINDO (linear interactive and discrete optimizer) for studying the East Nile Delta area. The ArcGIS 10.3 software and Google Earth were used for digitizing and locating the canals and water demands from the agriculture sector. The optimization model was then run, and the results compared the current case with local demands.

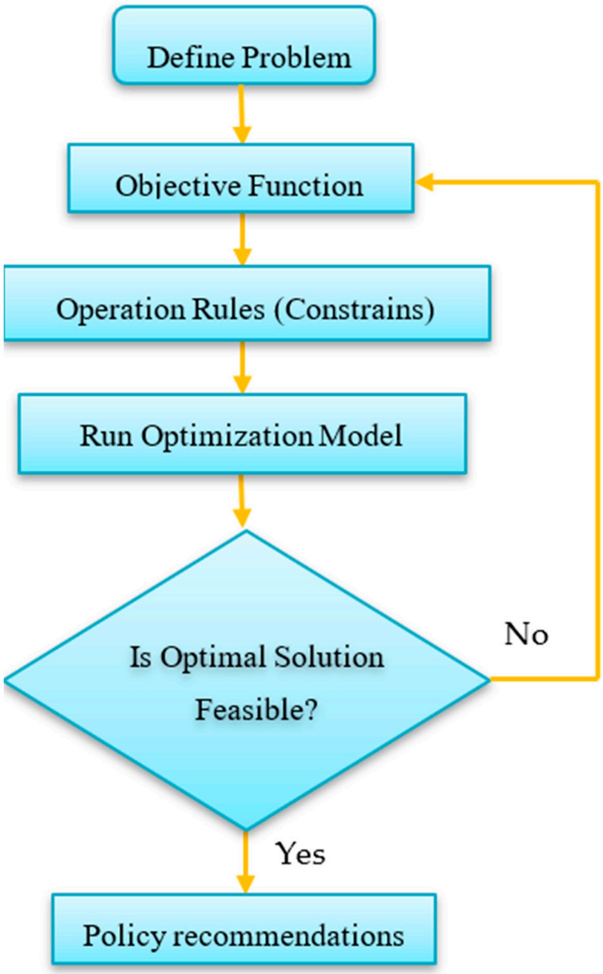

Figure 3. Simplified flowchart for optimization modelling.

If the gap between water supply and demands in all DEMs is minimized and local food requirements are met while water quality is affected positively, the model would be feasible. Finally, some scenarios are recommended to avoid future water deficits.

However, if the model did not minimize the water shortage, the model would not be considered to be feasible. In this case, the objective function and constraints must be changed in order to satisfy all DEMs and booster demands by redistributing the water across the total networks which are applicable according to all relevant authorities with water distribution and water irrigation under the Ministry of Water Resources and Irrigation (MWRI).

3.1. Model Setup

In this section, we will clarify the proposed mathematical model which includes objective functions, data sets, variables, and model constraints:

3.1.1. Sets and Indices

The water allocation model equations include several indices and sets. The basic elements of the model, such as periods and agricultural demands, are described here:

t: Time step (month)
dem: Agricultural demands,
sr: Surface water sources,
booster: Domestic demands,
gw: Groundwater sources
ru: Reuse water sources

3.1.2. Data Sets

Many data are required to specify the physical capacities of the elements of the water resources system associated with the Ismailia Canal. These include:

1. Supply characteristics

$SURFACE_{(sr,t)}$: Monthly surface water sources in the canal
$GW_{(gw,t)}$: Monthly groundwater from sources
$REUSE_{(ru,t)}$: Monthly reuse water sources

2. Demand characteristics

$I\_W_{(dem,t)}$: Monthly irrigation water demands
$D\_W_{(booster,t)}$: Monthly domestic water demands
$L\_S_{(sr,t)}$: Losses from canal

3.1.3. Variables

Several system variables are necessary to define the characteristics of the system, such as discharge from the canal node.

$R_{(sr,dem,t)}$: Discharge from the canal to agricultural demand area "dem" in time step "t"
$R_{(sr,\ booster,t)}$: Discharge from the canal to domestic demand site "booster" in time step "t"
$G_{(dem,t)}$: Groundwater pumped to agricultural demand area "dem" in time step "t"
$G_{(booster,t)}$: Groundwater pumped to domestic demand site "booster" in time step "t"
$RU_{(dem,t)}$: Reuse water pumped to agricultural demand area "dem" in time step "t"
$RS_{(booster,t)}$: The ratio of water supply to domestic demand site "booster" in time step "t"
$Sh_{(dem,t)}$: Water shortage between water supply and demands at agricultural demand area "dem" in time step "t".

3.1.4. Objective Functions

The optimization model was used to optimize a common basin's benefit from the water allocated to the rural, urban, and industrial sectors [38,39]. There is a strong public expectation in upstream areas to reduce the environmental water scarcity in the entire basin in order to optimize the water allocated to the downstream region.

In addition, the optimization model reflects the situation in which the transfer of water from the upstream area to the downstream region, which is typically underdeveloped, is minimized. This is because the generated surface water supplies are often used in upstream areas instead of being released downstream, reflecting the selfish actions of stakeholders who choose to use the limited water supplies to satisfy their own water needs rather than opening them to downstream stakeholders by choosing to maximize the minimum amount of water available to stakeholders at all times [40].

The main goal of the optimization model in this study is to reduce water deficits between supply and demand at all agricultural and domestic sites over all periods and demand sites.

$$\text{Minimize } X = \text{Min}\left[\sum Sh_{(dem,t)} + \sum Sh_{(booster,t)}\right] \tag{1}$$

3.1.5. Model Constraints

The model constraints are presented as follows:

1. Water balance at agricultural demand area "dem" in time step "t".

$$\sum Sh_{(dem,t)} + \sum R_{(dem,t)} + \sum G_{(dem,t)} + \sum RU_{(dem,t)} \geq \sum I\_W_{(dem,t)} \tag{2}$$

$$\sum Sh_{(dem,t)} \geq 0 \tag{3}$$

2. Water balance at domestic demand site "booster" in time step "t".

$$\sum Sh_{(booster,t)} + \sum R_{(booster,t)} + \sum G_{(booster,t)} + \sum Rain_{(dem,t)} \geq \sum D\_W_{(booster,t)} \quad (4)$$

$$\sum Sh_{(booster,t)} = 0 \quad (5)$$

3. Surface water source limit in time step "t".

$$\sum SURFACE_{(sr,t)} \geq \sum R_{(sr,dem,t)} + \sum R_{(sr,booster,t)} + \sum L\_S_{(sr,t)} \quad (6)$$

4. Ratio of water supply to domestic demand site.

$$\sum RS_{(booster,t)} = \frac{\sum R_{(sr,booster,t)} + \sum G_{(booster,t)}}{\sum D\_W_{(booster,t)}} \quad (7)$$

$$\text{For } \sum Sh_{(booster,t)} = 0, \text{ must } \sum RS_{(booster,t)} = 1 \quad (8)$$

5. Groundwater source limit.

$$\sum GW_{(gw,t)} \geq \sum G_{(booster,t)} + \sum G_{(dem,t)} \quad (9)$$

6. Reuse water source limit.

$$\sum REUSE_{(ru,t)} \geq \sum RU_{(dem,t)} \quad (10)$$

3.2. LINDO Software

The best software for solving problems with tens of thousands of constraints and hundreds of thousands of variables is LINDO, which is used all over the world. In Indonesia, LINDO was used to solve a model with hydrological constraints for optimal surface and groundwater activity for various crops [41]. In Andhra Pradesh, India, LINDO was used to solve an optimization model for determining the best groundwater and surface water allocation scheme. The results showed that the proposed canal command model was advantageous and practical, with surface water saved for 43,189 ha [42], In India, LINDO was also used to solve a model of hybrid energy systems to optimize costs and various types of resources [43].

3.3. Model Development

A mathematical optimization model is developed to optimize real data with theoretical data to solve the water deficit problem and prevent potential water shortages. To address any anticipated water shortage at any point in the study region, a water balance between water supplies Tables 1 and 2 and demands Tables 3–5 are established.

Table 1. Monthly discharge of surface water available in the study area (MWRI) [44].

Month	January	February	March	April	May	June	July	August	September	October	November	December	Sum
Total Monthly (Mm^3/Mon)	395.25	368.25	474.75	577.50	527.00	552.75	577.25	560.75	458.25	451.50	445.30	384.00	5772.55

Table 2. Available groundwater pumped in the study area [45,46].

No.	Name	Groundwater Pumping (m^3/day)
1	Al Khankah	14,428 Drinking
		17,208 Agriculture
2	Al-Sharkia	43,584 Agriculture
3	Ismailia	177,318 Agriculture
	Total	252,538

Table 3. Present domestic demand for the thirteen water boosters in the study area [47,48].

No	Booster Name	Present Demand (m^3/day)	No	Booster Name	Present Demand (m^3/day)
B1	Al Khankah	72,567	B8	Ismailia	310,000
B2	Al-Abassa	152,000	B9	Ain Ghadin	8000
B3	Al-Qurayn	25,920	B10	El Qantara West	34,000
B4	Al-Salhiya	22,464	B11	Abu Khalifa village	2000
B5	Tell El Kebir	68,000	B12	Fayed	119,000
B6	El Kasasin	14,000	B13	Sarabium village	16,000
B7	Abou Sweir	10,000			

Table 4. Name and area served of each agriculture demand node [33,36].

Demand Node	Area Name	Area Served (Feddan)	Demand Node		Area Served (Feddan)
Al-Qalyoubia governorate				Ismailia governorate	
D1	Shubra Al Khaymah	40,081	D9	Tell El Kebir	50,380
D2	Al Khusus & Al Khankah	21,286	D10	El Kasasin	37,009
Al-Sharkia governorate			D11	Abou Sweir	74,214
D3	Bilbies	72,920	D12	Ismailia	104,993
D4	Abu Hammad	54,850	D13	West-El Qantara	38,000
D5	Al Salhiya (1)	60,000	D14	Fayed	77,675
D6	Al Salhiya (2)	40,000		Port Said governorate	
D7	Al Salhiya (3)	18,371	D15	Port Said	85,000
D8	Al Qurayn	3877			
Total			778,656		

Table 5. Water Requirement for agricultural nodes (M.m^3/month) [45,49].

Dem & Booster	Month												Total
	January	February	March	April	May	June	July	August	September	October	November	December	
D1	21.19	19.74	25.43	30.94	28.24	29.64	30.94	30.04	24.56	24.19	23.85	20.57	309.33
D2	11.25	10.48	13.5	16.43	15	15.74	16.43	15.95	13.04	12.85	12.67	10.93	164.27
D3	44.59	41.53	53.51	65.1	59.44	62.37	65.1	63.21	51.69	50.91	50.19	43.29	650.93
D4	33.54	31.24	40.25	48.97	44.71	46.91	48.97	47.55	38.88	38.29	37.75	32.56	489.62
D5	36.69	34.18	44.03	53.57	48.91	51.32	53.57	52.01	42.53	41.89	41.3	35.62	535.62
D6	24.46	22.78	29.35	35.71	32.6	34.21	35.71	34.67	28.35	27.93	27.53	23.75	357.05
D7	11.23	10.46	13.48	16.4	14.97	15.71	16.4	15.93	13.02	12.83	12.65	10.91	163.99
D8	2.37	2.21	2.85	3.46	3.16	3.32	3.46	3.36	2.75	2.71	2.67	2.3	34.62
D9	26.8	24.96	32.16	39.12	35.72	37.48	39.12	37.98	31.06	30.59	30.16	26.01	391.16
D10	19.68	18.33	23.62	28.74	26.24	27.53	28.74	27.9	22.82	22.47	22.16	19.11	287.34
D11	39.47	36.77	47.37	57.63	52.61	55.21	57.63	55.95	45.76	45.06	44.43	38.32	576.21
D12	55.84	52.01	67.01	81.53	74.43	78.1	81.53	79.16	64.73	63.75	62.86	54.21	815.16
D13	20.21	18.83	24.25	29.51	26.94	28.27	29.51	28.65	23.43	23.07	22.75	19.62	295.04
D14	41.31	38.48	49.58	60.31	55.07	57.78	60.31	58.56	47.89	47.2	46.5	40.11	603.1
D15	39.02	36.35	46.83	56.97	52.01	54.58	56.97	55.32	45.23	44.55	43.92	37.88	569.63
Total	427.65	398.35	513.22	624.39	570.05	598.17	624.39	606.24	495.74	488.29	481.39	415.19	6243.07

As shown in Figure 4, the East Nile Delta area includes main canals as resources and nodes as demands and can be explained as the availability of water and the demand for water as the following:

- Water resources: Ismailia Canal with a total water discharge is about 5772.55 BMC/year [44], groundwater is about 0.25 mm^3/day, reuse drainage water about 34.44 m^3/s in Al-Sharkia and about 1.54 m^3/s in Ismailia governorate [45] and rainfall is between (25–50) mm/year [37].
- Water demands: agriculture land (15 demand nodes) and Al-Salhiya is the largest agricultural region in the study area, with 118,371 Feddan, so the area was divided into three demand nodes at the end of the Salhia canal network (D5, D6, D7), drinking purifications (13 boosters) and seepage is about 21.06% of the total discharge [50].

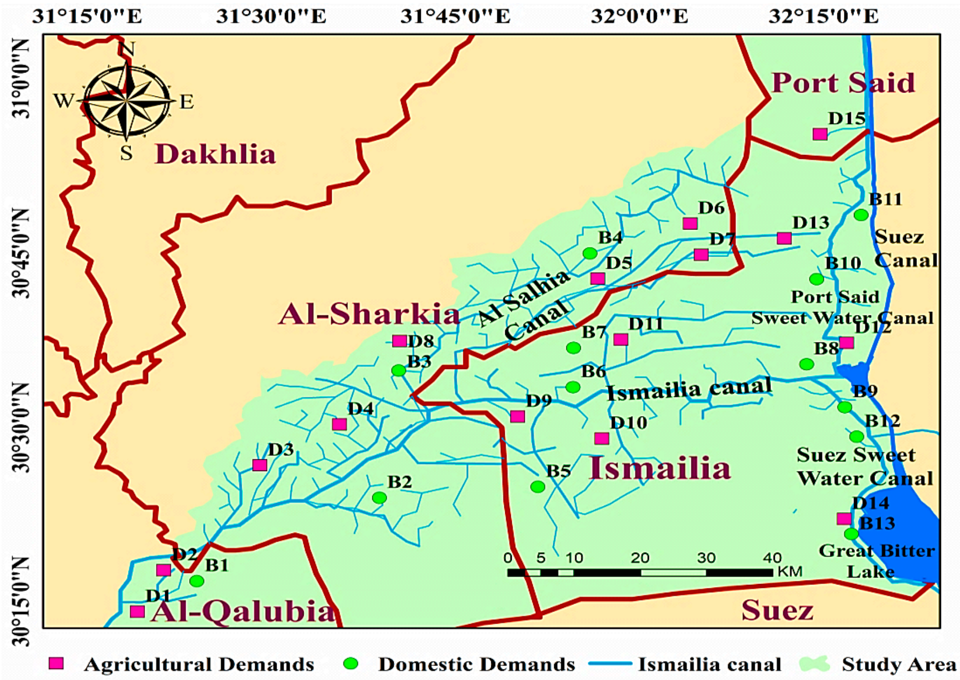

Figure 4. Ismailia canal and demand nodes in the study area.

Table 6 shows that the total water shortage in the study region is 1997.86 Mm^3/year, which is dispersed over all months with varying values, implying that more than 43.84 percent ($\frac{1997.86}{4556.5} \times 100$) of the study region's water resources are in a deficit because groundwater, drainage, and wastewater reuse are not used. However, in the optimization model, we consider groundwater and drainage reuse, which results in differing water deficit values.

Table 6. Theoretical total water shortage in the study area (MCM).

Month	January	February	March	April	May	June	July	August	September	October	November	December	Total
Total water use rate for DEMs (Mm^3/month)	427.65	398.35	513.22	624.39	570.05	598.17	624.39	606.24	495.74	488.29	481.39	415.19	6243.07
Total water use for boosters (Mm^3/month)	25.97	25.97	25.97	25.97	25.97	25.97	25.97	25.97	25.97	25.97	25.97	25.97	311.64
Losses (Mm^3/month)	83.36	155.00	76.39	121.79	84.794	116.57	121.74	118.26	96.64	68.131	71.65	81.00	1215.70
Total discharge (Mm^3/month)	395.25	368.25	474.75	577.50	527.00	552.75	577.25	560.75	458.25	451.50	445.30	384.00	5772.55
Total shortage in the study area (Mm^3/month)	−141.73	−211.07	−140.83	−194.65	−153.814	−187.96	−194.85	−189.72	−160.1	−130.891	−133.71	−138.16	−1997.86

4. Results and Discussion

The model analysis was first run with a focus on the Ismailia Canal Lining's effect, surface water's impact, and groundwater's impact.

4.1. Base Case

In this study, a mathematical optimization model was used in the East Delta to close the gap between water supply and demand by feeding the model surface water and groundwater and reusing the irrigation water distributed on 15 demand nodes and 13 boosters. The importance of prioritizing water boosters comes first, followed by prioritizing other demand nodes. The initial condition showed that there is a shortage in the demand nodes (D5, D6, D7, D12, D13, D14, D15) which are located in Al-Salhiya, Ismailia, El Qantara West, Fayed, and Port Said, as in Figure 5, Table 7 and Figure 6 the locations of deficit agricultural areas are shown. The unmet demand in the study region is approximately 789.81 Mm^3/year, or about 12.05 percent of the agricultural demand for water. Figure 5 depicts the greatest water shortage in Al-Salhiya as a result of illegal farming practices that have resulted in a water shortage in the northern Al Sharkia area. This water shortage is addressed by mixing water in drains with canals, increasing drainage and wastewater reuse after treatment in order to mitigate runoff, and increasing the amount of water delivered to the study area from the Nile River.

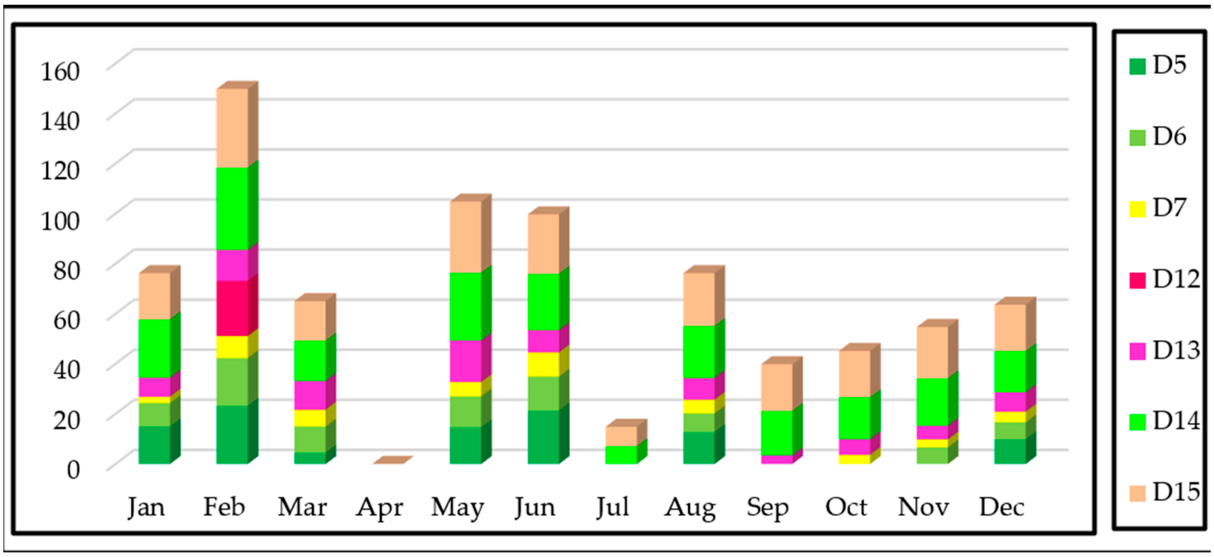

Figure 5. Monthly unmet demand for the current conditions for all demand nodes (MCM).

The total surface water delivered to the study area is 4577.26 Mm^3/year only, or about 78.3% of the total discharge, as shown in Table 8. This is due to seepage from the Ismailia Canal, which accounts for about 21.06% of the total discharge, or approximately 1195.29 Mm^3/year [50]. The lowest water was supplied in the month of February due to winter closures, as can be seen in Figure 7.

The lowest amounts of surface water delivered to the study area occurred at D5, D6, and D7 (located in Al-Salhiya at the end of the irrigation network of the Al-Salhiya Canal), and D15 (located in Port Said at the end of Port Said Sweet Water Canal—two branches of Ismailia canal). The percentage of water demands are shown in Table 8. The reasons for the low level of water supplied at the end of Al-Salhiya Canal and Port Said Sweet Water Canal are due to the bad behavior of some farmers who engage in detrimental activities, such as allowing rubbish to fall on canals, dumping waste, indiscriminating water withdrawal, and discharging sewage into the irrigation network.

Table 7. Shortage water in case study (MCM).

Dem & Booster	Monthly Unmet Demand (MCM)												Total
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	
D1–D4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D5	14.89	23.16	4.37	0.00	14.57	21.24	0.00	12.65	0.00	0.00	0.00	9.79	100.67
D6	9.43	19.12	10.58	0.00	12.43	13.64	0.00	7.52	0.00	0.00	6.62	6.81	86.15
D7	2.55	8.82	6.7	0.00	5.7	9.68	0.00	5.49	0.00	3.65	3.2	4.29	50.08
D8–D11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D12	0.00	21.94	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	21.94
D13	7.55	12.43	11.49	0.00	16.62	8.83	0.00	8.67	3.47	6.26	5.43	7.74	88.49
D14	23.33	32.83	16.08	0.00	26.98	22.52	7.06	20.73	17.64	16.69	18.89	16.43	219.18
D15	18.45	31.48	15.83	0.00	28.49	23.78	7.78	21.14	18.73	18.51	20.56	18.55	223.3
B1–B13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sum	76.2	149.78	65.05	0.00	104.79	99.69	14.84	76.2	39.84	45.11	54.7	63.61	789.81

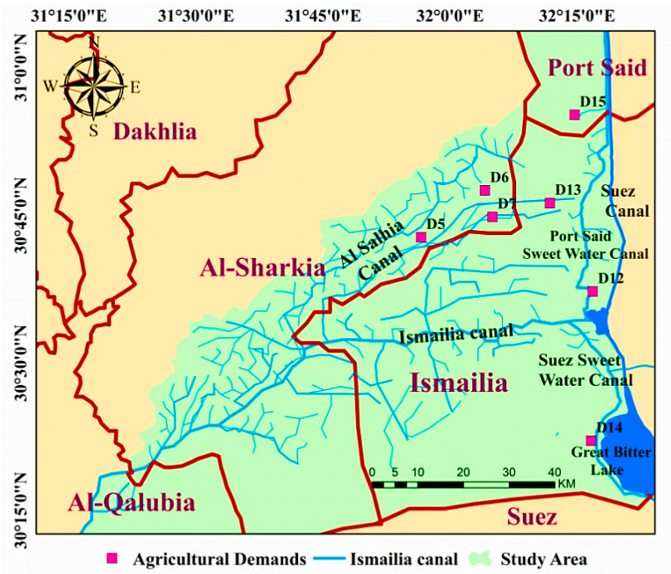

Figure 6. Location of agricultural areas that suffer from water deficits.

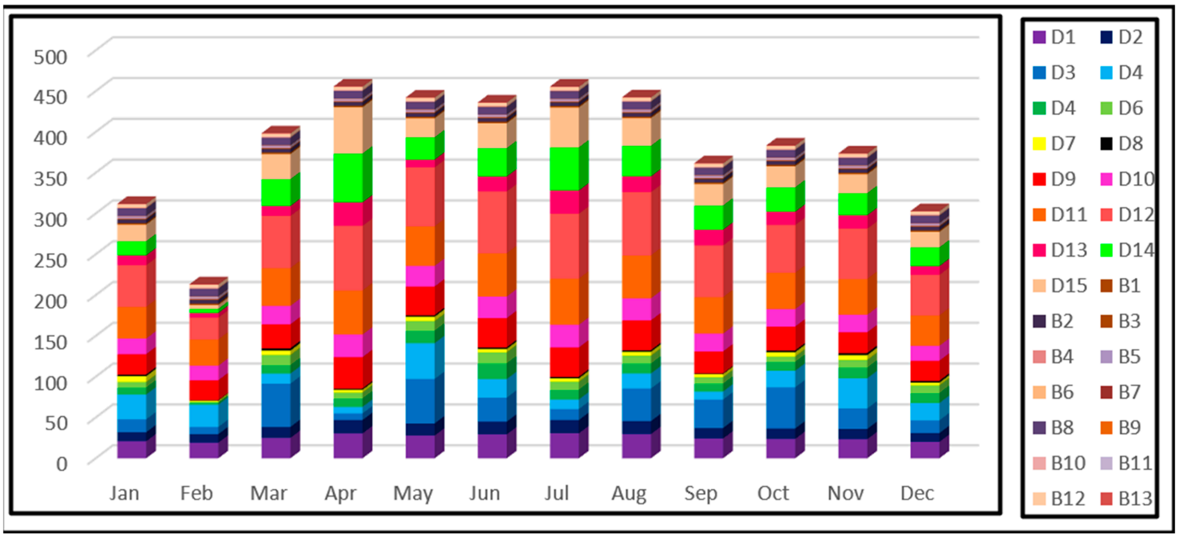

Figure 7. Supply delivered to study area (MCM).

Table 8. Monthly water distribution in the study area (MCM).

Dem & Booster	Monthly Delivered Water (MCM)												Total
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
D1	20.96	19.24	25.11	30.6	27.93	29.42	30.7	29.76	24.36	23.85	23.51	20.24	305.68
D2	10.96	10.34	13.29	16.25	14.76	15.46	16.19	15.78	12.74	12.66	12.53	10.67	161.63
D3	15.77	8.77	53.1	8.1	54.52	29.41	13.43	39.93	34.88	50.48	24.98	15.57	348.94
D4	30.38	27.31	12.25	7.97	43.79	22.67	11.66	18.41	9.78	20.19	37.01	21.19	262.61
D5	8.24	1.67	10.03	9.97	14.94	18.94	11.61	11.73	9.22	10.52	12.67	11.87	131.41
D6	7.33	2.04	12.96	7.71	12.24	14.01	10.27	10.22	8.41	7.11	9.94	9.91	112.15
D7	6.98	1.22	5.28	3.4	5.3	4.08	4.11	4.74	3.78	5.25	5.78	3.22	53.14
D8	2	0.68	2.85	1.46	1.91	1.91	1.91	1.91	0.89	2.01	2.67	2.3	22.5
D9	24.94	24.3	29.21	38.41	35.05	35.79	35.82	36.48	26.83	29.31	25.25	24.52	365.91
D10	19.31	17.96	22.77	27.82	25.41	26.59	27.91	27.17	21.95	21.56	21.63	18.44	278.52
D11	38.47	31.83	46.01	53.67	48.2	52.68	56.29	52.26	44.43	44.12	43.63	36.92	548.51
D12	51.43	27.16	64.31	79.69	72.62	76.23	79.95	77.93	63.78	59.02	62	50.05	764.17
D13	11.89	5.53	12	28.56	9.29	18.13	28.26	19.09	19.04	16.06	16.25	10.59	194.69
D14	17.14	4.89	32.67	59.59	27.22	34.51	52.64	37.31	29.47	29.67	26.87	22.71	374.69
D15	20.57	4.87	31	56.97	23.52	30.8	49.19	34.18	26.5	26.04	23.36	19.33	346.33
B1	1.78	1.68	1.76	1.78	1.75	1.79	1.81	1.83	1.79	1.76	1.81	1.72	21.26
B2	4.62	4.62	4.62	4.62	4.62	4.62	4.62	4.62	4.62	4.62	4.62	4.62	55.44
B3	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	9.48
B4	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	8.16
B5	2.07	2.07	2.07	2.07	2.07	2.07	2.07	2.07	2.07	2.07	2.07	2.07	24.84
B6	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	5.16
B7	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	3.6
B8	9.43	9.43	9.43	9.43	9.43	9.43	9.43	9.43	9.43	9.43	9.43	9.43	113.16
B9	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	2.88
B10	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	12.36
B11	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.72
B12	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62	43.44
B13	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	5.88
Sum	311.9	213.25	398.36	455.71	442.21	436.18	455.51	442.5	361.61	383.37	373.65	303.01	4577.26

The study regions of the Al-Qalyoubia governorate rely on groundwater as a source of drinking water and for irrigation water and daily use, but the study regions of the Al-Sharkia and Ismailia governorates rely on groundwater as irrigation water only, as shown in Table 3.

Figure 8 shows the contour map of the Quaternary aquifers at the Nile Delta. It represents the water table in shallow and deep wells and hydrogeological parameters (hydraulic conductivity, storativity, transmissivity, and specific yield).

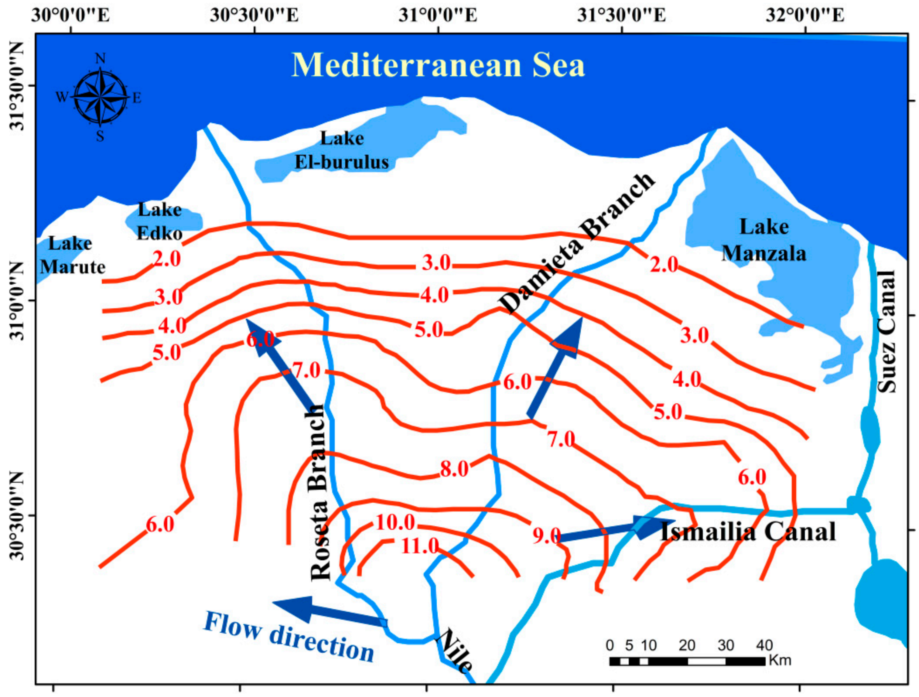

Figure 8. Contour map of the Quaternary aquifers at the Nile Delta [51].

Running the model revealed that the amount of groundwater pumped to the study area is approximately 92.05 Mm^3/year, as shown in Table 9. Figures 9 and 10 show that the direction of groundwater flow is to the north, heading towards the cities of Shubra Al Khaymah, Al Khusus, Al Khankah, Bilbies, Abu Hammad, and Al Salhiya and to the east towards the cities of Tell El Kebir, El Kasasin, Abou Sweir, Ismailia, West-El Qantara and Fayed. The largest quantity groundwater was pumped to the area in the month of February (during the time of the winter closure). Abu Hammad is the center which benefits the most from groundwater in Al-Sharkia governorate, because it contains about 34 wells [40] and most of the groundwater is pumped to the Ismailia governorate, which contains about 1278 wells and 29553 feddan benefit from [34] (see Figure 9).

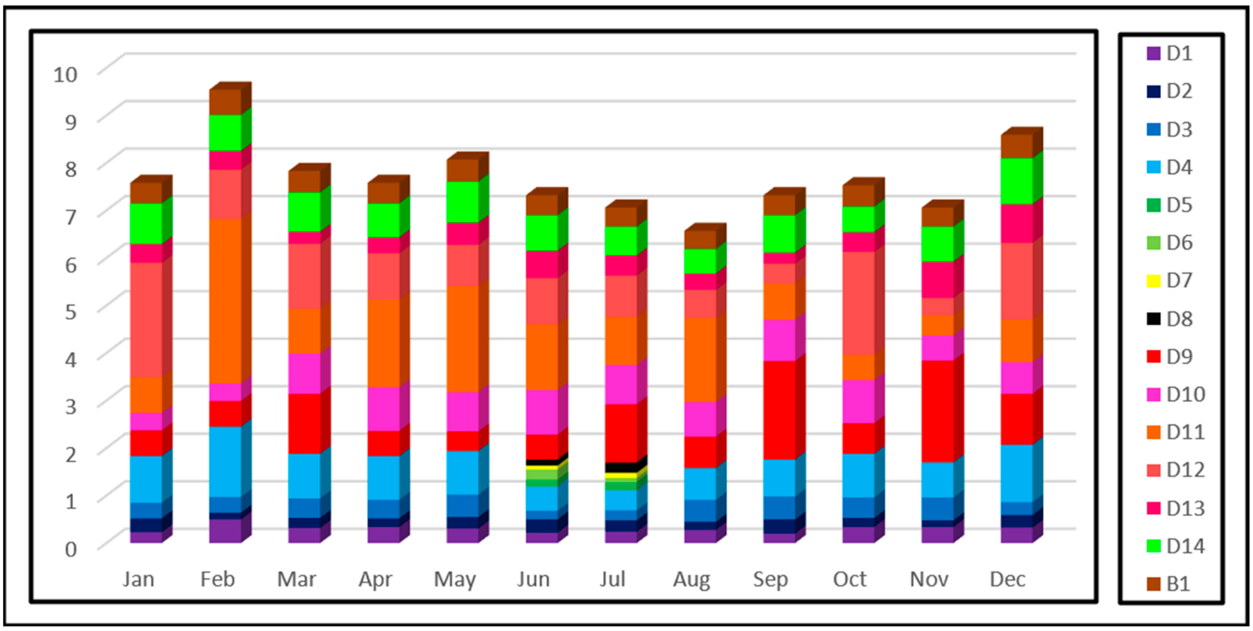

Figure 9. Groundwater pumped to study area (MCM).

Table 9. Monthly groundwater pumped to study area (MCM).

Dem & Booster	Monthly Groundwater Pumped (MCM)												Total
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
D1	0.23	0.5	0.32	0.34	0.31	0.22	0.24	0.28	0.2	0.34	0.34	0.33	3.65
D2	0.29	0.14	0.21	0.18	0.24	0.28	0.24	0.17	0.3	0.19	0.14	0.26	2.64
D3	0.33	0.33	0.41	0.39	0.47	0.18	0.21	0.46	0.48	0.43	0.48	0.27	4.44
D4	0.98	1.48	0.94	0.92	0.92	0.51	0.42	0.67	0.78	0.92	0.74	1.21	10.49
D5	0.00	0.00	0.00	0.00	0.00	0.14	0.17	0.00	0.00	0.00	0.00	0.00	0.31
D6	0.00	0.00	0.00	0.00	0.00	0.22	0.09	0.00	0.00	0.00	0.00	0.00	0.31
D7	0.00	0.00	0.00	0.00	0.00	0.08	0.11	0.00	0.00	0.00	0.00	0.00	0.19
D8	0.00	0.00	0.00	0.00	0.00	0.13	0.22	0.00	0.00	0.00	0.00	0.00	0.35
D9	0.54	0.54	1.26	0.53	0.41	0.52	1.22	0.66	2.07	0.64	2.14	1.07	11.6
D10	0.37	0.37	0.85	0.92	0.83	0.94	0.83	0.73	0.87	0.91	0.53	0.67	8.82
D11	0.75	3.46	0.94	1.84	2.23	1.38	1.01	1.77	0.76	0.53	0.42	0.89	15.98
D12	2.41	1.04	1.37	0.98	0.87	0.98	0.87	0.59	0.42	2.17	0.37	1.62	13.69
D13	0.39	0.39	0.25	0.33	0.46	0.57	0.42	0.34	0.23	0.41	0.76	0.81	5.36
D14	0.86	0.76	0.83	0.72	0.87	0.75	0.61	0.52	0.79	0.54	0.74	0.97	8.96
D15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B1	0.43	0.53	0.45	0.43	0.46	0.42	0.4	0.38	0.42	0.45	0.4	0.49	5.26
B2–B13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sum	7.58	9.54	7.83	7.58	8.07	7.32	7.06	6.57	7.32	7.53	7.06	8.59	92.05

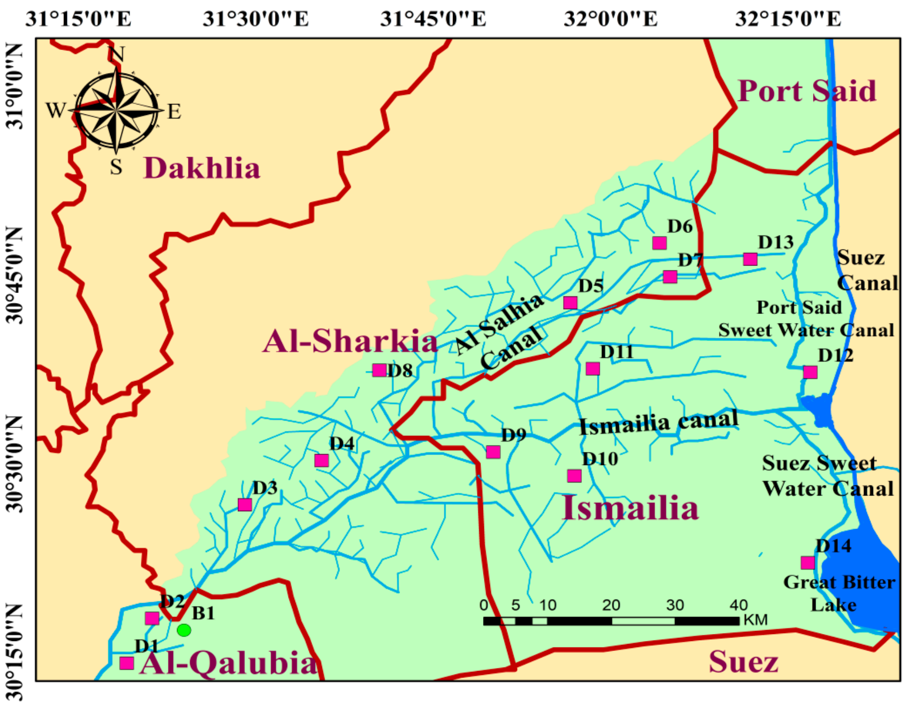

Figure 10. Location of DEMs and Boosters which groundwater pumped to them.

Drainage water reuse is considered to be the most unconventional water resource in study regions of Ismailia and Al-Sharkia. The reuse of agricultural drainage water is the second most used water resource of the Ismailia and Sharkia governorates, with

93 water mixing stations available in the Sharkia governorate with 1.4 BCM, and serving approximately 140,700 feddan [33]. The length of the covered drains in the Ismailia governorate reached 120 km in 2017, and was comprised of 21 drains serving of approximately 47,000 feddans. On the other hand, the open-drain lengths in the Ismailia governorate reached 204 km in 2017 with served of about 58,000 feddan [34].

Running the model showed that, in the study area, the amount of reused drainage water that arrived at the agricultural area was approximately 1095.37 Mm^3/year, as shown in Table 10. The center which benefited the most from the reused drainage water was Al Salhiya, which is situated at the end of the Al Salhiya Canal (a branch of the Ismailia Canal), as shown in Figure 11.

Table 10. Monthly reuse water distribution in the study area (MCM).

DEM & Booster	Monthly Reuse Water Distribution (MCM)												Total
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
D1-D2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D3	8.57	32.43	0.00	56.61	4.45	32.78	51.46	22.82	16.33	0.00	24.73	27.45	277.63
D4	22.49	2.65	27.06	40.08	0	23.73	36.89	28.47	28.32	17.18	0.00	10.16	237.03
D5	13.56	9.35	29.63	43.6	19.4	11	41.79	27.63	33.31	31.37	28.63	13.96	303.23
D6	7.43	1.52	5.81	28	7.93	6.34	25.35	16.93	19.94	20.82	10.76	7.03	157.86
D7	1.7	0.42	1.5	13	3.97	1.87	12.18	5.7	9.24	3.92	3.67	3.4	60.57
D8	0.25	1.53	0.00	2	1.25	1.28	1.33	1.45	1.86	0.7	0.00	0.00	11.65
D9	0.22	0.12	1.69	0.35	0.26	1.17	2.08	0.84	2.16	0.64	2.77	0.42	12.72
D10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D11	1.35	1.48	0.42	2.12	2.18	1.15	0.33	1.92	0.57	0.41	0.38	0.51	12.82
D12	2.00	1.87	1.33	0.86	0.94	0.89	0.71	0.64	0.53	2.56	0.49	2.54	15.36
D13	0.38	0.48	0.51	0.62	0.57	0.74	0.83	0.55	0.69	0.34	0.31	0.48	6.5
D14–D15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B1–B13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sum	57.95	51.85	67.95	187.24	40.95	80.95	172.95	106.95	112.95	77.94	71.74	65.95	1095.37

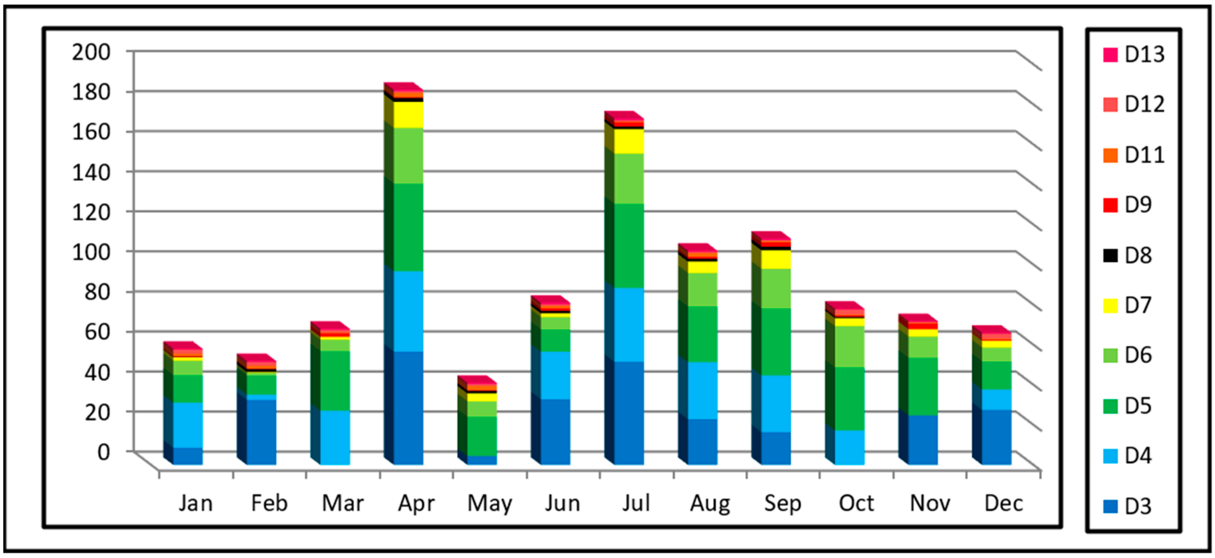

Figure 11. Reused drainage water in agriculture area (MCM).

Figure 12 shows the location of the DEMs which benefit from reused drainage water, as drain water is pumping into the Ismailia Canal, resulting in mixed water.

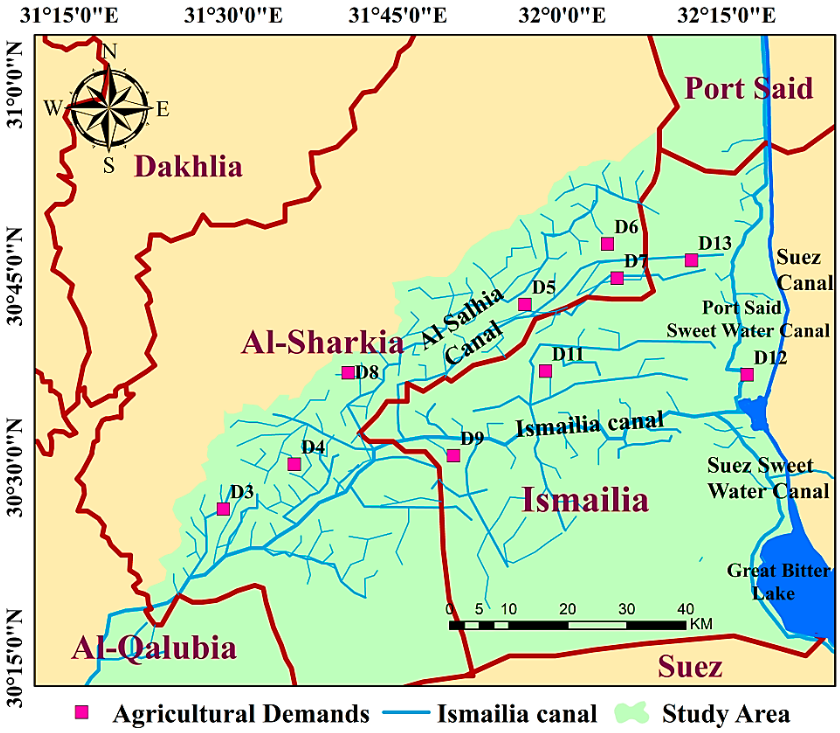

Figure 12. Location of DEMs which benefit from reused drainage water.

4.2. The Impact of Lining the Ismailia Canal

A length of 56 km of the Ismailia Canal was found to be responsible for 21.06% of the total discharge of water losses. Therefore, the Ismailia Canal was considered to be the worst case in terms of seepage problems and erosion. The Ministry of Water Resources and Irrigation (MWRI) implemented preliminary technical studies in order to locate the most critical sections along the Ismailia Canal which have the maximum seepage losses [50].

Geosynthetic polymeric materials were used for geotechnical problems in canals, such as seepage losses, with cost-effectiveness, low environmental impact, and quantifiable performance. Lining samples (100 m^2 in area) by standard income were executed in 2016, whereby four sections of lining with a total length of 61 km were defined [50], as shown in Figure 13.

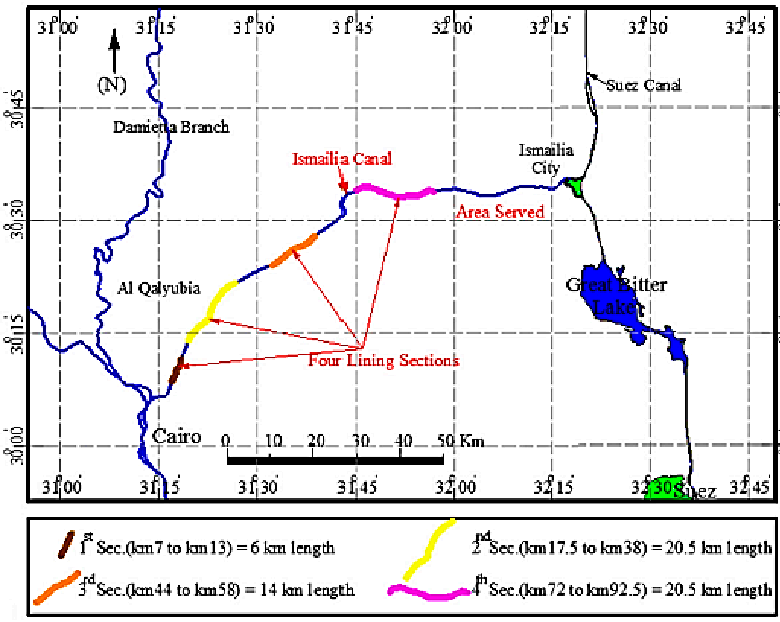

Figure 13. Ismailia Canal from its inlet at Cairo until it reaches the Ismailia governorate showing the four lining sections and their length [52].

The lining project had been implemented in three stages [23,35]. In the first stage, the German Hochster company used impermeable geotextile techniques in December 2014. In the second stage, the Italian Carpi company used impermeable geomembrane techniques with concrete fill to fix the membrane in February 2016. The third stage was implemented by the German Knawe company using Geotextile by stone in March 2016. After lining four sections of the Ismailia Canal, seepage decreased from 21.06% to 7.5% [50,53–55] Recently, Eltarabily et al. [50] used a simulation model for lining the optimum three sections, comprising a length of 57 km, which decreased the seepage from 21.06% to 10.16%.

We adopted these two cases (lining three reaches with a total length of 57 km and lining four reaches with a total length of 61 km) to run scenarios for the current case study area, as follows:

4.2.1. Lining Three Reaches with a Total Length of 57 km

Both the assumptions and data in this scenario are the same as in the base case, but the seepage rate is reduced from 21.06 percent to 10.16 percent of the total Ismailia Canal discharge [50]. As shown in Table 11, Figure 14, the unmet demand is 291.99 MCM/year at D5, D6, D7, D13, D14, and D15, which reflect Al-Salhiya, El Qantara West, Fayed, and Port Said.

4.2.2. Lining Four Reaches with a Total Length of 61 Km

In this scenario, all assumptions and data in the base case are the same, but the seepage rate is decreased from 21.06% to 7.5% [50,53–55]. Note that unmet demand is 173.9 MCM/year at D7, D13, D14, and D15, which represent Al-Salhiya, El Qantara West, Fayed, and Port Said, as shown in Table 12, Figure 15. This represents the largest cultivated area at the end of the network.

It means that reducing seepage is one of the most effective ways to minimize the study area's water shortage.

4.3. The Impact of Surface Water

Both the base case's data and assumptions are the same in this case, however, the surface water from the Ismailia Canal is changed and the impact on the water scarcity value is studied, as follows:

Table 11. Monthly unmet demands (MCM) of lining three sections.

Dem & Booster	Monthly Unmet Demand (MCM)												Total
	January	February	March	April	May	June	July	August	September	October	November	December	
D1–D4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D5	0.00	5.33	0.00	0.00	4.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.66
D6	0.00	6.57	0.00	0.00	5.87	0.00	0.00	0.00	0.00	0.00	0.00	0.00	12.44
D7	0.00	6.81	0.00	0.00	5.92	0.00	0.00	0.00	0.00	0.00	0.00	0.00	12.73
D8–D12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D13	5.65	7.43	4.43	0.00	7.62	3.89	0.00	0.00	0.00	0.00	3.43	4.74	37.19
D14	11.57	22.83	9.78	0.00	17.98	19.62	0.00	7.65	0.00	2.59	6.58	8.43	107.03
D15	15.78	20.48	11.25	0.00	19.13	15.78	0.00	7.27	0.00	7.22	7.56	8.47	112.94
B1–B13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sum	33.00	69.45	25.46	0.00	60.85	39.29	0.00	14.92	0.00	9.81	17.57	21.64	291.99

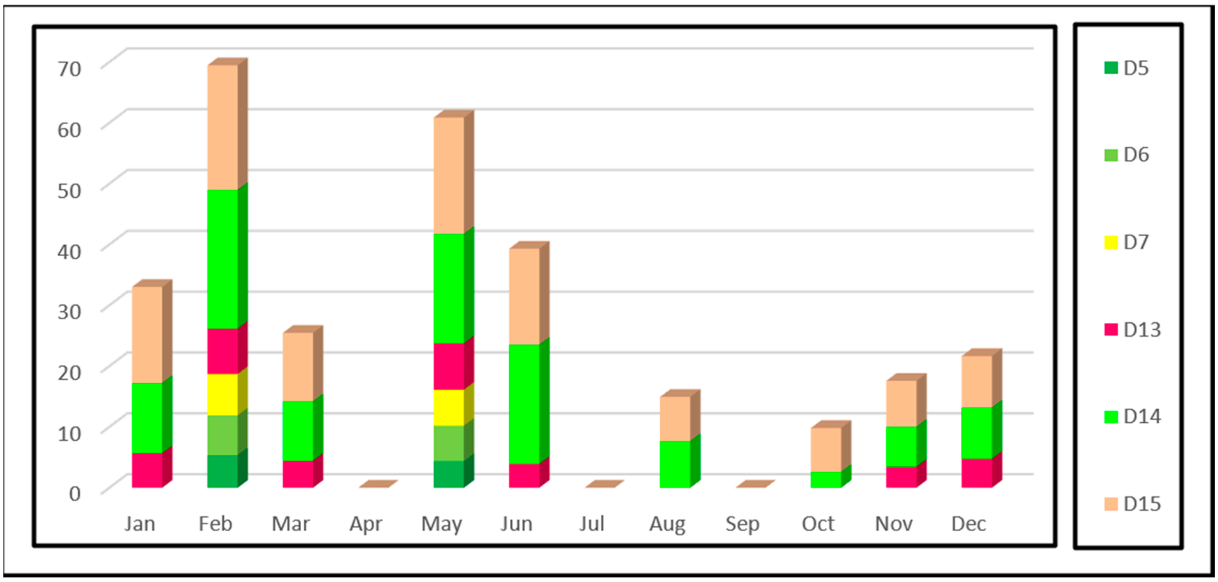

Figure 14. Monthly unmet demand (MCM) of lining three sections.

Table 12. Monthly unmet demands (MCM) of lining four sections.

DEM & Booster	Monthly Unmet Demand (MCM)												Total
	January	Feberuary	March	April	May	June	July	August	September	October	November	December	
D1–D6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.79
D7	0.00	3.79	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.79
D8–D12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D13	3.14	6.89	2.79	0.00	6.92	3.53	0.00	0.00	0.00	0.00	0.00	2.45	25.72
D14	8.87	19.76	6.28	0.00	16.36	9.31	0.00	0.00	0.00	0.00	3.78	3.58	67.94
D15	10.51	17.52	6.78	0.00	18.43	11.78	0.00	0.00	0.00	1.23	4.78	5.42	76.45
B1–B13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sum	22.52	47.96	15.85	0.00	41.71	24.62	0.00	0.00	0.00	1.23	8.56	11.45	173.9

4.3.1. Increased Water Surface of the Ismailia Canal by 15%

Both the base case's data and assumptions are the same in this case. However, due to increased surface water from the neighboring governorate; decreased seepage achieved by lining the Ismailia Canal; water quality considerations; and, forcing farmers to grow crops which consume less water and providing alternative crops with a good gross revenue return to farmers, the surface water for the study area of the Ismailia Canal is increased by

15%. The results of this case are represented in Figure 16 and Table 13. The unmet demand fell from 789.81 to 159.8 MCM/year and the water deficits were distributed on D5, D6, D7, D13, D14, and D15, which represent Al-Salhiya, El Qantara West, Fayed, and Port Said.

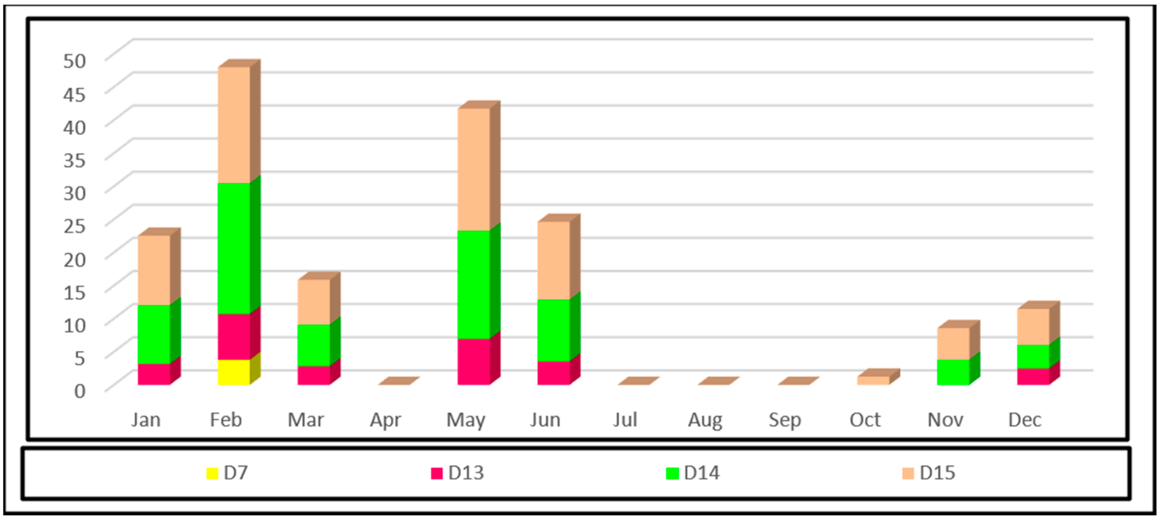

Figure 15. Monthly unmet demand (MCM) of lining four sections.

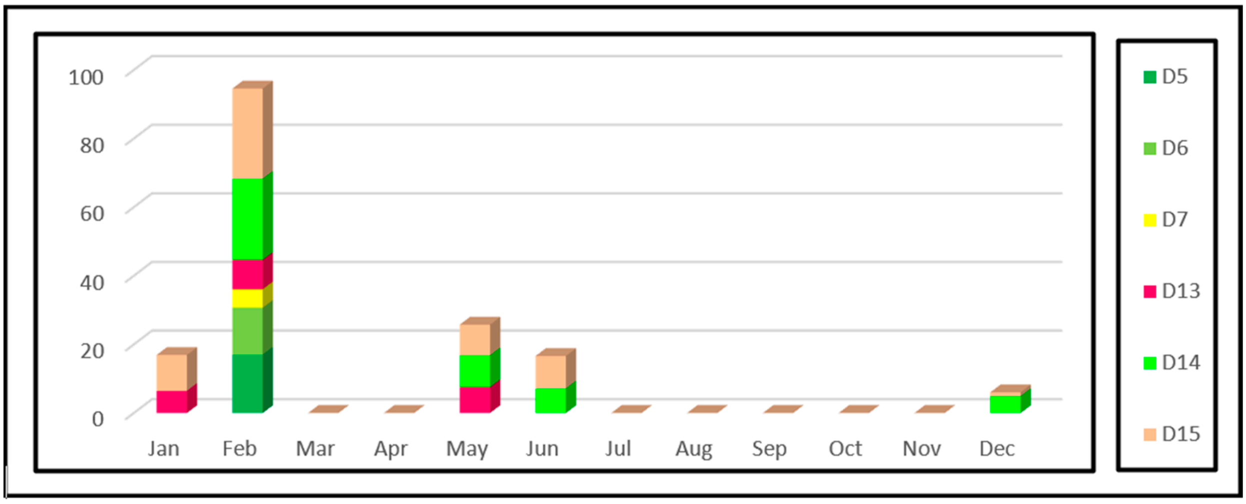

Figure 16. Monthly unmet demands (MCM) resulting from increase in Ismailia Canal head flow by 15%.

Table 13. Monthly unmet demands (MCM) resulting from increase in Ismailia Canal head flow by 15%.

DEM & Booster	Monthly Unmet Demand (MCM)												Total
	January	Feberuary	March	April	May	June	July	August	September	October	November	December	
D1–D4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D5	0.00	16.94	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	16.94
D6	0.00	13.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	13.74
D7	0.00	5.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.38
D8–D12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
D13	6.47	8.57	0.00	0.00	7.52	0.00	0.00	0.00	0.00	0.00	0.00	0.00	22.56
D14	0.00	23.64	0.00	0.00	9.28	7.13	0.00	0.00	0.00	0.00	0.00	4.89	44.94
D15	10.44	26.27	0.00	0.00	8.94	9.47	0.00	0.00	0.00	0.00	0.00	1.12	56.24
B1–B13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sum	16.91	94.54	0.00	0.00	25.74	16.6	0.00	0.00	0.00	0.00	0.00	6.01	159.8

4.3.2. Decrease in Ismailia Canal Head Flow by 10%

All of the assumptions and data in the base case are the same in this operation scenario, but due to hydrological and political alterations, the Ismailia Canal head flow is reduced by 10%.

The outcomes of this case are shown in Figure 17 and Table 14. The unmet demand rises from 789.81 MCM/year to 1199.16 MCM/year, and the water deficits are distributed across eight demand nodes (D5, D6, D7, D11, D12, D13, D14, and D15), which perform in Al-Salhiya, Abou Sweir, Ismailia, El Qantara West, Fayed, and Port Said.

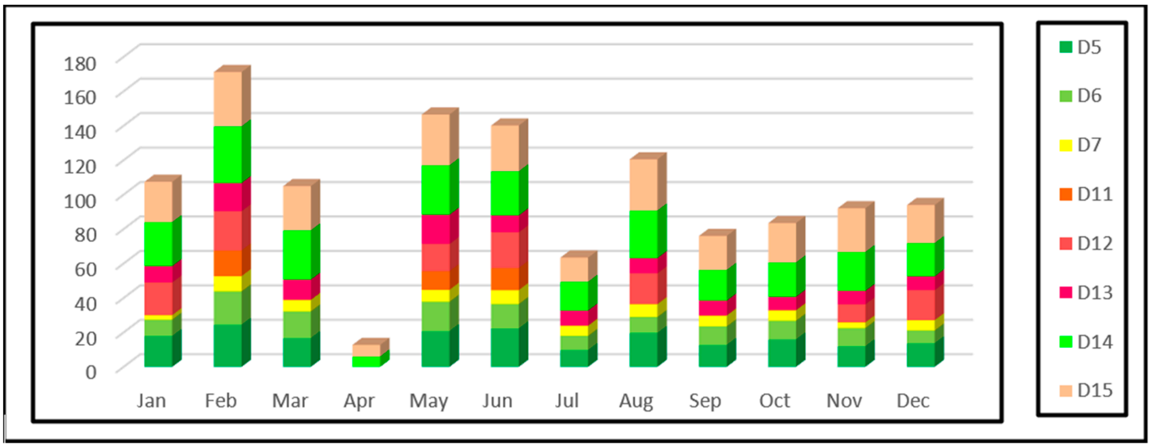

Figure 17. Monthly unmet demands (MCM) resulting from decrease in the Ismailia Canal head flow by 10%.

Table 14. Monthly unmet demands (MCM) resulting from decrease in the Ismailia Canal head flow by 10%.

DEM & Booster	Monthly Unmet Demand (MCM)												Total
	January	February	March	April	May	June	July	August	September	October	November	December	
D1–D4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D5	17.72	24.24	16.53	0.00	20.57	22.11	9.58	19.53	12.56	15.75	11.81	13.56	183.96
D6	9.70	19.56	15.68	0.00	17.23	14.36	8.43	9.42	10.93	11.03	10.73	7.56	134.63
D7	2.56	8.82	6.65	0.00	6.84	8.03	5.86	7.41	6.29	6.07	3.23	5.94	67.7
D8–D10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D11	0.00	14.83	0.00	0.00	10.78	12.73	0.00	0.00	0.00	0.00	0.00	0.00	38.34
D12	19.06	22.94	0.00	0.00	15.94	20.92	0.00	17.98	0.00	0.00	10.57	17.53	124.94
D13	9.41	16.28	11.74	0.00	16.92	9.73	8.79	8.78	8.63	7.81	7.71	7.89	113.69
D14	25.51	32.85	28.56	5.95	28.64	25.54	16.62	27.57	17.76	19.87	22.54	19.3	264.76
D15	23.43	31.58	25.72	6.74	29.57	26.64	14.11	29.76	19.83	22.92	25.45	22.13	271.14
B1–B13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sum	107.39	171.1	104.88	12.69	146.49	140.06	63.39	120.45	76.00	83.45	92.04	93.91	1199.16

In this scenario, soil salinity will be increased which reduces productivity and crop quality in the agricultural land surrounding the Ismailia canal. As such, any new strategy of water resource management or any political changes, like constructing the Grand Ethiopian Renaissance Dam (GERD), may harm water resources across the whole country in general, and particularly in the Delta.

4.3.3. Use Surface-Water Only from the Ismailia Canal

All of the assumptions and data in this scenario are based on only using surface water from the Ismailia Canal, with no use of groundwater or reuse of drainage water. The results of this case are represented in Figure 18 and Table 15. The unmet demand fell from 789.81 to 1977.45 MCM/year and the water deficits were distributed across 10 demand nodes (D5, D6, D7, D9, D10, D11, D12, D13, D14, and D15), which perform in Al-Salhiya, Tell El Kebir, El Kasasin, Abou Sweir, Ismailia, El Qantara West, Fayed, and Port Said.

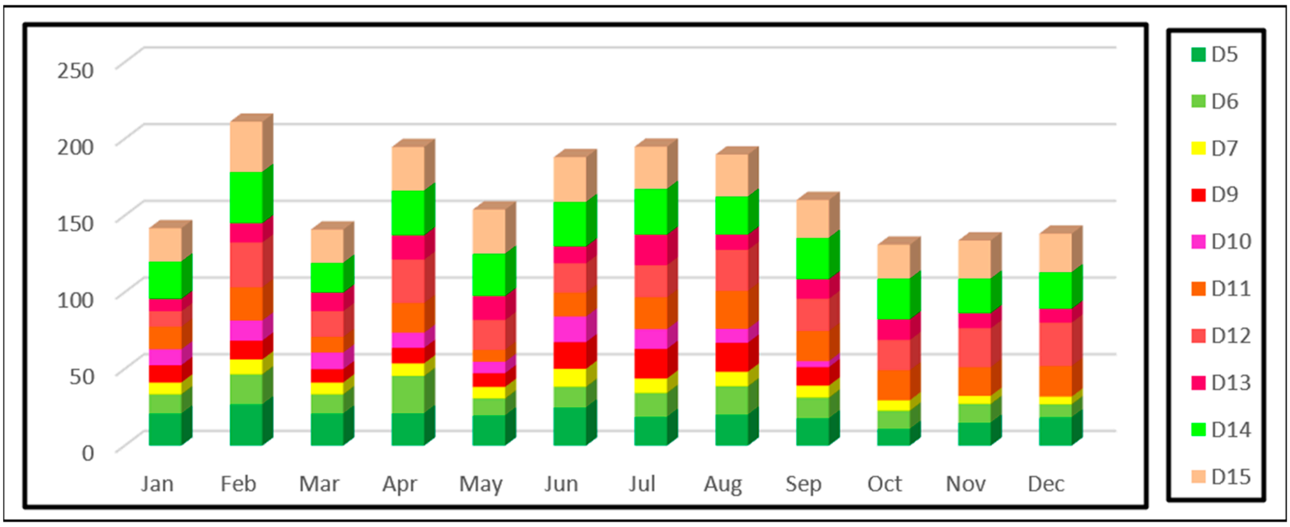

Figure 18. Monthly unmet demands (MCM) resulting from surface water only.

Table 15. Monthly unmet demands (MCM) resulting from surface water from Ismailia Canal only.

DEM & Booster	Monthly Unmet Demand (MCM)												Total
	January	February	March	April	May	June	July	August	September	October	November	December	
D1–D4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D5	20.62	26.62	20.62	20.91	19.46	24.68	18.51	19.96	17.53	10.64	14.76	18.22	232.53
D6	12.89	19.89	12.89	24.53	11.31	13.69	15.87	18.79	13.79	12.16	12.43	8.73	176.97
D7	7.66	9.66	7.66	8.21	7.49	11.68	9.37	9.43	7.84	6.74	5.24	4.94	95.92
D8–D10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D9	11.23	12.23	8.62	10.00	8.93	17.37	19.23	18.86	11.94	0.00	0.00	0.00	118.41
D10	10.42	13.21	10.96	10.00	7.43	16.78	13	9.16	4.02	0.00	0.00	0.00	94.98
D11	14.54	21.54	10.00	19.22	7.75	15.37	20.57	24.59	19.46	19.45	18.61	19.87	210.97
D12	10.34	29.43	17.00	28.51	19.61	19.39	21.18	26.91	21.24	19.94	25.56	28.53	267.64
D13	7.9	12.38	11.97	15.72	15.46	10.83	19.74	9.83	12.62	13.33	9.76	8.89	148.43
D14	24.33	33.33	19.33	29.06	27.54	28.93	29.76	24.76	26.93	26.49	22.43	23.74	316.63
D15	21.78	32.78	21.78	28.49	28.83	29.24	27.62	27.43	24.73	22.14	24.92	25.23	314.97
B1–B13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sum	141.71	211.07	140.83	194.65	153.81	187.96	194.85	189.72	160.1	130.89	133.71	138.15	1977.45

4.4. The Impact of Groundwater

The total groundwater pump to the study area decreased at a rate of 34.2% from 2016 to 2017, being at an amount of approximately 92.05 mm^3/year in 2017 [45]. This represents about 1.3% of the total water delivered to the study area, and, thus, the groundwater has a small effect in the study area. In these scenarios, all of the assumptions and data in the current case are the same data, but there are changes in terms of the groundwater, and the deficit areas are D5, D6, D7, D12, D13, D14, and D15, which represent Al-Salhiya, Ismailia, El Qantara West, Fayed, and Port Said. These cases are described in the following:

- Where the use of groundwater is increased by 20%, the unmet demand decreases from 789.81 to 718.7 MCM/year;
- By decreasing by 10%, the unmet demand increases from 789.81 to 829.4 MCM/year; and
- Using Surface water and reuse water only (without using any groundwater), results in the unmet demand increasing from 789.81 to 883.48 MCM/year.

The effect of groundwater in the case study is shown in Figure 19 and Table 16.

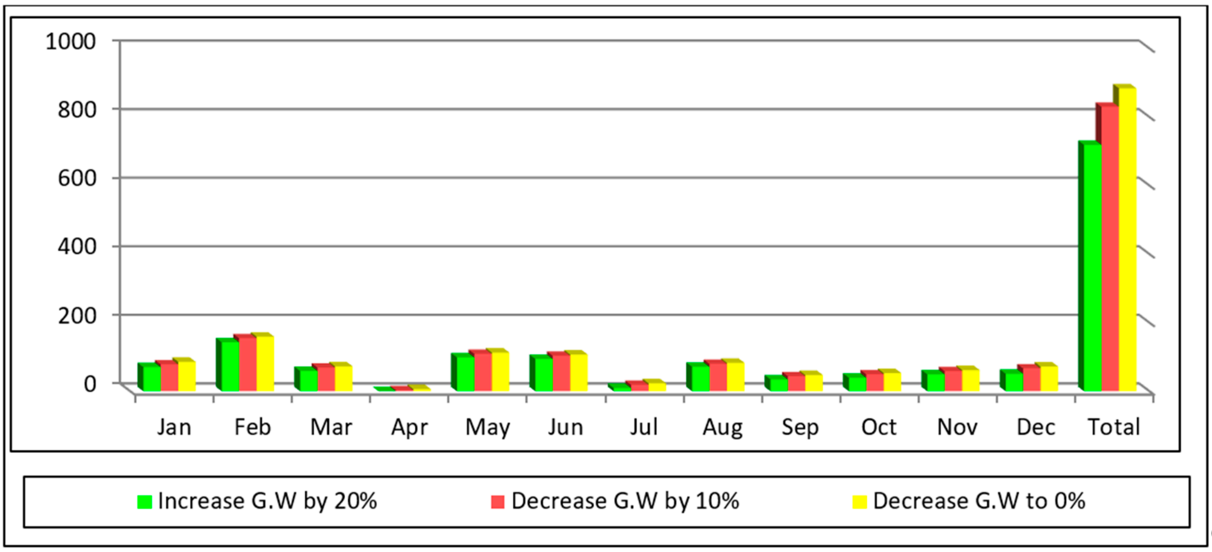

Figure 19. Monthly unmet demands (MCM) resulting from the effect of groundwater.

Table 16. Monthly unmet demands (MCM) resulting from the effect of groundwater.

DEM & BOOSTER	Month												Total
	January	February	March	April	May	June	July	August	September	October	November	December	
Increase G.W by 20%	70.31	142.62	59.05	0.00	98.6	94.08	9.33	71.16	34.27	39.08	49.28	50.92	718.7
Decrease G.W by 10%	77.8	154.23	68.57	2.79	108.65	103.18	18.21	79.28	43.44	48.88	58.07	66.3	829.4
Decrease G.W to 0%	85.69	159.18	72.68	6.1	112.86	107.01	23.14	82.77	47.15	52.94	61.76	72.2	883.48

Table 17 and Figure 20 show the comparison between the base case and different cases.

Table 17. Yearly unmet demands (MCM).

Scenario		The effect of Lining Ismailia Canal		The Effect of Surface Water			The Effect of Groundwater		
	Base Case	1	2	3	4	5	6	7	8
Unmet Demand MCM/year	789.81	291.99	173.90	159.80	1199.16	1977.45	718.70	829.40	883.48

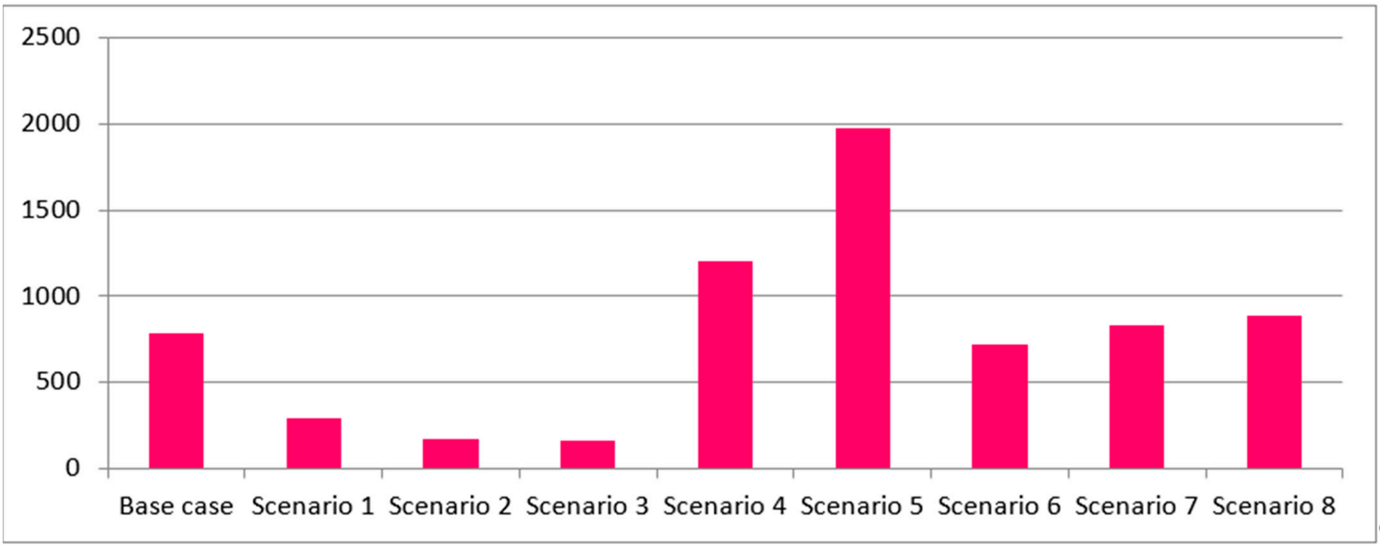

Figure 20. Unmet demand for base case and scenarios (MCM).

5. Conclusions

A mathematical model has been applied for the Ismailia Canal which displays the best approach to water resource management in the East Nile Delta. The model shows the amount of water which is distributed from the Ismailia Canal at an amount of 5772.55 Mm^3/year, approximately (representing approximately 9% of Egypt's water resources), and shows an active method for providing surface water and using groundwater and drainage reuse water effectively, leading to a significant impact on water management practices in Egypt once implemented.

According to the optimization model and scenarios, the area served by the Ismailia Canal will face a water shortage issue which will worsen over time, as agricultural and municipal demands develop. The value of water shortage is 789.81MCM/year at the ends of the irrigation network at DEMs (D5, D6, D7, D13, D14, D15), which are located in Al-Salhiya, El Qantara West, Fayed, and Port Said. This is a result of farmers' unlawful actions. The impacts of water shortage can be reduced by lining the Ismailia Canal and minimizing emissions by treating drain water and mixing it with canal water.

The operational scenarios get the following results:

1. Lining the Ismailia Canal results in an inverse proportion with the water scarcity value, reduced seepage from 21.06 percent to 10.16 percent, and a lowered water shortage, from 789.81 MCM to 291.99 MCM. Lining three sections of the canal reduced seepage from 21.06 percent to 7.51 percent, and lowered the water shortage from 789.81 MCM to 173.9 MCM;
2. When the surface water of the Ismailia Canal is increased by 15%, water shortage decreases to 159.8 MCM/year, but when the surface water of the Ismailia Canal is decreased by 10%, water shortage increases to 1199.16 MCM/year. When relying on surface water without groundwater and reusing water, the shortage increases to 159.8 MCM/year; and,
3. The value of a water shortage is inversely proportional to the amount of groundwater available. For example, increasing the groundwater by 20% reduces the water shortage to 718.7 MCM/year. However, if groundwater is reduced by 10%, the water deficit rises to 829.40 MCM/year. When relying on surface water and reusing it instead of groundwater, the annual shortage rises to 883.48 MCM.

6. Recommendations

It is suggested, based on the above inference and previous studies, to evolve the following points of research:

An interdependency-based multi-objective optimization model between different operational rules exists between the countries that share a river which makes the operation process more efficient and reliable,

- It is essential to create a locally comprehensive optimization model to include operational guidance that takes into account the various management variables, as well as the surface and groundwater salt balance to achieve optimum operation;
- In future research, evaporation and precipitation modes should be taken into account;
- Research on the effects of climate change on water supply and demand;
- Economic factors influencing water resources, as a result of GIS studies;
- Raising citizen consciousness is a good idea;
- Increasing the number of treatment plants to reduce waste; and
- Using cutting-edge irrigation and land-leveling technologies.

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