Agricultural Water Management 304 (2024) 109064

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Optimizing Irrigation Systems for Water Efficiency and Groundwater Sustainability in the Coastal Nile Delta

Ismail Abd-Elaty [a,*], Elsayed M. Ramadan [a], Ibrahim A. Elbagory [a], Ahmed M. Nosair [b], Alban Kuriqi [c,d], Luis Garrote [e], Ashraf A. Ahmed [f,*]

[a] Department of Water and Water Structures Engineering, Faculty of Engineering, Zagazig University, Zagazig 44519, Egypt
[b] Environmental Geophysics Lab (ZEGL), Geology Department, Faculty of Science, Zagazig University, Zagazig 44519, Egypt
[c] CERIS, Instituto Superior Técnico, Universidade de Lisboa, Av. RoviscoPais 1,, Lisbon 1049-001, Portugal
[d] Civil Engineering Department, University for Business and Technology, Pristina 10000, Kosovo
[e] Department of Civil Engineering: Hydraulics, Energy and Environment, Universidad Politécnica de Madrid, Madrid 28040, Spain
[f] Department of Civil and Environmental Engineering, Brunel University London, Uxbridge UB83PH, UK

ARTICLE INFO

Keywords:
Agriculture water management
Land
Drip irrigation
SEAWAT
Water scarcity
Coastal aquifers

ABSTRACT

This study investigates 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. The primary objectives were to determine the optimal agricultural area for implementing MIS and to assess the effects of these systems on groundwater quantity and quality in the region. To achieve this, the LINDO software was employed to optimize land allocation for each irrigation method. At the same time, the SEAWAT code was utilized to simulate saltwater intrusion (SWI) in the Nile Delta aquifer. The transition from traditional surface irrigation to MIS resulted in significant water savings, reaching 2.15 × 10^9 m^3. However, groundwater modeling indicated a decrease in groundwater levels, leading to an 8 % increase in aquifer salinity due to reduced infiltration of recharge water. These findings underscore the urgent need to revise outdated irrigation practices and enhance water management strategies in the Nile Delta to mitigate salinity issues in coastal aquifers. This research's outcomes are crucial for decision-makers and stakeholders in selecting appropriate irrigation methods, particularly in arid and semi-arid regions, to ensure sustainable water use and agricultural productivity.

1. Introduction

Globally, the irrigated area from groundwater is about 43 %, while the surface water is 57 % (Siebert et al., 2010). Furthermore, global groundwater irrigation returned to the hydrological systems through return flows and conveyance losses to groundwater and rivers is approximately 30 % (Pulido-Bosch et al., 2018). Salinity and drought are the main abiotic stresses influencing crop productivity (Cominelli et al., 2013). Salinization in arid and semi-arid zones is common due to limited annual precipitation (Jalali, 2007). More than 75 % of the global population lives in subtropical and semi-arid areas where 80 % of the cropped land is located, and 75 % is in developing countries; 25 % of the land (2000 million acres) worldwide is affected by high salt concentration (Junk et al., 2013). More than one billion people do not have access to clean drinking water. Approximately 2.3 billion people (i. e., 29 % of the world population) live in regions with water shortages (Kummu et al., 2010).

Hyper-arid and arid water resources are limited compared to humid and wet regions (Abd-Elaty et al., 2021). Numerous techniques are used to manage water resources and improve water shortage in high-stress areas. Harvesting water for human development by collecting flood water for irrigation and domestic and human is needed. Aly et al. (2022) showed that water scarcity represents a main obstacle that prevents the stability of residents. Also, Rainwater Harvesting (RWH) is one of the most effective solutions for water scarcity problems in arid and semi-arid regions. Ibrahim et al. (2019) studied the selection of a

* Corresponding authors.
E-mail addresses: Eng_abdelaty2006@yahoo.com, Eng_abdelaty@zu.edu.eg (I. Abd-Elaty), smokhtar@zu.edu.eg (E.M. Ramadan), Ibrahimelbagory@yahoo.com (I.A. Elbagory), ahmed_nosair@zu.edu.eg (A.M. Nosair), alban.kuriqi@tecnico.ulisboa.pt (A. Kuriqi), l.garrote@upm.es (L. Garrote), Ashraf.ahmed@brunel.ac.uk (A.A. Ahmed).

https://doi.org/10.1016/j.agwat.2024.109064
Received 14 May 2024; Received in revised form 12 September 2024; Accepted 12 September 2024
Available online 23 September 2024
0378-3774/

suitable site for RWH and storage; their study showed that the RWH is widely used in countries frequently affected by drought. Elewa et al. (2021) investigated the possibility of runoff water harvesting in dry regions; the study presented that the high and very high soil classes are the most suitable for runoff water harvesting, with about 33.24 % of the total watershed area.

Despite its high cost, brackish and seawater desalination is already being implemented or planned in some countries. National exploitation ratios of over 50 %, or even near 100 % in several Mediterranean countries, show that actual water consumption exceeds conventional renewable water resources (Vinci et al., 2021). Abd-Elaty and Zelenakova (2022) utilized the SEAWAT code to manage seawater intrusion (SWI) in two key areas for the shallow Gaza coastal aquifer in Palestine and the deep Nile Delta aquifer in Egypt. Their approach incorporated several strategies, including subsurface physical barriers like cut-off walls and subsurface dams, hydraulic methods such as wastewater treatment and recharge, abstraction and desalination of brackish water, and land reclamation using the earth-fill method. The SEAWAT simulation results showed that subsurface barriers and land-fill methods are ineffective for managing seawater intrusion in deep coastal aquifers. In contrast, hydraulic methods demonstrated a positive impact on controlling SWI in both shallow and deep aquifers. Additionally, reverse osmosis membranes are used to treat water sources (i.e., often groundwater sources) within a range of 1000–10,000 $mg\,L^{-1}$ of TDS (Chen et al., 2018; Imbulana et al., 2020). Salem and Hasan (2021) revealed that 37.7% of the Nile Delta, primarily the coastal and central regions, falls under the high vulnerability category for seawater intrusion. The southern portion, covering 62.3% of the study area, is moderately vulnerable to this hazard.

Modern irrigation systems have the potential to narrow the gap between water supply and demand. In Egypt, available water resources are currently estimated at 55.5 billion cubic meters per year (BCM yr^{-1}), supplemented by an additional 1.3 BCM yr^{-1} from effective rainfalls. Simultaneously, the water requirements across various sectors are estimated to be approximately 79.5 BCM yr^{-1}. This results in a deficit of around 20 BCM yr^{-1} between water demand and availability. The overall irrigation water use efficiency for the Nile system in Egypt is approximately 75 % (Mahmoud and El-Bably, 2019). This gap is overcome by reusing non-conventional water sources such as water harvesting, agricultural drainage water, wastewater treatment, desalination of seawater, and brackish water. Although treated sewage water cannot be added to Egypt's freshwater resources, the modern irrigation system will improve the water shortage. The water that returns to drains from irrigated areas is relatively high ($\approx$ 25–30 %). The total volume of reused water in 2013 is estimated to be 13 BCM (Gad, 2017). In addition, it may be crucial to use it if the water demand exceeds all other available water resources. However, its use will depend on technological development in this field (Al-Saidi et al., 2017). Near coastal areas in arid and semi-arid regions, irrigated agriculture has a great impact on the hydrological cycle and groundwater quality (Foster et al., 2018). Smart farming was established in response to the issues that agricultural production faces in terms of productivity, food safety, and sustainability as a result of climate change (Francis et al., 2023). Moursy et al., (2023) studied the productivity and profitability of modern irrigation methods through the application of on-farm drip irrigation on some crops in the Northern Nile Delta of Egypt. The study showed that the total cost of a drip irrigation system was decreased compare with surface irrigation system. Also, the drip irrigation gave more efficient water uses and water saving under different summer and winter crops. Yazdanpanah et al., (2023) studied the socio-economic, innovation characteristics, and social capital values for using different modern irrigation systems in the Khuzestan province of southwest Iran. The study showed that the farmers' delayed adoption of drip irrigation technologies was due to the complexity of the application process and the availability of family and work social capital. 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. Wael et al., (2024) conducted a comparative analysis of modern irrigation systems and traditional flood irrigation with respect to their effects on groundwater potential in ancient clayey soils within the Qalyubia Governorate of the Nile Delta, Egypt. Their findings indicate 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. The first optimization model for flood control and water supply was created in 1923 (Varlet, 1923). The optimization model was designed for supplying sources by considering water quality, water distribution capability, and the current relations between water supply and water demands (Al-Saidi et al., 2017). The optimization model enhanced the allocation of water resources to maximize the benefits across rural, urban, and industrial sectors within a shared basin (Al-Saidi et al., 2017). Devi et al. (2004) used a linear programming model for optimal water allocations in a large river basin system in the Subarnarekha River in India to find the maximum annual benefits from irrigation and hydropower subject to various constraints on the system. Gupta et al. (2006) and Al-Saidi et al. (2017) used the LINDO 6.10 version to solve a model of hybrid energy systems to optimize costs and multiple types of resources in India. Al-Saidi et al. (2017) applied the optimization model of LINDO 6.1 (linear interactive and discrete optimizer) software in Andhra Pradesh, India, to determine 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. Ramadan et al. (2021) applied the LINDO software to face a water shortage in the eastern Nile delta through three scenarios, including Ismailia canal lining, surface water's impact, and groundwater's impact. Water scarcity was proportional to lining four sections at a length of 61 km, which is considered to be an optimal scenario, which predicts that the Ismailia canal head flow will rise by 15 % to reduce water scarcity in Egypt.

Modern irrigation systems are a good tool for managing agricultural water resources, especially in arid and semi-arid regions. Still, they also affect the degree of groundwater salinity for drinking and irrigation purposes (Abd-Elaty et al., 2023). In the eastern Nile Delta of Egypt, groundwater recharge is being augmented by surplus irrigation and rainfall. This process aids in conserving freshwater and managing groundwater salinity in coastal areas impacted by saltwater intrusion. Therefore, the main objective of the current study is to simulate and optimize the agriculture area for applying modified MIS using pivot sprinkler irrigation, horizontal sprinkler irrigation, surface drip irrigation, and sub-surface drip irrigation compared with the current situation using flooding irrigation. Also, the study investigated how the type of irrigation system affects the dynamics of coastal groundwater and, consequently, the water and soil.

Due to the shortage of water resources in arid regions, especially coastal areas, and the high stress of climate change by increasing crop water requirements, the application of modern irrigation systems is required to solve the water crisis in these regions. For that purpose, agriculture water management is applied using the optimization software LINDO and the variable density of the groundwater code of SEAWAT. The application of coupled models in this study introduced a novel approach for investigating the optimal agricultural area and assessing the salinity of coastal aquifers in the Nile Delta, Egypt. By estimating the spatial distribution and quality of groundwater using the MIS and comparing it with the current surface irrigation practices; this research provides valuable insights for decision-makers and stakeholders in water-stressed regions.

2. Eastern Nile delta aquifer

2.1. Location of study area

The numerical simulation for different irrigation methods to overcome the shortage in water resources in high-stress water scarcity is applied in the Eastern Nile Delta aquifer, Egypt, as a case study; this aquifer is subject to top-down infiltration due to recharge (i.e., rainfall plus irrigation) (DRI, 1989; Mabrouk et al., 2013; Abd-Elaty et al., 2019). The study area is geographically defined by the Mediterranean Sea and Lake El Manzala to the North, the Ismailia Canal to the South, the Suez Canal to the east, and the Damietta Branch to the west. Covering an area of approximately 9688.42 km^2, it is situated between latitudes 31̊00' and 32̊30' N and longitudes 29̊30' and 32̊30' E, as illustrated in Fig. 1. The eastern Nile Delta is characterized by hot, arid climate and rainless in the summer. The annual rainfall decreased in the southern parts and increased in the northern parts near to the Mediterranean Sea. The potential evapotranspiration increased in the southern parts and decreased in the northern parts (Figure A1a, appendix) (Armanuos and Negm, 2019)

2.2. Land use and land cover

The eastern Nile Delta is distinguished into three main regions: the first is agricultural land by 5657.80 km^2, which includes the traditionally cultivated areas and the newly reclaimed areas; the second is wetland by 1116 km^2, consists of the coastal lakes and the marshlands; and the third is a desert portion by 2915 km^2 (Farid, 1980). Additionally, the study area is dominated by rural-built areas in addition to small areas of flooded vegetation, rangeland, and bare ground (Fig. 2a). The topographic elevations of the study area vary between $<$3 (a.m.s.l) in the northern parts and about 50 m (a.m.s.l) in the southeastern parts and generally decrease towards the north close to El-Manzala Lake (Fig. 2b).

2.3. Geology of the study area

Generally, the clay Holocene layer increased from the southern parts towards the northern parts of the eastern Nile Delta (Zaghloul, 1958; Sallouma, 1983, Nosair et al., 2022) (Figure A1b, appendix). The geological formations of the Nile Delta are mostly composed of the Quaternary deposits overlying Miocene, Eocene, and Oligocene deposits (CONOCO, 1987) (Figure A2a and A2b, appendix). The Quaternary deposits represent the main aquifer in the Nile Delta area and are composed of Holocene and Pleistocene deposits (Elewa et al., 2013; Kasem et al., 2024). Holocene sediments, made up of alternating sand, silt, and clay beads with thicknesses varying from 5 m to 20 m in the southern and central parts of the eastern Nile Delta, reaching to about 70 m in the northeastern parts close to El Manzala lake and Mediterranean Sea and disappearing to the southeast around Ismailia canal and in some of eastern parts near to Suez canal (El-Fayoumy, 1968; Elewa et al., 2013). On the contrary, Pleistocene sediments are composed of coarse-grained quartzite sands and gravels with discontinuous occasional clay lenses that increase toward the North with an average thickness of 700 m. The hydrological strata are sands and gravels (Pleistocene and Holocene) containing a few lenses of clay that are considered the main water-bearing formations. The Nile Delta aquifer (Quaternary deposits) is a semiconfined aquifer system increasing in thickness from about 200 m in the South, near Cairo, to more than 900 m in the Mediterranean Sea (Figure A2c, appendix).

Furthermore, the Nile Delta aquifer is one of the largest fresh groundwater aquifers worldwide due to the extension in area and thickness of its layer with a total capacity of 500 Bm^3. The most permeable layer in the Nile Delta Aquifer has been found at depths between 55 and 150 m from the land surface (Abd-Elaty et al., 2019; Dawoud et al., 2005). The Nile Delta aquifer is mainly recharged from the distributed freshwater canals in addition to seepage from drains and irrigation return flow (Sherif et al., 2012; Eltarabily et al., 2020; Abu Salem et al., 2022) (Figure A3a, appendix). Groundwater levels decreased from the southern parts to the northern parts of the eastern Nile Delta aquifer and varied between 1 m and 15 m (Nosair et al., 2022; Kasem et al., 2024) (Figure A3b, appendix).

2.4. Hydraulic parameters

The main hydraulic parameters of the Nile Delta include the horizontal (K_h) hydraulic conductivity (K_v), which ranges from 0.25 m day^{-1} to 100 m day^{-1} for the clay cap and the Quaternary aquifer layers, respectively. The vertical hydraulic conductivity (K_v) varied between 0.0025 m day^{-1} and 10 m day^{-1} across the model domain. Furthermore, the aquifer-specific storage and the storativity (S) were 0.20 m^{-1} and $2.5 \times 10^{-3,}$ respectively, and the effective porosity ranged from 20 % to 50 %. The longitudinal and lateral dispersivities of the study area reached 100 m and 10 m, respectively, while the diffusion coefficient (D*) was 10^{-4} m^2 day^{-1} (Morsy, 2009; Mabrouk et al., 2013; Abd-Elaty

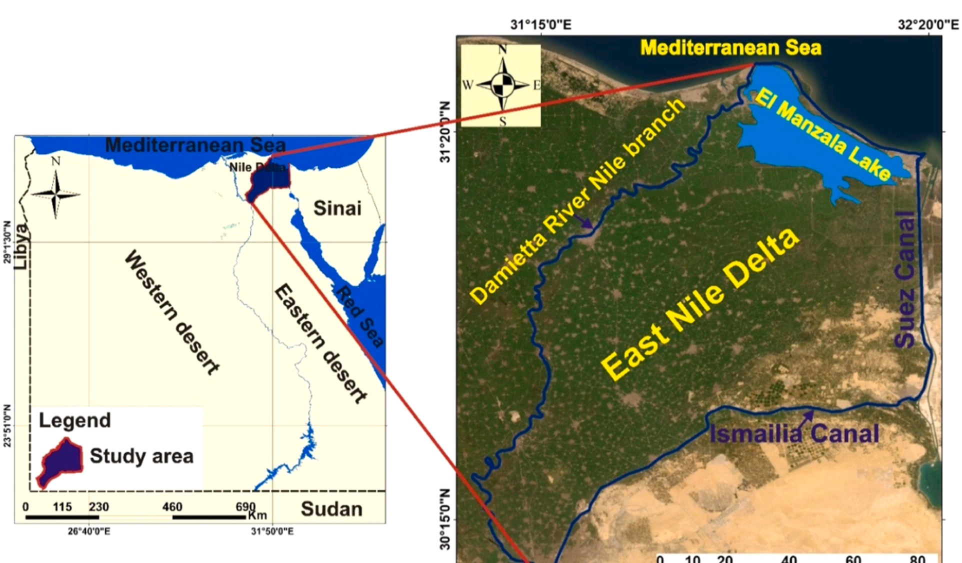

Fig. 1. Location of the study area.

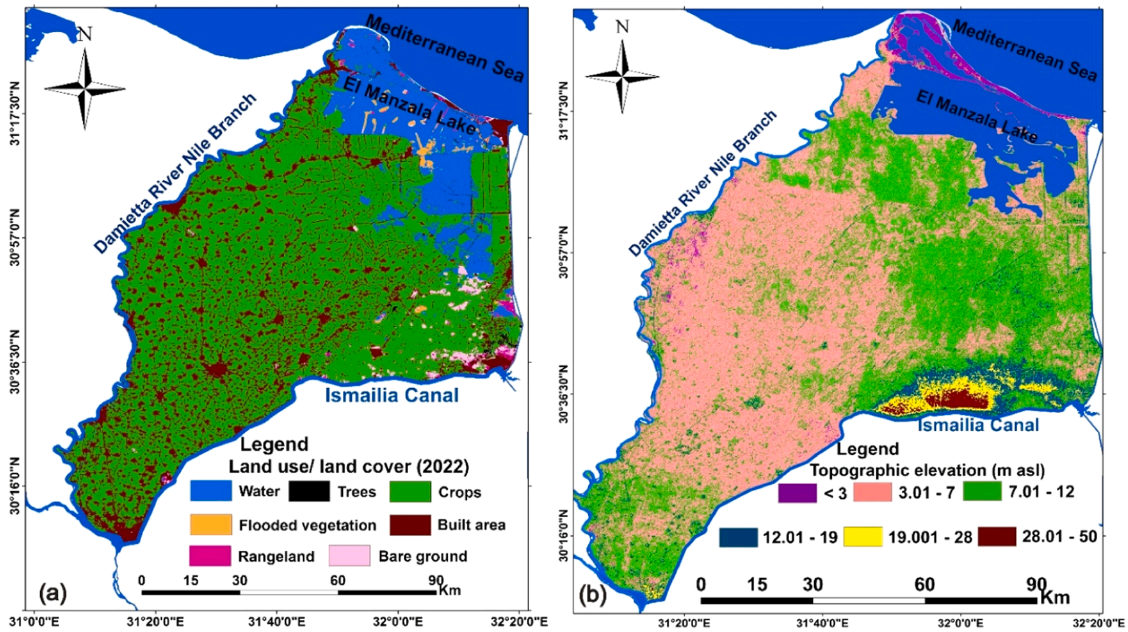

Fig. 2. Characterization of the stud area: a) Land use /land cover (year 2022) extracted from Sentenal-2 land cover; b) topographic elevations extracted from digital elevation model (DEM) resolution 30 m.

et al., 2024).

3. Materials and methods

3.1. Seawater intrusion finite difference model

In this study, the miscible variable-density process is governed by the coupled system of flow and transport equations using the SEAWAT code.

The Variable-Density Flow (VDF) Process solves the following variable-density groundwater flow equation (Guo and Langevin, 2002):

$$\nabla\left[\rho * \frac{\mu_o}{\mu} * K_o\left(\nabla * h_0 + \frac{\rho-\rho_f}{\rho_f} * \nabla Z\right)\right] = \rho * S_{S,0}\left(\frac{\partial h_O}{\partial t}\right) + \theta * \left(\frac{\partial \rho}{\partial C}\right)\left(\frac{\partial C}{\partial t}\right) - \rho_S * q^{\backslash}{}_S \quad (1)$$

The Integrated MT3DMS Transport (IMT) process solves the following solute transport equation (Zheng and Wang, 1999):

$$\left(1+\frac{\rho_b * K_d{}^k}{\theta}\right)\frac{\partial(\theta * C)}{\partial t} = \nabla\left(\theta D * \nabla C^k\right) - \nabla\left(q * C^k\right) - \left(q^{\backslash}{}_s * C_s{}^k\right) \quad (2)$$

Where ρ_o: is the fluid density $[ML^{-3}]$, ρ: is the density of saline ground water $[ML^{-3}]$, μ_o: is the dynamic viscosity of the fresh groundwater $[ML^{-1}T^{-1}]$, μ: is the dynamic viscosity of saline ground water $[ML^{-1}T^{-1}]$, K_0: is the hydraulic conductivity $[LT^{-1}]$, h_0: is the hydraulic head [L], $S_{s,0}$: is the specific storage $[L^{-1}]$, t: is time [T]; θ: is porosity [-]; C: is salt concentration $[ML^{-3}]$; and q'_s:is a source or sink $[T^{-1}]$ of fluid with density ρ_s, ρ_b: is the bulk density $[ML^{-3}]$, K_d^k: is the distribution coefficient of species k $[L^3 M^{-1}]$, C_k: is the concentration of species k $[ML^{-3}]$, D: is the hydrodynamic dispersion coefficient $[L^2T^{-1}]$, q: is specific discharge $[LT^{-1}]$, and C_s^k: is the source or sink concentration $[ML^{-3}]$ of species k.

3.1.1. Model discerption and parameters

The subsurface flow and solute transport model SEAWAT is applied to simulate and investigate SWI. The study area domain is divided into 160 rows and 124 columns with a cell area of 1 km^2 and a variable depth from 1000 m in the North to 200 m in the South (Figure A4a, appendix). The domain is divided into eleven layers; layer #1 represents a clay cap with a thickness that varies from 20 m in the South to 50 m in the North, while layers #2 to #11 represent the Quaternary aquifer with equal thickness; this clay cap keeps the Quaternary aquifer as a semi-confined aquifer. Two vertical sections are taken in the X and Y directions (Figure A4b and A4c, appendix).

The study area boundary conditions were assigned as follows: i) along the Northern boundary, a zero constant head was set to assign the Mediterranean Sea, ii) a river package at the eastern boundary by the Ismailia canal starting with a head range from 16.15 m at the South to 7 m at its Eastern point. The Nile River represents a western boundary with a head of 16.96 m to 16.60 m. Damietta Nile branch head started from 13.66 m in the South to 0.25 m in the North, iii) the no-flow boundary condition at the east boundary was set free, iv) a drain boundary package was assigned for three main open drains by Bahr Baker drain in the east starting from 11 m to 0.25 m, Bahr Hadus in the center from 8 m to 0.25 m, and the west for El-Serw drains with the head from 12 m to 0.50 m (a.m.s.l). The initial hydrodynamic parameters used as input values for the Eastern Nile delta model were fed to the SEAWAT model based on the previous studies (Morsy, 2009; Mabrouk et al., 2013; Abd-Elaty et al., 2019).

Furthermore, the net recharge to the aquifer ranges from 0.25 to 0.80 mm day^{-1} from the precipitation, river and canal seepage, drainage practices, soil, and irrigation type. The discharge was carried out by abstraction from the aquifer for irrigation and drainage water supplies by 3.78 $\times 10^9$ m^3 yr^{-1} in 2008.

3.1.2. Model calibration

The current Eastern Nile Delta aquifer model was calibrated using historical records for hydraulic head measurements in several piezometer wells in the study based on the RIGW in 2008 (Morsy, 2009; Moghazy and Kaluarachchi, 2020) by using 30 observation wells. The calculated heads were compared with the heads observed from the field measurements. The calibration process changed the hydraulic parameters to optimize the simulation model results with the filed data. The statistical results for the current simulation showed that the residual range is between −0.02 and 1.05 m, the residual mead is 0.002 m, the absolute residual mead is 0.54 m, the standard error of the estimate is 0.11 m, the root mean square (RMS) of the residuals was equal to 0.61 m with and a normalized RMS of 3.60 % (i.e., normalized with respect to the maximum difference in the observed head values).

The real view of the groundwater heads in the study area is presented in Fig. 3a, which shows the flow direction from the high head in the South to the low head in the North, which agrees with the observed field data described in Moghazy and Kaluarachchi (2020).

The variable flow model was calibrated by changing the hydro-dispersive parameters (i.e., α_L and α_T) contained in Eq. 1 and comparing the field measurements of total dissolved salts (TDS) according to Ding et al. (2020) and Abd-Elaty et al. (2019). Overall, the TDS model results agree with the field data. Fig. 3b represents a real view of TDS distribution in the middle of the aquifer (layer #6); depths of this view are 450 m in the North and 100 m in the South, with an average depth of 225 m from the ground surface. The vertical TDS distribution in the aquifer is represented in Fig. 3c, the isochlorines at 35,000 and 1000 ppm reached 75.80 km and 90.40 km from the coast.

3.2. Optimization of water model

The optimal agriculture area for each irrigation method in the eastern Nile delta was simulated and carried out using LINDO (Linear, Interactive, Discrete Optimizer) software. It is a mathematical model with physical constraints (mass balances) used to optimize the water balance between the water supplies (i.e., surface water, groundwater, and water reuse) and water demands for the agriculture sector. The best software for solving problems with tens of thousands of constraints and hundreds of thousands of variables is LINDO (Khare and Jat, 2006).

3.2.1. Objective functions

The objective function of the irrigation method optimization is to maximize the total net irrigation area by determining and selecting the optimal area for each type of irrigation method.

$$\text{Max AA} = \text{Max}\Sigma\left[A_{si} + A_{sdi} + A_{ssdi} + A_{hsi} + \quad A_{psi}\right] \tag{3}$$

Where: AA: total agriculture area in Hectare (ha), A_{si}: total irrigated agriculture area with surface irrigation (ha), A_{sdi}: total irrigated agriculture area with surface drip irrigation (ha), A_{ssdi}: total irrigated agriculture area with subsurface drip irrigation (ha), A_{hsi}: total irrigated agriculture area with horizontal sprinkler irrigation (ha), and A_{psi}: total irrigated agriculture area with pivot sprinkler irrigation (ha).

3.2.2. Model constraints

Water availability: This restriction reduces irrigated water use. Water supply: For different irrigation methods, the total water

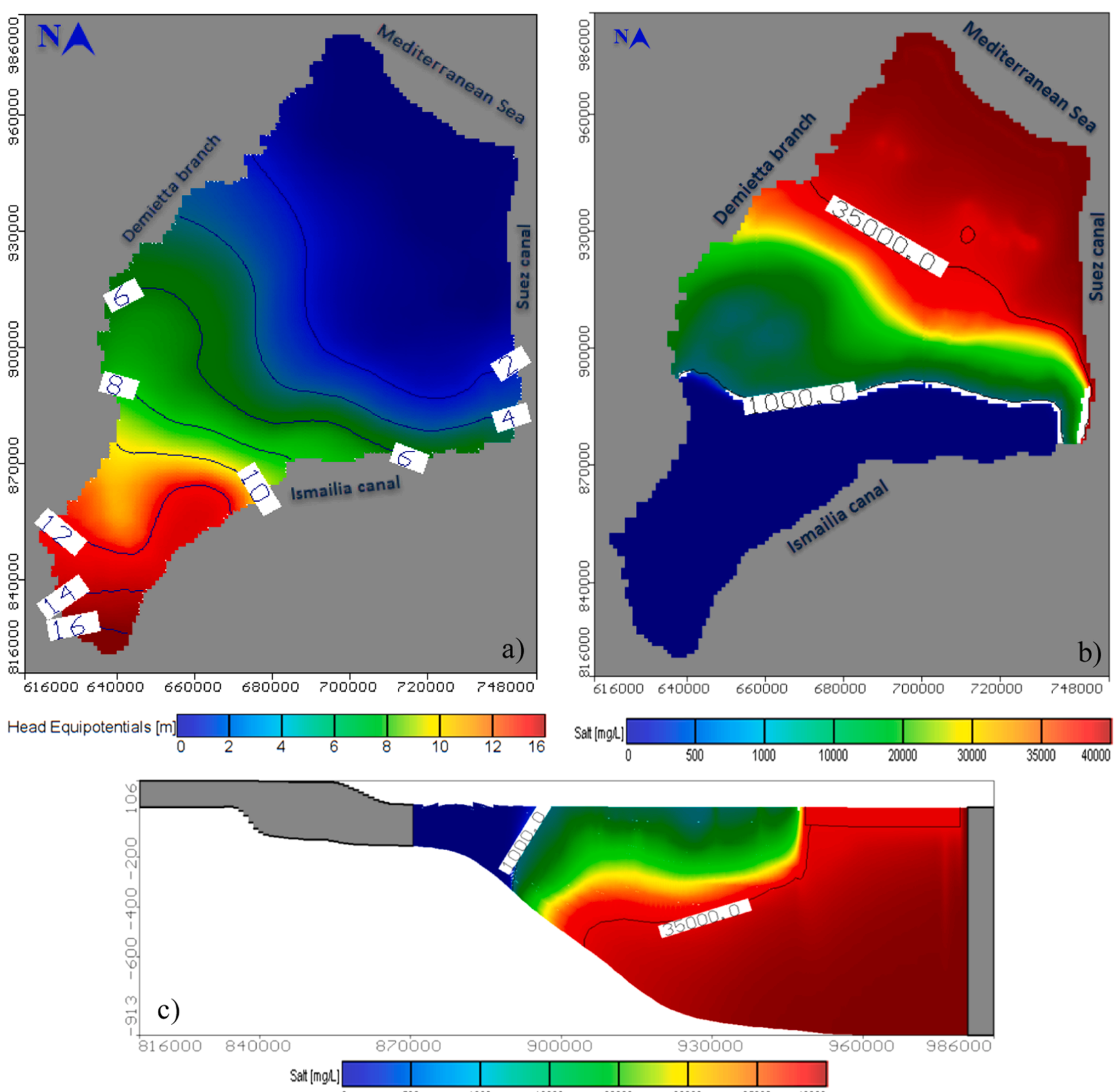

Fig. 3. Groundwater maps of the studied aquifer using the current situation for a) A real view of Groundwater flows, b) A real view of TDS, and c) Vertical distribution of TDS.

consumption should be less or equal to the total available water in the field during the year. Table 1 shows the study area's water resources and water demands based on the published literature (Morsy, 2009).

$$\Sigma WR \leq \Sigma W_{Ti} \tag{4}$$

$$W_{Ti} = \Sigma\left[21170A_{si} + 12410A_{sdi} + 8687\ \ A_{ssdi} + 13870\ \ A_{hsi} + 1022\ \ A_{psi}\right] \tag{5}$$

Where: ΣWR is the water requirement for each irrigation method [m^3]; it is 12.16 $\times 10^9$ m^3 in the current study, and ΣW_{Ti} is the total water demand for each irrigation method [m^3].

Land area limits in agriculture during different irrigation methods; the total area assigned to the plant must be equal to or less than the total area actually cultivated and soil type. The land data for the soil type, agriculture, and total area are presented in Table 2, based on the published materials by (Ali, 2012; Alnaimy et al., 2022; Arafa et al., 2022).

$$AA \leq A_{Ti} \tag{6}$$

$$A_{Ti} = 8572.43 \quad [\text{ha}]$$

A_{Ti} = Gravel sand and gravel [239.73 ha] + silty clay [4876.70 ha] + clay loam [817 ha] + dissected sandy limestone [82 ha] + sand and clay loam [827 ha] + sand and carbonates [1730 ha]Where: A_{Ti}: are the total cultivation areas for all irrigation methods (ha),

$$A_{si} \geq \text{area of rice crop} \tag{7}$$

Area required for Rice = 10 % of the area of old land

$$A_{sdi} + A_{hspi} + A_{psi} \leq A_{Tss} \tag{8}$$

$$A_{sdi} \geq 40\% \quad A_{Tss} \tag{9}$$

$$A_{hsi} \geq 20\% \quad A_{Tss} \tag{10}$$

$$A_{psi} \geq 20\% \quad A_{Tss} \tag{11}$$

Where: A_{TSS}: is the total area of sandy soil [ha], which is divided politically between different suitable irrigation types.

$$A_{psi} \geq \quad A_{nr} \tag{12}$$

Where: A_{nr}: is the total area of newly reclaimed land (ha) that is politically suitable for pivoting sprinkler irrigation type.

$$A_{ssdi} \geq \quad 50\% \quad A_{ss} \tag{13}$$

Where: A_{ss}: is total the area of sand soil (ha) is 50 % of sand soil to decrease evaporation losses.

Table 1
Water supply and water demands in the Nile aquifer after Morsy (2009).

Case	Parameter / Method	Quantity	Unit
Water Supplies	Well Abstraction	1.38 $\times 10^9$	m^3 $year^{-1}$
	Surface Irrigation	8.68 $\times 10^9$	m^3 $year^{-1}$
	Reuse Drainage Water	2.10 $\times 10^9$	m^3 $year^{-1}$
	Total Water Supply	12.16 $\times 10^9$	m^3 $year^{-1}$
Water Demands by Irrigation Methods	Surface	21,170	m^3 $hectare^{-1}$ $year^{-1}$
	Sprinkler	13,870	m^3 $hectare^{-1}$ $year^{-1}$
	Central Pivot	10,220	m^3 $hectare^{-1}$ $year^{-1}$
	Drip surface	12,410	m^3 $hectare^{-1}$ $year^{-1}$
	Drip subsurface	8687	m^3 $hectare^{-1}$ $year^{-1}$

$$A_{si} \geq \quad A_{sc} \tag{14}$$

Where: A_{sc}: is the total area of silty clay soil (ha),

$$A_{ssdi} \geq \quad A_{gsg} \tag{15}$$

Where: A_{gsg}: is the total area of gravelly sand and gravel soil (ha),

3.3. Case scenarios

Five proposed irrigation methods, including the base case for applying the current situation of surface irrigation and four modified methods using modern irrigation, the % of aquifer recharge for each proposed method, including sprinkler irrigation, central pivot irrigation, surface drip irrigation, and subsurface drip irrigation were developed based on the published data by Morsy (2009). The using of three scenarios is very hard to apply in the current study area due to the saltwater intrusion problem in the North by the Mediterranean Sea and the increasing abstraction rates by the production wells for drinking water and irrigation; on the other side, the problem of water stress due to increasing the population growth rates which required more water supplies. So, this study is required to identify the results of applying the modern irrigation system to the groundwater resources in this arid region. The following are the base case of current irrigation and the proposed scenarios:

i. ***Surface irrigation*** is the current irrigation method in the study area. This system is applied to the study area in the current situation for most agricultural areas, which is suitable for many crops and required to mitigate the influence of saltwater intrusion, in which the Mediterranean Sea connects the study area. Table 3 presents the main parameters of the irrigation methods assigned in the model, including the average flow to the aquifers reaching 0.80 mm day^{-1} (Jalali, 2007; Morsy, 2009; Mabrouk et al., 2019).
ii. ***Sprinkler irrigation*** is applied to the study area in the eastern Nile delta by changing irrigation methods, which is critical for arid and semi-arid regions with reduced water resources due to increasing population and the consequences of climate change on the environment. The flow to the aquifers was assigned to the model to be 0.40 mm day^{-1}, by 50 % from the current aquifer recharge.
iii. ***Central pivot irrigation is*** carried out in the study area based on the optimized area for the irrigation using a central pivot. The recharge rate to the aquifer is 40 % of the current surface irrigation (0.8 mm), i.e., to 0.32 mm day^{-1}.
iv. ***Surface drip irrigation*** is applied in the current study area by changing surface irrigation to drip irrigation; the flow to the aquifers was assigned and reached 0.24 mm day^{-1}, i.e., 30 % of the current situation of the flow to the aquifer, which is 0.8 mm. This indicates that the aquifer recharge is reduced compared to the sprinkler and surface recharge, but the water saving increases.
v. ***Subsurface drip irrigation*** is proposed in the study, and 20 % of the current aquifer recharge was taken, i.e., flow to the aquifers was taken at 0.16 mm.day^{-1}. This scenario is best for irrigation water saving in agriculture but the worst for aquifer recharge.

The irrigation methods rates flow to the aquifers reached the value of 0 mm day^{-1}, which means that no irrigation applies for this region; it is the Lake Manzala or lagoon, which is a brackish water lake located in northeastern Egypt on the Nile Delta. In addition, the application of the irrigation method and the limitation of the current methodology depend on the Nile hydrograph for water supplies, the type of soil for clay, sand, and silt, the crop pattern, and the using of high water consumption as the rice crop which required to grow in the north Nile delta to increase the

Table 2
Soil type for each land area and soil texture in the Nile aquifer (Ali, 2012; Alnaimy et al., 2022; Arafa et al., 2022).

Soil type	Total area (km^2)	Agriculture Area (km^2)	Average Sand (%)	Average Silt (%)	Average Clay (%)
Gravelly Sand and Gravel	257.18	169.73	91	4	5
Silty Clay	4886.28	3224.95	5	47	48
Clay Loam	771.52	509.20	40	29	31
Dissected Sandy Limestone	85.72	56.58	87	8	5
Sand and Clay Loam	857.24	565.78	50	27	23
Sand and Carbonates	1714.49	1131.56	90	5	5
Total Area Without Water Bodies	8572.43	5657.80	-	-	-

Table 3
Water budget analysis for the modified irrigation methods.

Boundary Parameter	Current Situation		Modified Irrigation Method	
	m^3 day^{-1}	%	m^3 day^{-1}	%
Flow Into the Aquifer	4,332,442.40	88	3,297,796.90	73
River and Canal Leakage	492,323	10	1,084,207.20	24
Lake Leakage	49,232.30	1	45,175.30	1
Constant Head	49,232.30	1	90,350.60	2
Total Inflow	4,923,230	100	4,517,530	100
Well Abstraction	3,790,921.75	77	3,749,553.71	83
Lake	590,793	12	587,279.50	13
River and Canal Leakage	393,862	8	90,350.69	2
Drain Leakage	98,465.5	2	45,175.35	1
Constant Head	49,232.75	1	45,175.35	1
Total Outflow	4,923,275	100	4,517,535	100

aquifer water recharge to overcome the saltwater intrusion, the practice of the stakeholders and farmers where the land currently divided into subsector, and the feasibility of the irrigation method in which the main problem for thigh high cost to changing from surface irrigation to modern irrigation system.

4. Results

4.1. Optimization of agriculture lands and irrigation dynamics

The study area land use for water bodies reached 1162.61 km^2, representing 12 % of the total area of the eastern Nile delta land; the trees reached 96.88 km^2, representing 1 %. The flooded vegetation is 96.88 km^2, representing 1 %; crops are 6394.36 km^2, representing 66 %; the building area is 1550.15 km^2, representing 16 %; the bare ground is 193.77 km^2, representing 2 %, and the rangeland is 193.77 km^2 representing 2 %. The total area of the eastern Nile Delta is 9688.42 km^2 (Fig. 4a). Furthermore, the new reclamation areas reach 565.78 km^2 while the old lands are 5092.02 km^2 in the eastern Nile Delta with a total agriculture area of 5657.80 km^2. Fig. 4b shows the LINDO optimization model results.

It showed that the application of the modified irrigation method for surface irrigation is 3621 km^2, representing 64 % of the total area; the sprinkler irrigation is 396.05 km^2, representing 7 %; the central pivot irrigation is 735.51 km^2, representing 13 %; the surface drip irrigation is 735.51 km^2, representing 13 %. The subsurface drip irrigation is 169.73 km^2, representing 3 %. Also, the total area without surface water bodies is 8572.73 km^2, while the agricultural area is 5657.80 km^2. The water demands for using the modified irrigation methods reached 10.01 BCM compared to 12.16 BCM for the current situation with water saving reached 2.15 BCM.

4.2. Effect of modified irrigation methods on groundwater resources

This study compared the current irrigation system with the modified modern irrigation methods, namely sprinkler irrigation, central pivot irrigation, surface drip irrigation, and subsurface drip irrigation, employing a calibrated groundwater flow model. The flow rates to the aquifer ranged from 0.05 mm day^{-1} to 1.10 mm day^{-1} for the base case when using surface irrigation. The recharge rate values were taken as 0.40 mm day^{-1} and 0.32 mm day^{-1} for sprinkler and central pivot irrigation. In comparison, it reached 0.24 mm day^{-1} and 0.16 mm day^{-1} for the surface and subsurface drip irrigation methods, respectively.

The groundwater flow model results of the water budget for source IN and sink OUT are presented in Table 3. The results show that the flow into the aquifer decreased after applying the modified irrigation system from 4,332,442.40 m^3 day^{-1} to 3,297,796.90 m^3 day^{-1}, representing 88 % and 73 % of the total inflow, respectively. The total inflow was 4,923,230 m^{3}day^{-1} for the current system and 4,517,530 m^3 day^{-1} for applying the modified irrigation system. The reduction of the flow is due to the application of the modified modern irrigation system, which decreased the infiltration to the aquifer. The combined river leakage by the Damietta Nile branch and irrigation canal network reached 492,323 m^3 day^{-1} and 1,084,207.20 m^3 day^{-1} before and after the modified irrigation system, respectively. This represents an increase of 10 % and 24 %, respectively, with respect to the total inflow. The inflow from the river and canals increased for the modified irrigation system due to the reduced recharge infiltration associated with the modified irrigation system. The leakage from El Manzala Lake reached 49,232.30 m^3 day^{-1} and 45,175.30 m^3 day^{-1} before and after the modified irrigation system, which represents an increase of 1 % and 1 %, respectively, with respect to the total inflow. This increase in the coastal lake leakage is due to the decline of the groundwater heads in the aquifer after applying the new irrigation system. Because of the saline water coming to the aquifer from the Mediterranean Sea, the constant head values were around 49,232.30 m^3 day^{-1} and 90,350.60 m^3 day^{-1} before and after the application of the new irrigation system, which represents an increase of 1 % and 2 %, respectively. The total inflow

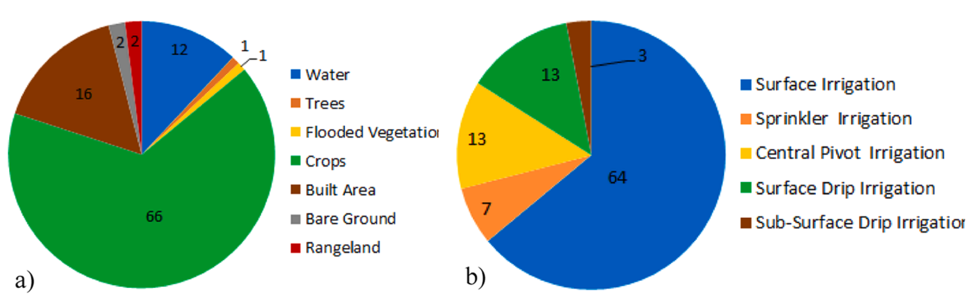

Fig. 4. Percentage of the area in the study area for a) different land use in the eastern Nile delta and b) optimized agriculture land for different irrigation methods.

decreased to 4,923,230 m^3 day^{-1} and 4,517,530 m^3 day^{-1} before and after the application of the new irrigation system, with a decrease of 8 %, respectively. This showed that the reduced aquifer inflow led to an increase in river and lake leakage to compensate for this water shortage (Fig. 5a).

In contrast, the total outflow decreased down to 4,923,275 m^3 day^{-1} and 4,517,535 m^3 day^{-1}, respectively. To overcome the shortage of freshwater storage, the well budget was kept constant at 3,790,921.75 m^3 day^{-1} and 3,749,553.71 m^3 day^{-1} representing 77 % and 83 % of the total outflow. The percentage of the well abstraction budget increased due to a decline in the aquifer recharge by the modified irrigation systems compared with the total outflow. The lake budget was reduced to 590,793 m^3 day^{-1} and 587,280 m^3 day^{-1}, representing 12 % and 13 %, respectively, the total outflow. The river leakage decreased to 393,862 m^3 day^{-1} and 90,350.69 m^{3}day^{-1} with 8 % and 2 %, respectively. The drain leakage decreased to 98,465.5 m^3 day^{-1} and 45,175.35 m^3 day^{-1} with 2 % and 1 %, respectively. All these percentages are before and after the modified irrigation system with respect to the total outflow.

This reduction in the lake, river, and drain in the outflow budget is due to a reduction in the recharge flow resulting from applying a new, modified irrigation system. The constant heads increased from 49,232.75 m^3 day^{-1} to 45,175.35 m^3 day^{-1} before and after modified irrigation system, representing 1 % and 1 % of the total outflow, respectively (Fig. 5b).

Fig. 6a shows the results of applying the modified irrigation systems, including the base case and the four modern irrigation methods: sprinkler irrigation, central pivot irrigation, surface drip irrigation, and subsurface drip irrigation. Comparing these results with those in Fig. 3a for the current irrigation system indicated a decrease in the charge flow to the aquifer due to applying the modified modern irrigation system, which led to a decline in groundwater heads in the eastern Nile delta.

4.3. 4.3. Effect of modified irrigation methods on SWI

The SEAWAT model was used to study the seawater intrusion in the aquifer before and after applying the modified irrigation methods: sprinkler irrigation, central pivot irrigation, surface drip irrigation, and subsurface drip irrigation, considering the base case of surface irrigation. The groundwater heads are presented in Fig. 6a, where the water level declined with the application of modern irrigation systems in the study. They are compared with the current situation presented in Fig. 3a.

The solute transport model results are shown in Fig. 6b. Comparing the results of Fig. 6b of the modified irrigation system with those in Fig. 3b for the current irrigation system shows a reduction in the aquifer recharge, which leads to further sweater intrusion into the aquifer and, consequently, in aquifer salinity. Furthermore, the intrusion length of the equi-concentration line 1000 ppm reached 94.30 km after applying the modified irrigation methods using pivot sprinkler irrigation, horizontal sprinkler irrigation, surface drip irrigation, and sub-surface drip irrigation, as shown in Fig. 6c compared with 90.4 km in Fig. 3c for the base case where surface irrigation was used.

Moreover, the mass salt balance for the four scenarios is simulated. The source IN of mass salt increased and reached 11.74 $\times 10^{13}$ kg compared to 11.13 $\times 10^{13}$ kg at the base case. Also, the sink-out mass salt increased and reached 8.35 $\times 10^{13}$ kg compared to 8 $\times 10^{13}$ kg at the base case. The total mass salt IN reached 11.74 $\times 10^{13}$ kg compared to 11.13 $\times 10^{13}$ kg at the base case, respectively. In contrast, the total mass salt OUT reached 11.74 $\times 10^{13}$ kg compared to 11.13 $\times 10^{13}$ kg at the base case. The aquifer salinity was increased due to the inflow of saltwater intrusion in the land direction due to the reduction of the aquifer recharge and the freshwater storage by applying the modern irrigation system.

The aquifer salt is different from the salt mass balance between the source IN and Sink Out; this salt is the saline water storage and reached 3.39 $\times 10^{13}$ kg (11.74 $\times 10^{13}$ kg - 8.35 $\times 10^{13}$ kg = 3.39 $\times 10^{13}$ kg) compared to 3.13 $\times 10^{13}$ kg (11.13 $\times 10^{13}$ kg - 8 $\times 10^{13}$ kg = 3.13 $\times 10^{13}$ kg) at the base case, with the changing percentage of aquifer salinity reaching +8 %.

5. Discussion

Salinity, water shortages, and low water quality are the main problems for agricultural production (Junk et al., 2013). A suitable irrigation system is required to address soil salinization based on soil conditions, water salinity level, crop type, and available resources (Armanuos and Negm, 2019). The lands affected by increased soil salinity were due to poor irrigation practices, high evaporation rates, and groundwater salinity (Mikhailova, 2001). The irrigation method greatly affects water consumption and crop productivity (Cominelli et al., 2013; Moursy et al., 2023).

Over the last three decades, irrigation improvement projects in Egypt have been tested, implemented, and modified to respond to several irrigation management challenges (Molle et al., 2019). This study simulated the base case of surface irrigation and four modified irrigation methods: sprinkler irrigation, central pivot irrigation, surface drip irrigation, and sub-surface drip irrigation. The results of the groundwater resources showed a decrease in aquifer flow when the modern irrigation system was applied. The total inflow decreased and reached 4923230 m^{3}day^{-1} and 4517,530 m^{3}day^{-1} before and after the modified irrigation system, respectively, representing a decrease of 8.20 %. In contrast, the total outflow decreased and reached 4923,275 m^3 day^{-1} and 4517,535 m^{3}day^{-1} before and after applying the modified irrigation system, respectively. This indicates that the freshwater in the aquifer is lowered, and more saltwater enters the aquifer, replacing the fresh groundwater. The results are in line with Shinawi et al. (2022), who showed that the decline in groundwater heads in the Nile Delta decreased and affected the water balance. Also, Pool et al. (2021) indicated that flood irrigation techniques using surface water are practiced on permeable soils, considered a major source of groundwater recharge and the predominant one in arid terrains. Abd-Elaty et al. (2022) studied the water budget in the Nile Delta for using the lining and

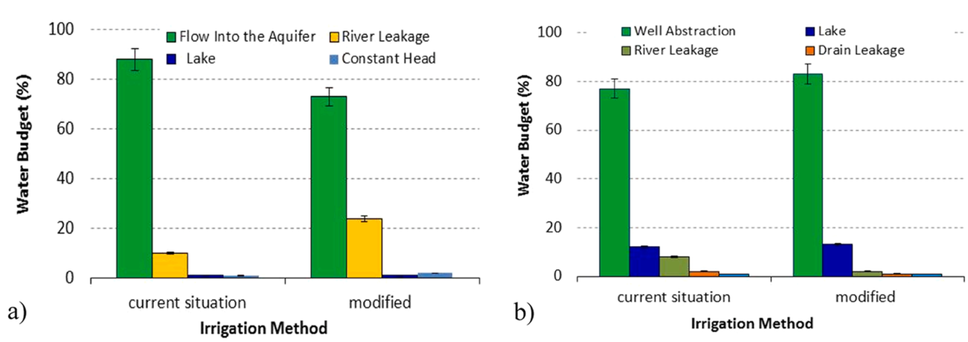

Fig. 5. Water zone budget for total inflows and total outflows.

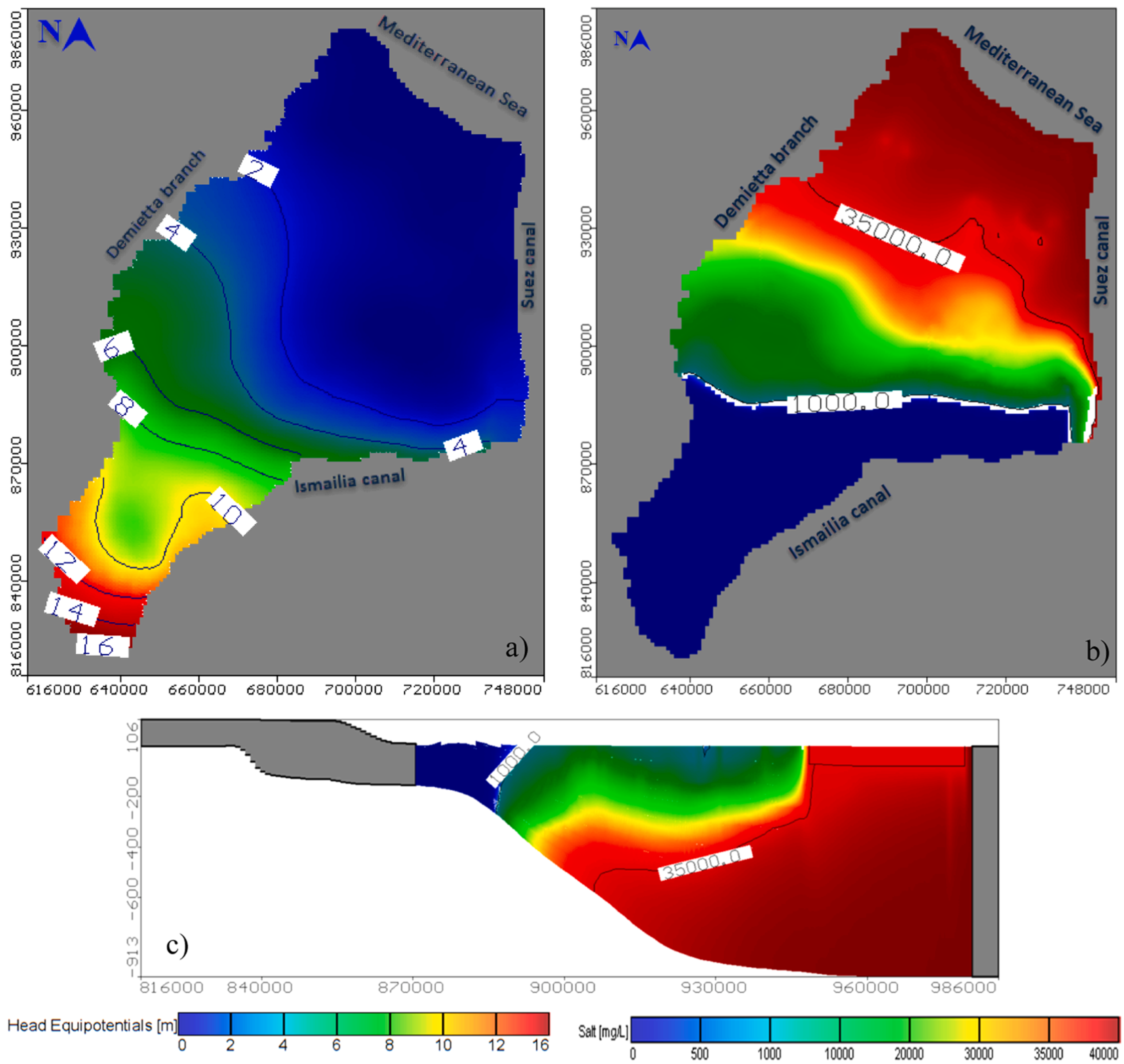

Fig. 6. Modified modern irrigation maps for a) A real view of Groundwater flows, b) A real view of TDS, and c) Vertical distribution of TDS.

covering of the irrigation canals. The results showed that decreasing the leakage from irrigation canals and rivers decreased the aquifer freshwater storage and the inflow. Abd-Elaty et al. (2023) studied the Impact of modern irrigation methods on groundwater storage and land subsidence in high-water stress regions in the Nile Delta Aquifer (NDA). Their study showed that changing irrigation methods Impacted land subsidence, and the groundwater drawdown reached 2.60 m, 4.20 m, and 6.50 m.

The salinity results of the aquifer increased and reached +8.20 when applying the four modified irrigation methods, sprinkler irrigation, subsurface drip irrigation, and drip irrigation, relative to the base case, as presented in Fig. 7. The results are consistent with those of Zaman et al. (2018), who showed that soil salinity depends on the irrigation method and the shape of the seedbeds for various irrigation systems. Foster et al. (2018) showed that reducing the utility of groundwater for the public and industrial water supply increases the salinity of water resources. Abd-Elaty et al. (2024) studied the impact of Grand Ethiopian Renaissance Dam (GERD) on water budget and the salinity including three filling scenarios were considered for the GERD reservoir at elevations 600 m, 621 m, and 645 m above mean sea level (AMSL) for the storage volumes of 17 billion cubic meters (BCM), 37.30 BCM and 74 BCM considering a combined SLR of 25 cm with increasing the pumping rates by 25%, 50%, and 100%, respectively. The results showed that the GERD reservoir filling could alter the freshwater, in which the aquifer salinity increased by 4.47%, 11.48%, and 29.99% for the three scenarios, respectively.

Moreover, the results showed that a modern irrigation system would increase the salt mass source IN and the Sink Out due to decreased freshwater storage in the aquifer and increased saltwater intrusion. Zaman et al. (2018) developed a field study that showed that selecting suitable irrigation systems, including the drip surface, subsurface, sprinkler, bubbler, and pore, can improve water use efficiency and manage root zone salinity. Moursy et al. (2023) showed that drip irrigation has high water use efficiency. However, the surface irrigation system gave high productivity value due to higher salinity, which required control of the salinity using additional leaching water. Eltarabily et al. (2023) studied the influence of climate change on evapotranspiration and groundwater recharge of the Nile Delta aquifer, Egypt; the study showed that the zone budget analysis revealed that the increase of evapotranspiration would decrease the inflow and decrease the groundwater head.

Fig. 7a shows the optimization area for modified irrigation methods for surface irrigation, which is 3621 km^2 by 64 %, sprinkler irrigation, 396.05 km^2 by 7 %, central pivot irrigation, 735.51 km^2 by 13 %, and surface drip irrigation, 735.51 km^2 by 13 %. In comparison, the subsurface drip irrigation is 169.73 km^2 by 3 %.

The soil types for gravelly sand and gravel, silty clay, clay loam, dissected sandy limestone, sand and clay loam, and sand and carbonates

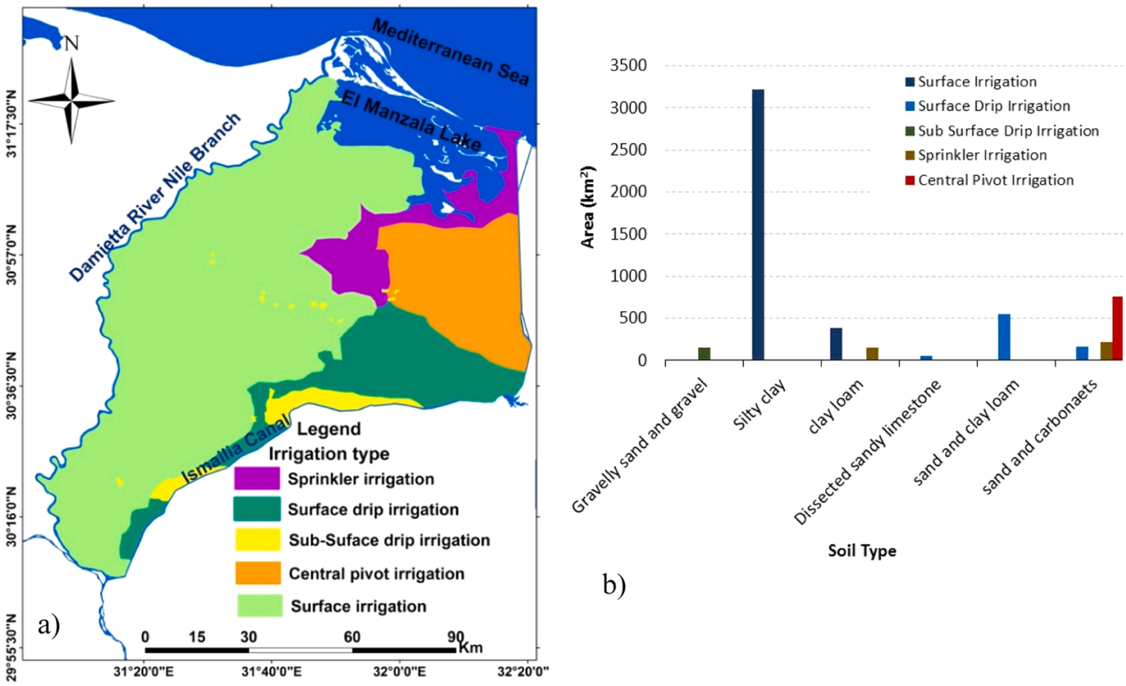

Fig. 7. Maps for (a) modified irrigation method and (b) agriculture area for each soil type.

reached 169.73 km^2, 3224.95 km^2, 509.20 km^2, 56.58 km^2, 565.78 km^2, and 1131.56 km^2 by 3 %, 57 %, 9 %, 1 %, 10 % and 20 % respectively (Fig. 7b). Also, the total area without surface water bodies (1162.61 km^2) is 8525.81 km^2, while the agricultural area including old land (565.78 km^2) and new reclamation (5092.02 km^2) is 5657.80 km^2.

Dengiz (2006) showed that drip irrigation increases land suitability by 38 % compared to surface irrigation. Rajurkar et al., (2012) showed that drip irrigation is an effective application for water and fertilizer management. Molle and Tanouti (2017) assessed the Green Morocco Plan, which subsidizes both the conversion to drip irrigation and the expansion of intensive farming. Berbel et al., (2019) showed that the use of modern irrigation systems has increased irrigation efficiency from 65 % to 87 % in Spain. Moursy et al., (2023) showed that the drip irrigation system gave the best value for efficient water use and water saving under different summer and winter crops. Also, the surface irrigation system had a higher productivity value compared with the drip irrigation system due to the decrease in soil and water salinity, so additional fresh water is required for soil leaching to sustain the salinity level in the soil. Kishor et al., (2024) showed that the application of drip irrigation led to enhanced crop and water productivity by reducing the frequency of irrigations or the overall water consumption.

The future influence of climate change on crop water consumption with the application of modern MIS could be considered in old land worldwide to manage irrigation water resources, especially in arid/semi-arid regions. This study is limited to estimating the impact of modern irrigation methods on saltwater intrusion and groundwater salinity only. Nevertheless, future studies are needed to assess the economic, social, and environmental impact of modern irrigation methods compared to this study and/or additional methods, especially under high stress in freshwater resources. Also, optimization modeling is required to select suitable crops and keep the soil water saline, especially in old delta's worldwide.

6. Conclusions

Managing agricultural irrigation water in arid and semi-arid regions impacted by saltwater intrusion (SWI) is crucial for sustaining freshwater resources. This study investigated the effects of transitioning irrigation methods in the Nile Delta's old agricultural lands, focusing on water savings and groundwater salinity in coastal aquifers. A combination of LINDO software for land optimization and SEAWAT codes for groundwater modeling was used to assess the impacts of modern irrigation systems on water management and aquifer health. The results revealed that implementing modified modern irrigation systems (MIS) in the Nile Delta reduced aquifer recharge from irrigation water, leading to increased river seepage and promoting saltwater intrusion (SWI) into the aquifer. Simultaneously, MIS significantly decreased crop water consumption, highlighting a trade-off between water savings and the impact on groundwater salinity. The land use optimization results, using LINDO software, indicated that surface irrigation covered 3,621 km^2 (64%), while modern irrigation systems (MIS) accounted for 390.4 km^2 (7%), 735.5 km^2 (13%), 735.5 km^2 (13%), and 175.4 km^2 (3%) for sprinkler, central pivot, surface drip, and subsurface drip, respectively. SEAWAT code water balance results showed a total inflow of 4,923.2 m^3/day, which decreased to 4,517.5 m^3/day after MIS application—an 8% reduction. The total outflow dropped from 4,923.3 m^3/day to 4,517.5 m^3/day.

Future research would focus on the effects of the MIS combined with other SWI management techniques to develop more effective irrigation strategies for the Nile Delta and similar regions globally. An economic feasibility study is also needed to assess the implementation of modern irrigation systems in the Nile Delta. The goal is to find a balance between water conservation and promoting aquifer recharge, especially in areas dependent on groundwater resources.

Ethics approval

Not applicable.

Consent to participate

Yes.

Consent for publication

Yes.

Funding

This study did not receive any funding.

CRediT authorship contribution statement

Ismail Abd-Elaty: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ibrahim Elbagory:** Writing – review & editing, Writing – original draft, Software, Conceptualization. **Sayed Muktar:** Writing – review & editing, Validation, Formal analysis, Data curation, Visualization, Validation. **Alban Kuriqi:** Writing – review & editing, Supervision. **Ahmed M. Nosair:** Writing – review & editing, Visualization, Resources, Data curation. **Ashraf A. Ahmed:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition. **Luis Garrote:** Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

Acknowledgment

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 (https://doi.org/10.54499/UIDB/04625/2020).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2024.109064.

References

Abd-Elaty, I., Fathy, I., Kuriqi, A., John, A.P., 2023. Impact of Modern Irrigation Methods on Groundwater Storage and Land Subsidence in High-water Stress Regions. Water Resour. Manag. 1 (14).

Abd-Elaty, I., Kuriqi, A., Ramadan, E.M., Ahmed, A.A., 2024. Hazards of sea level rise and dams built on the River Nile on water budget and salinity of the Nile Delta aquifer. ISSN 2214-5818 J. Hydrol. Reg. Stud. Volume 51 (2024), 101600. https://doi.org/10.1016/j.ejrh.2023.101600.

Abd-Elaty, I., Sallam, G.A., Strafacec, S., Scozzari, A., 2019. Effects of climate change on the design of subsurface drainage systems in coastal aquifers in arid/semi-arid regions: Case study of the Nile delta. Sci. Total Environ. 672, 283–295. https://doi.org/10.1016/j.scitotenv.2019.03.483.

Abd-Elaty, I., Straface, S., Kuriqi, A., 2021. Sustainable saltwater intrusion management in coastal aquifers under climatic changes for humid and hyper-arid regions. Ecol. Eng. Vol (171. https://doi.org/10.1016/j.ecoleng.2021.106382.

Abd-Elaty, I., Zelenakova, M., 2022. Saltwater intrusion management in shallow and deep coastal aquifers for high aridity regions. J. Hydrol. Reg. Stud. 40, 101026. https://doi.org/10.1016/j.ejrh.2022.101026.

Abd-Elaty, I., Pugliese, L., Bali, K.M., Grismer, M.E., Eltarabily, M.G., 2022. Modelling the impact of lining and covering irrigation canals on underlying groundwater stores in the Nile Delta, Egypt. Hydrol. Process. 36, e14466.

Abu Salem, H.S., Gemail, K.S., Junakova, N., Ibrahim, A., Nosair, A.M., 2022. AnIntegrated Approach for Deciphering Hydrogeochemical Processes during SeawaterIntrusion in Coastal Aquifers. Water (Switzerland) 14 (7). https://doi.org/10.3390/w14071165.

Ali, R.R., 2012. The impact of land degradation on soil productivity in irrigated agriculture: a case study from El sharkia governorate, Egypt. Aust. J. Basic Appl. Sci. 6 (12), 453–463.

Alnaimy, M.A., Shahin, S.A., Afifi, A.A., Ewees, A.A., Junakova, N., Balintova, M., Abd Elaziz, M., 2022. Spatio prediction of soil capability modeled with modified RVFL using Aptenodytes forsteri optimization and digital soil assessment technique. Sustainability 14 (22), 14996. https://doi.org/10.3390/su142214996.

Al-Saidi, M., Elagib, N.A., Ribbe, L., Schellenberg, T., Roach, E., Oezhan, D., 2017. Water-energy-food security nexus in the eastern Nile Basin: assessing the potential of transboundary regional cooperation. Water-Energy-Food Nexus. Princ. Pract. Geophys Monogr. 229, 103–116.

Aly, M.M., Sakr, S.A., Zayed, M.S.M., 2022. Selection of the optimum locations for rainwater harvesting in arid regions using WMS and remote sensing. Case Study: Wadi Hodein Basin, Red Sea, Egypt. Alex. Eng. J. 61, 9795–9810. https://doi.org/10.1016/j.aej.2022.02.046.

Arafa, N.A., Zenhom, E.S., Ghorab, M.A., Soliman, S.A., Abdeldayem, A.L., Moustafa, Y. M., Hosni, H., Ghazala, H.H., 2022. Evaluation of groundwater sensitivity to pollution using GIS-Based Modified DRASTIC-LU model for sustainable development in the Nile Delta Region. Sustainability 14 (2022), 14699. https://doi.org/10.3390/su142214699.

Armanuos, A.M., Negm, A., 2019. Integrated Groundwater Modeling for Simulation of Saltwater Intrusion in the Nile Delta Aquifer, Egypt. In: Negm, A.M. (Ed.), Groundwater in the Nile Delta. Springer International Publishing, Cham, pp. 489–544.

Berbel, J., Expósito, A., Gutiérrez-Martín, C., Mateos, L., 2019. Effects of the irrigation modernization in Spain 2002–2015, 2019 Water Resour. Manag. 33 (5), 1835–1849. https://doi.org/10.1007/s11269-019-02215-w.

Chen, B., Jiang, C., Wang, Y., Fu, R., Liu, Z., Xu, T., 2018. Selectrodialysis with bipolar membrane for the reclamation of concentrated brine from RO plant. Desalination 442, 8–15. https://doi.org/10.1016/j.desal.2018.04.031.

Cominelli, E., Conti, L., Tonelli, C., Galbiati, M., 2013. Challenges and perspectives to improve crop drought and salinity tolerance. N. Biotechnol. 30, 355–361. https://doi.org/10.1016/j.nbt.2012.11.001.

CONOCO. (Continental Oil Company). Geological Map of Egypt (Scale 1: 500,000); Continental Oil Company Inc.; Freie Universitat Berlin—Universitat Berlin: Berlin, Germany, 1987.

Dawoud, M.A., Darwish, M.M., El-Kady, M.M., 2005. GIS-Based Groundwater Management Model for Western Nile Delta. Water Resour Manage 19, 585–604. https://doi.org/10.1007/s11269-005-5603-z.

Dengiz, O., 2006. A Comparison of different irrigation methods based on the parametric evaluation approach. Turk. J. Agric. For. 30 (2006), 21–29.

Devi, S., Srivastava, D.K., Mohan, C., 2004. Optimal water allocation for the transboundary Subernarekha River, India. J. Water Resour. Plan. Manag. 131 (4). https://doi.org/10.1061/(ASCE)0733-9496(2005)131:4(253).

Ding, Z., Koriem, M.A., Ibrahim, S.M., Antar, A.S., Ewis, M.A., He, Z., Kheir, A.M.S., 2020. Seawater intrusion impacts on groundwater and soil quality in the northern part of the Nile Delta, Egypt. Environ. Earth Sci. 79, 313. https://doi.org/10.1007/s12665-020-09069-1.

DRI (1989) Drainage Research Institute, Cairo, Egypt: Land Drainage in Egypt, edited by: Amer, M. H. and de Ridder, N. A., Drainage Research Institute, Cairo, Eg.

Elewa, H.H., Shohaib, R.E., Qaddah, A.A., Nousir, A.M., 2013. Determining groundwater protection zones for the Quaternary aquifer of northeastern Nile Delta using GIS-based vulnerability mapping. Environ. earth Sci. 68, 313–331.

Elewa H.H., Zelenakova M., Nosair A.M. (2021) Integration of the Analytical Hierarchy Process and GIS Spatial Distribution Model to Determine the Possibility of Runoff Water Harvesting in Dry Regions: Wadi Watir in Sinai as a Case Study. Water.

El-Fayoumy, I.F., 1968. Geology of groundwater supplies in the Eastern region of the Nile Delta and its extension in the North Sinai. PhD thesis. Fac. Sci. Cairo Univ. Egypt 1–207.

Eltarabily M.G., Abd-Elaty I., Elbeltagi A., Zeleňáková M., Fathy I. (2023) Investigating Climate Change Effects on Evapotranspiration and Groundwater Recharge of the Nile Delta Aquifer, Egypt. Water.

Eltarabily, M.G., Moghazy, H., Abdel-Fattah, S., Negm, A.M., 2020. The use of numerical modeling to optimize the construction of lined sections for a regionally-significant irrigation canal in Egypt. Environ. Earth Sci. 79, 80.

Farid M.S. (1980) Nile Delta Groundwater study. Cairo University.

Foster, S., Pulido-Bosch, A., Vallejos, Á., Molina, L., Llop, A., MacDonald, A., 2018. Impact of irrigated agriculture on groundwater-recharge salinity: a major sustainability concern in semi-arid regions, 26, 2781–2791.

Francis, M., Anbananthen, K.S.M., Chelliah, D., Kannan, S., Subbiah, S., Krishnan, J., 2023. Smart farm-care using a deep learning model on mobile phones. Emerg. Sci. J. 7 (2), 480–497.

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 Pollut. 235, 127. https://doi.org/10.1007/s11270-024-06934-8.

Gad, W.A., 2017. Water scarcity in Egypt: causes and consequences. IIOAB J. 8, 40–47.

Guo W., Langevin C.D. (2002) User's guide to SEAWAT: A computer program for the simulation of three-dimensional variable-density ground-water flow. USGS Techniques of Water Resources Investigations Book 6, Chapter A7. USGS.

Gupta, A.; Saini, R.; Sharma, M. Modelling of Hybrid Energy System for Off Grid Electrification of Clusters of Villages. In Proceedings of the 2006 International Conference on Power Electronic, Drives and Energy Systems, New Delhi, India, 12–15 December 2006; pp. 1–5. 10.1109/PEDES.2006.344272.

Ibrahim G.R., Rasul A., Ali Hamid A., Ali Z.F., Dewana A.A. (2019) Suitable Site Selection for Rainwater Harvesting and Storage Case Study Using Dohuk Governorate. Water.

Imbulana, S., Oguma, K., Takizawa, S., 2020. Evaluation of groundwater quality and reverse osmosis water treatment plants in the endemic areas of Chronic Kidney Disease of Unknown Etiology (CKDu) in Sri Lanka. Sci. Total Environ. 745, 140716. https://doi.org/10.1016/j.scitotenv.2020.140716.

Jalali, M., 2007. Salinization of groundwater in arid and semi-arid zones: an example from Tajarak, western Iran. Environ. Geol. 52, 1133–1149. https://doi.org/10.1007/s00254-006-0551-3.

Junk, W.J., An, S., Finlayson, C.M., Gopal, B., Květ, J., Mitchell, S.A., Mitsch, W.J., Robarts, R.D., 2013. Current state of knowledge regarding the world's wetlands and their future under global climate change: a synthesis. Aquat. Sci. 75, 151–167. https://doi.org/10.1007/s00027-012-0278-z.

Kasem, A.M., Xu, Z., Jiang, H., Liu, W., Zhang, J., Nosair, A.M., 2024. Nitrate Source and Transformation in Groundwater under Urban and Agricultural Arid Environment in the Southeastern Nile Delta, Egypt. water 16, 22. https://doi.org/10.3390/w16010022.

Khare, D., Jat, M., 2006. Ediwahyunan Assessment of counjunctive use planning options: a case study of Sapon irrigation command area of Indonesia. J. Hydrol. 328, 764–777. https://doi.org/10.1016/j.jhydrol.2006.01.018.

Kishor, N., Manoj Khanna, G.A., Rajanna, Man Singh, Anupama Singh, Shrawan Singh, Tirthankar Banerjee, Neeraj Patanjali, Jitendra Rajput, B., Kiruthiga, 2024. Soil water distribution and water productivity in red cabbage crop using superabsorbent polymeric hydrogels under different drip irrigation regimes. ISSN 0378-3774 Agric. Water Manag. Volume 295 (2024), 108759. https://doi.org/10.1016/j.agwat.2024.108759.

Kummu, M., Ward, P.J., de Moel, H., Varis, O., 2010. Is physical water scarcity a new phenomenon? Global assessment of water shortage over the last two millennia. Environ. Res. Lett. 5, 034006. https://doi.org/10.1088/1748-9326/5/3/034006.

Mabrouk M., Jonoski A., Oude Essink G.H.P., Uhlenbrook S. (2019) Assessing the Fresh–Saline Groundwater Distribution in the Nile Delta Aquifer Using a 3D Variable-Density Groundwater Flow Model. 11:1946.

Mabrouk, M.B., Jonoski, A., Solomatine, D., Uhlenbrook, S., 2013. A review of seawater intrusion in the Nile Delta groundwater system – the basis for assessing impacts due to climate changes and water resources development. Hydrol. Earth Syst. Sci. Discuss. 10, 10873–10911. https://doi.org/10.5194/hessd-10-10873-2013.

Mahmoud, M.A., El-Bably, A.Z., 2019. Crop Water Requirements and Irrigation Efficiencies in Egypt. In: Negm, A.M. (Ed.), Conventional Water Resources and Agriculture in Egypt. Springer International Publishing, Cham, pp. 471–487.

Mikhailova, M.V., 2001. Hydrological Regime of the Nile Delta and Dynamics of Its Coastline. Water Resour. 28, 477–490. https://doi.org/10.1023/A:1012320920434.

Moghazy, N.H., Kaluarachchi, J.J., 2020. Assessment of groundwater resources in Siwa Oasis, Western Desert, Egypt. Alex. Eng. J. 59, 149–163. https://doi.org/10.1016/j.aej.2019.12.018.

Molle, F., Rap, E., Al-Agha, D.E., Abou El Hassan, W., Freeg, M., 2019. Irrigation improvement projects in the Nile Delta: Promises, challenges, surprises. Agric. Water Manag. 216, 425–435.

Molle, F., Tanouti, O., 2017. Squaring the circle: agricultural intensification vs. water conservation in Morocco. Agric. Water Manag 192 (Supplement C), 170–179. https://doi.org/10.1016/j.agwat.2017.07.009.

Morsy W.S. (2009) Environmental management to groundwater resources for Nile Delta region.

Moursy, M.A.M., ElFetyany, M., Meleha, A.M.I., El-Bialy, M.A., 2023. Productivity and profitability of modern irrigation methods through the application of on-farm drip irrigation on some crops in the Northern Nile Delta of Egypt. ISSN 1110-0168 Alex. Eng. J. Volume 62 (2023), 349–356. https://doi.org/10.1016/j.aej.2022.06.063.

Moursy, M.A.M., ElFetyany, M., Meleha, A.M.I., El-Bialy, M.A., 2023. Productivity and profitability of modern irrigation methods through the application of on-farm drip irrigation on some crops in the Northern Nile Delta of Egypt. Alex. Eng. J. 62, 349–356. https://doi.org/10.1016/j.aej.2022.06.063.

Nosair, A.M., Shams, M.Y., AbouElmagd, L.M., Hassanein, A.E., Fryar, A.E., Abu Salem, H.S., 2022. Predictive model for progressive salinization in a coastal aquifer using artificial intelligence and hydrogeochemical techniques: a case study of the Nile Delta aquifer, Egypt. Environ. Sci. Pollut. Res. 29, 9318–9340.

Pool, S., Francés, F., Garcia-Prats, A., Puertes, C., Pulido-Velazquez, M., Sanchis-Ibor, C., Schirmer, M., Yang, H., Jiménez-Martínez, J., 2021. Hydrological modeling of the effect of the transition from flood to drip irrigation on groundwater recharge using multi-objective calibration. Water Resour. Res. 57, e2021WR029677.

Pulido-Bosch, A., Rigol-Sanchez, J.P., Vallejos, A., Andreu, J.M., Ceron, J.C., Molina-Sanchez, L., Sola, F., 2018. Impacts of agricultural irrigation on groundwater salinity. Environ. Earth Sci. 77, 197. https://doi.org/10.1007/s12665-018-7386-6.

Rajurkar, G., Patel, N., Rajput, T.B.S., Varghese, C., 2012. Varghese soil water and nitrate dynamics under drip irrigated cabbage. J. Soil Water Conserv. 11 (2012), 196–204.

Ramadan, Elsayed M., Abdelwahab, Heba F., Vranayova, Zuzana, Zelenakova, Martina, Negm, Abdelazim 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. https://doi.org/10.3390/w13182481.

Salem, Z.E., Hasan, S.S., 2021. Use of GALDIT model and HFE-Diagram to assess seawater intrusion vulnerability in West Nile Delta, Egypt. Arab. J. Geosci. 14, 1318. https://doi.org/10.1007/s12517-021-07678-z.

Sallouma M.K.M. (1983) Hydrogeological and hydrochemical assessment of the Quaternary aquifer in the eastern Nile Delta, Egypt: PhD thesis. Faculty of Science, Ain Shams University, Egypt, p 166.

Sherif, M., Sefelnasr, A., Javadi, A., 2012. Incorporating the concept of equivalent freshwater head in successive horizontal simulations of seawater intrusion in the Nile Delta aquifer, Egypt. J. Hydrol. 464–465, 186–198.

Shinawi, A.E., Zeleňáková, M., Nosair, A.M., Abd-Elaty, I., 2022. Geo-spatial mapping and simulation of the sea level rise influence on groundwater head and upward land subsidence at the Rosetta coastal zone, Nile Delta, Egypt. J. King Saud. Univ. - Sci. 34, 102145. https://doi.org/10.1016/j.jksus.2022.102145.

Siebert, S., Burke, J., Faures, J.M., Frenken, K., Hoogeveen, J., Döll, P., Portmann, F.T., 2010. Groundwater use for irrigation – a global inventory. Hydrol. Earth Syst. Sci. 14, 1863–1880. https://doi.org/10.5194/hess-14-1863-2010.

Varlet, M., 1923. Étude Graphique des Conditions d'Exploitation d'un Réservoir de Régularisation. Ann. Ponts Chauss-.-. ées Partie Technol. 2, 93.

Vinci, G., Maddaloni, L., Mancini, L., Prencipe, S.A., Ruggeri, M., Tiradritti, M., 2021. The Health of the Water Planet: challenges and opportunities in the Mediterranean Area. An overview. Earth 2, 894–919.

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 (4), 102776. https://doi.org/10.1016/j.asej.2024.102776. ISSN 2090-4479.

Yazdanpanah, M., Zobeidi, T., Mirzaei, A., et al., 2023. Comparison of different modern irrigation system adopters through socio-economic, innovation characteristics and social capital values. Reg. Environ. Change 23, 152. https://doi.org/10.1007/s10113-023-02147-7.

Zaghloul, M.G. (1958). Flow distribution through the groundwater aquifer of the Nile Delta. Master thesis, Faculty of Engineering, Alexandria University, Cairo – Egypt.

Zaman M., Shahid S.A., Heng L. (2018) Guideline for salinity assessment, mitigation and adaptation using nuclear and related techniques. Springer Nature.

Zheng C., Wang P.P. (1999) MT3DMS: A Modular Three- Dimensional Multispecies Transport Model for Simulation of Advection, Dispersion and Chemical Reactions of Contaminants in Groundwater Systems. Vicksburg, Mississippi: Waterways Experiment Station, U.S. Army Corps of Engineers.