




Impact of Modern Irrigation Methods on Groundwater Storage and Land Subsidence in High-water Stress Regions

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Abstract

Water resources management in high-stress regions is a large-scale problem affecting food and water security. Therefore, modern irrigation systems such as sprinklers, subsurface, and drip irrigations are applied to manage the water shortage in regions of the Nile delta. Because of the increase in population rate and climate change, freshwater supplies are significantly limited and must be efficiently managed. Consequently, Egypt plans to implement MIS in the old land of the Nile delta. The current study aims to investigate and model the recharge from the excess irrigation system that affects groundwater storage and land subsidence unexpectedly. The visual modflow was applied to investigate the groundwater heads and drawdown. At the same time, the analytical solution based on Terzaghi theory, and the surfer software was used to estimate and map the land subsidence.

For this reason, we investigated the groundwater drawdown in the high-water shortage of Egypt's Nile delta. Three scenarios were considered by changing irrigation methods and their impact on land subsidence in the Nile Delta Aquifer (NDA). Therefore, the results of this study demonstrated that the groundwater drawdown reached 2.60 m, 4.20 m, and 6.50 m, respectively. In contrast, the land subsidence outstretched 26 m, 44 m, and 65 cm for the sprinkle sub-surface. Future design infrastructures such as pipelines, roads, irrigation networks, canals, and water structures should consider land subsidence due to modern irrigation systems (MIS).

Keywords Drawdown · Land subsidence · Modern irrigation · Nile delta · Visual Mudflow

1 Introduction

Subsidence due to the rearrangement of the soil grains is a vertical movement of the surface of the Earth by compression of unconsolidated and partly consolidated sediments. Subsequently, land subsidence has greatly affected infrastructures such as roads, buildings, railways, pipeline networks, irrigation lining canals, closed pipes, drains, earth berms, and banks (El Shinawi et al. 2022; Maliva 2021). The retaining walls were subjected to failure

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due to sliding. Furthermore, irrigation structures for crossing work, namely bridges, culverts, siphons, aqueducts, and heading-up structures, including weirs, regulators, and dams, are subjected to differential settlement due to land subsidence and the influence stability of the structures. (Bagheri-Gavkosh et al. 2021).

The subsidence rate of the Nile delta in the coastal region is 8 mm year^{-1} , with a relatively lower 4 to 6 mm year^{-1} around the Manzala lagoon (Becker and Sultan 2009). Also, Fugate (2014) found subsidence rates of 8 mm year^{-1} with a maximum of about 10 mm year^{-1} .

As we all know, irrigation is the most important water use sector, accounting for approximately 70% of worldwide freshwater withdrawals and 90% of consumptive water use. There are four types of irrigation systems in Egypt, depending on how water is applied to the land: (1) surface irrigation, (2) sprinkler irrigation, (3) drip irrigation, and (4) sub-surface irrigation systems. Surface irrigation is often called flood irrigation, in which water moves by gravity surface flow (Elmesery 2020). The most common problem associated with surface irrigation is water loss through seepage due to inadequate water at the beginning of the irrigation route. Sprinkler irrigation is a technique in which water is sprayed in small water droplets into the air, much like natural rainfall (Abdelhafez et al. 2020; Elmesery 2020). The disadvantage of sprinkle irrigation is that most water is lost when it leaves the nozzle and reaches the soil. Drip irrigation, often known as trickle irrigation, is a technique in which water is applied to plants' roots in small drops (Chhabra 2021; Issaka et al. 2018).

Drip irrigation is regarded as the most effective type of water irrigation. It typically has an efficiency of 80–90%. In addition, subsurface irrigation is a technique that applies precise volumes of water straight to the root zone. Also, subsurface irrigation is applied in locations where the water table is artificially increased to moisture below the root zone of the plants. Subsurface irrigation is ideal for medium to large-scale production because it is relatively complex and is likely automated. In Egypt, surface irrigation was the most frequent irrigation method total of $6683 \text{ m}^3 \text{ fed}^{-1}$, $4010 \text{ m}^3 \text{ fed}^{-1}$, $2798 \text{ m}^3 \text{ fed}^{-1}$, and $2619 \text{ m}^3 \text{ fed}^{-1}$ of irrigation water were applied by the surface, sprinkler, subsurface, and drip systems, respectively (Abu-Hashim et al. 2021). As a result, the largest amount of excessive irrigation water is from surface irrigation systems. The lowest amount of excessive irrigation water comes from drip irrigation systems. Excessive irrigation water affects the aquifer recharge as the aquifer is recharged through percolation from excess irrigation water, rainfall, and seepage from river branches, canals, and drainage systems. Decreased excess irrigation water leads to decreased aquifer recharge. Sprinkle, subsurface, and drip irrigation systems reduced aquifer recharge by 60, 39.2, and 20%, individually, except for surface irrigation systems (Eltarabily and Negm 2019; Mohamed 2020). As aquifer recharge decreased with constant abstraction rates, the groundwater level dropped, so land subsidence occurred.

Numerical models and analytical solutions predict the land subsidence in the Nile delta aquifer due to changing modern irrigation methods in the future. On that account, SURFER 13 is also used to map ground heads and the subsidence in the study area. Moreover, the future management of land subsidence hazards for applying the MIS should be considered today to mitigate its negative impact on groundwater resources. Therefore, possible remedial measures can be taken to reduce groundwater pumping in the study region.

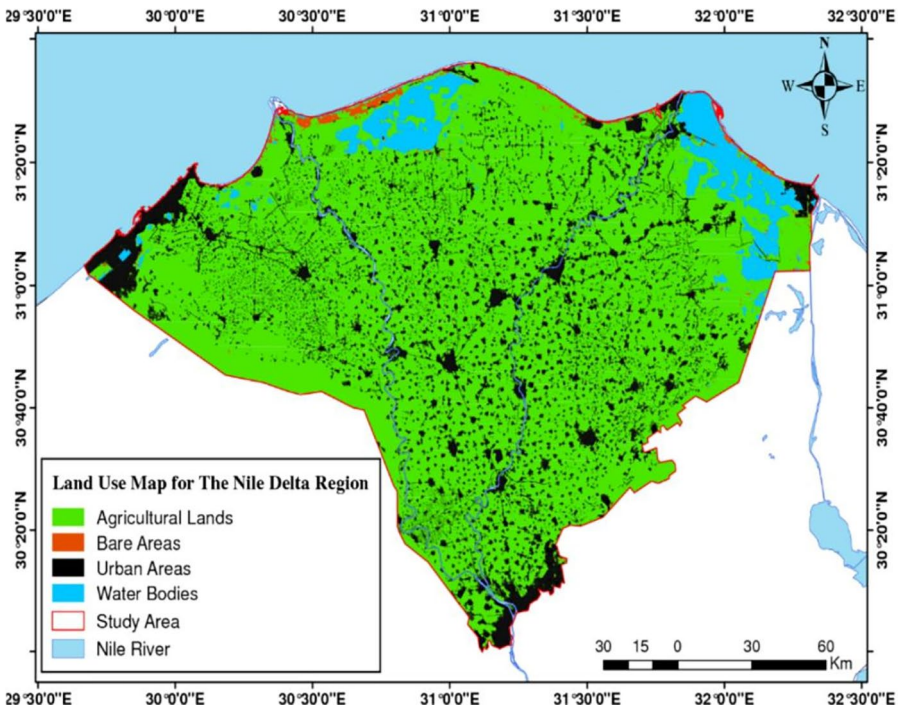


Fig. 1 Study case location, adapted after El-Quilish et al. (2023)

2 Materials and Methods

2.1 Study Site

The study area is in the northwest part of the Nile delta between Latitudes $30^{\circ} 00'$ and $31^{\circ} 45' N$ and longitudes $29^{\circ} 30'$ and $32^{\circ} 30' E$ (Fig. 1). Egypt is the most populous country in the Middle East and the third most populous African continent, with nearly 97% of the country's 82.5 million (2012 estimate). The projected population of Egypt is estimated as 104 million by 2025 and 146 million by 2050, and 237 million by 2100 (Abd-Elaty et al. 2021b; Gado and El-Agha 2021). The Nile delta and the narrow valley of the Nile comprise 5.5% of the total area of Egypt (Abd-Elaty et al. 2019). Due to the concentration of most of the infrastructure and development in Egypt, along with low coastal lands and the reliance on the Nile delta for prime agricultural land, coastal floods or saline intrusion caused by anthropogenic climate change-induced sea-level rise will have a direct and critical impact on the entire economy (Abutaleb et al. 2018).

The study of the face of terrain and its genesis, structure, and topography (Thornbury, 1969). The ground elevation ranges between about 18 m above mean sea level (AMSL) in the south at Knater El-Khairia to about 5 m (AMSL) near Tanta, sloping very gently in the northward direction by an average value of 1 m/10 km (Saleh, 1980).

The current Evaporation rates in Egypt range from 7 mm day^{-1} in upper Egypt to about 4 mm day^{-1} on the Northern Mediterranean coast (Abd-Elaty and Zelenakova, 2022; Abutaleb et al., 2018; Alheiji et al., 2021).

2.2 Geological Properties

Groundwater-bearing formations in the Nile Delta can be differentiated into two main aquifer systems: tertiary aquifers. There are the Miocene, Oligocene, and Eocene aquifers. The second is quaternary aquifers, in which the Holocene aquifer mainly comprises silt and sandy clay. Its thickness ranges from 10 to 70 m. The Pleistocene aquifer, which underlies the clay cap rock to 1000 m, consists of graded quartzitic sands with clay lenses (Hegazy et al. 2020).

The early Pleistocene is composed of loose coarse quartzitic sands and cherty pebbles with thicknesses reaching 500 m in the Mit Ghamr area and about 900 m at El Matariya. The Middle Pleistocene comprises coarse-grained Quartzitic sands and gravels with discontinuous occasional clay lenses with an average thickness of 700 m (Hefny, 1980). The Late Pleistocene can be divided into old fluviomarine deposits, composed of alternating sands and clay capped by a thin hard crusty sandy limestone bed in some places with a considerable thickness of about 70 m at Port Said. Fluvial deposits (River sands) are composed of fine to medium quartzitic sands with thin intercalations of clay and silt with a maximum thickness of about 30 m (El Shazly, et al. 1975).

2.3 Hydrological and Hydraulic Characteristics

Egypt's current irrigation water delivery system was developed over the past century with barrage construction on the Nile in 1861. About 80% of irrigation water was delivered from the river source (Abd-Elaty et al. 2021a). The groundwater level in the study area ranges between 16.96 m above mean sea level (a.m.s.l) at the southern border and 0 m a.m.s.l at the northern border (Abd-Elaty et al. 2019).

Three sources consider the recharge of groundwater in the study area. The first source comes from rainfall, with an average rainfall of $25 \text{ mm per year}^{-1}$ (Mohamed 2020). The second source is the results of the downward leakage due to irrigation excess water (i.e., originating from the River Nile), and canal infiltration towards the aquifer ranges between 0.25 and 0.80 mm day^{-1} , depending on the soil type, irrigation, and drainage practices. The third source is an inter-aquifer flow to groundwater (Abd-Elhamid et al. 2019; Abdelhafez et al. 2020). Abstraction rates in the last 30 years increased between 1980–and 2010 (Mohamed 2020). In 2010, extraction wells reached about $4.6 \times 10^9 \text{ m}^3 \text{ year}^{-1}$. The increase of abstraction from the Nile Delta is linearly by about $0.1 \times 10^9 \text{ m}^3 \text{ year}^{-1}$, except from 2003 to 2010. The abstraction increases dramatically at a rate of $0.2 \times 10^9 \text{ m}^3 \text{ year}^{-1}$ (Ding et al. 2020).

2.4 Numerical Simulation

The finite difference of SEAWAT code used in a miscible variable-density process is applied for the current study. The code was applied for different areas and gave good simulation results (Mukherjee et al., 2007; Garg et al., 2016; Sandip and Mahanta, 2019). The SEA-

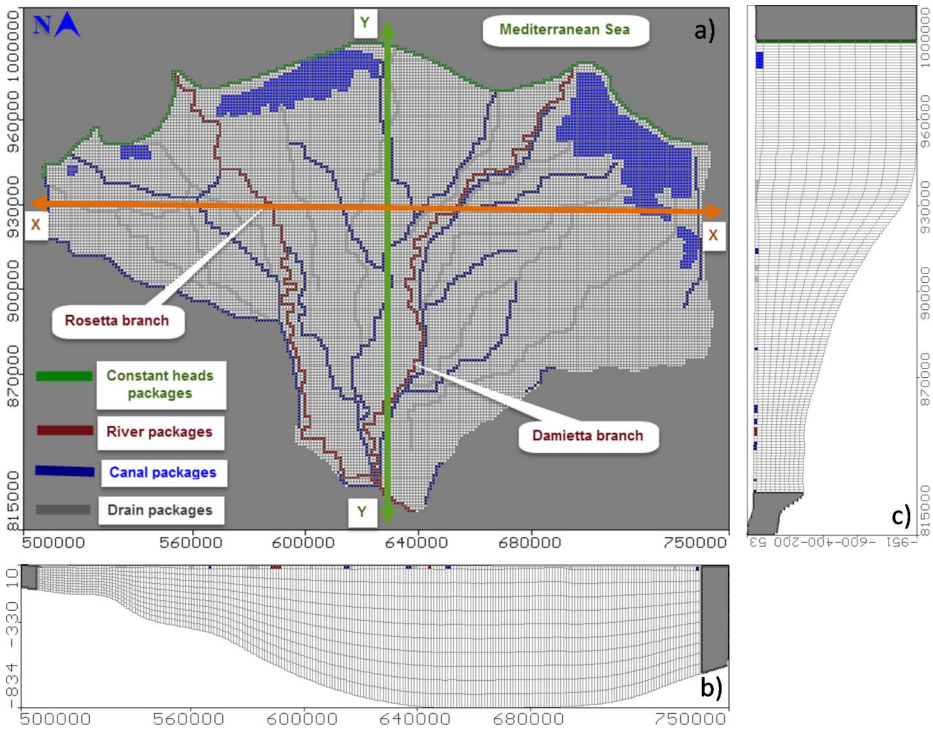


Fig. 2 Digitized simulation model and boundary conditions for WNDA: (a) aerial view, (b) vertical section in the Y-Y direction and (c) vertical section in the X-X direction

WAT is governed by the equations coupled system of flow and transport (Langevin et al. 2008) to simulate the current and future scenarios for groundwater flow and salt transport in the current study area of the NDA under different irrigation methods. The model input data include topographical, stratigraphy levels, hydraulic parameters, and boundary conditions.

2.4.1 Geometry and Digitalization

The stratigraphy model is the first step in the model development; it was built using Modflow, utilizing 260 columns and 194 rows for active and inactive cells (Borgia et al. 2011; Harbaugh 2005). The cell dimension was 1×1 km, as shown in Fig. 2, with a variable depth of 1000 m at the sea's shoreline and 400 m at Cairo. The model was divided into ten layers based on the hydrological data of the aquifer layers. The levels of each layer were assigned in the Mudflow using the grid module. The first layer represents a clay cap, and the topographical features are used in the top layer. In contrast, the Other layers from the second to the tenth represented the Quaternary aquifer divided into equal thicknesses. The first layer varied in depth between 20 m in the South and 50 m in the North; this clay cap maintains the Quaternary aquifer as a semi-confined aquifer.

Quaternary layers represent the main body of the aquifer, increasing from South to North with an average depth of 200 m near Cairo to 1000 m at the coastline, respectively, with silty and sandy clay.

Table 1 The calibrated input values of the hydraulic parameters for the Nile Delta aquifer

Hydraulic Parameters	Horizontal hydraulic conductivity (K_h) (m day ⁻¹)	Vertical hydraulic conductivity (K_v) (m day ⁻¹)	Effective Porosity (n_{eff})(-)	Total Porosity (n_T) (-)	Specific Storage (Ss) (1/m)	Specific yield (Sy) (-)
Aquitard	0.10–0.25	0.01–0.025	50–60	55	1×10^{-7}	0.10
Quaternary	5–100	0.50–10	20–30	0.25–0.40	0.0005–0.0025	0.15–0.20

Two vertical sections took in the middle of the model in two directions: the first in X-direction from the East at Suez Canal to the west at Nubaria canal, the second in Y-direction from the North at the coastal area to the South in Cairo as shown in Fig. 2a and b respectively. The topography of the ground surface level in the model varies from zero level to 18.00 above MSL. The thickness of the clay layer between 20 and 50 m increases at the north boundary.

2.4.2 Hydrological Conditions

The model's boundary and the hydrological setting were established at the Northern boundary. The constant head was assigned using Dirichlet boundary conditions at the Northern boundary bounded as zero value along the shoreline. The constant head bounded the south boundary as 16.96 m above a.m.s.l. The east boundary was left free because of the flow of water perpendicular to the contour line of water. The Ismailia canal constrained the southeast boundary as the water level in the field started at 16.17 m from South to 7.01 m east a.m.s.l. El Rayah El Behery bounded the southwest boundary and Nubaria canal as the water level in the field starts at 16.00 m from the South to 0.50 m to the north a.m.s.l.

2.4.3 Hydraulic Parameters

The initial values of hydraulic parameters in the study area used as input data are presented in Table 1. Since the clay unit is absent in the area of the turtleback, recharge to groundwater depends on the values of water seepage from the canal plus the excess water from the irrigation process and rainfall value (Abutaleb et al. 2018).

The meteorological factors such as limited rainfall values, evapotranspiration, and infiltration were considered in the study area, and the net infiltration towards the aquifer was assigned between 0.25 mm day^{-1} and 0.80 mm day^{-1} . Therefore, the abstraction wells from groundwater were assigned as the data collected by RIGW. The total abstraction rate in the study area was $2.78 \times 10^9 \text{ m}^3 \text{ year}^{-1}$ in 2008 for individual wells. The initial concentration and sink terms for salt are assigned by 1000 ppm.

2.4.4 Analytical Solution for Land Subsidence

The analytical solution for estimation LS is applied in the current study based on the consolidation due to change in effective stress (σ_e). The solution is based on the Terzaghi 1D consolidation theory of Terzaghi et al. (1996). Therefore, the aquifer-specific storage is $S_s = \gamma_w \alpha$.

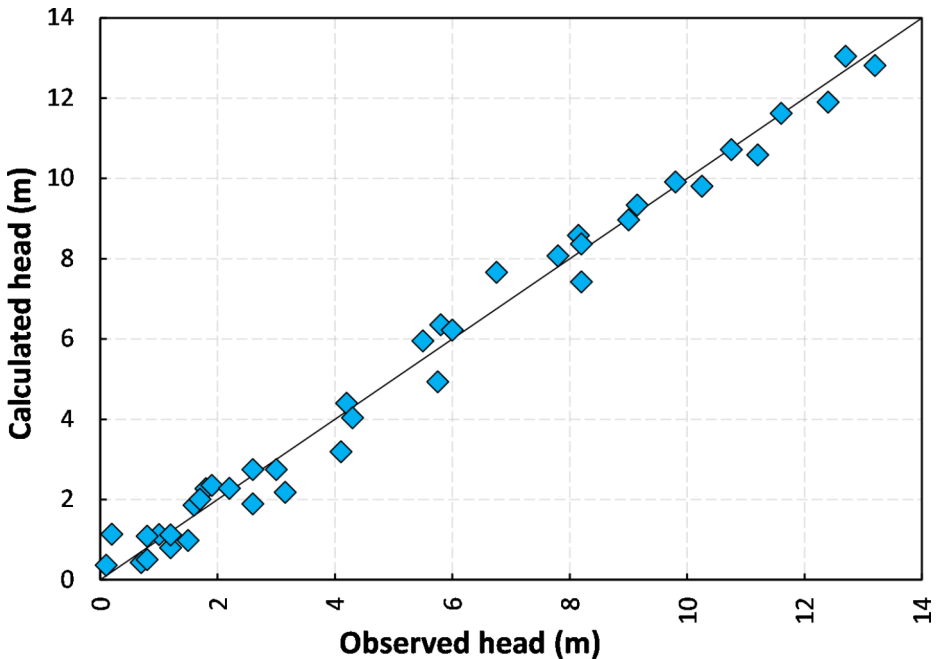


Fig. 3 Calculated and Piezometric groundwater heads in the NDA study area

Land subsidence for a multi-layer aquifer system (δ) with a thickness (b_i) can be calculated by accumulating the compaction of single soil layers as follows:

$$\delta_i(t) = \sum_{n=1}^n \delta i(t) = \sum_{n=1}^n S s i \Delta s i(t) b i \quad (1)$$

3 Results

3.1 Model Calibration

Calibration is a process that shows the difference between the calculated head from the model and the Piezometric head from an observation well in the field, considering the available data of piezometric head obtained from RIGW for observation records during the year 2008. Forty observation wells were distributed in the study area and used in the calibration based on the piezometric head map in 2008 (see Fig. 3). At the same time, the maximum and minimum difference between the calculated results (X_{cal}) and the observed results (X_{obs}) with root mean square (RMS) is 0.16 m. The normalization root means square is approximately 4%.

The groundwater level (GWL) in the model indicated in Fig. 3 shows that the water level varies from 16.96 m in the South to 0 in the North, compared with the Contour map of groundwater in the Quaternary aquifer recorded in 2008 (Fig. 4).

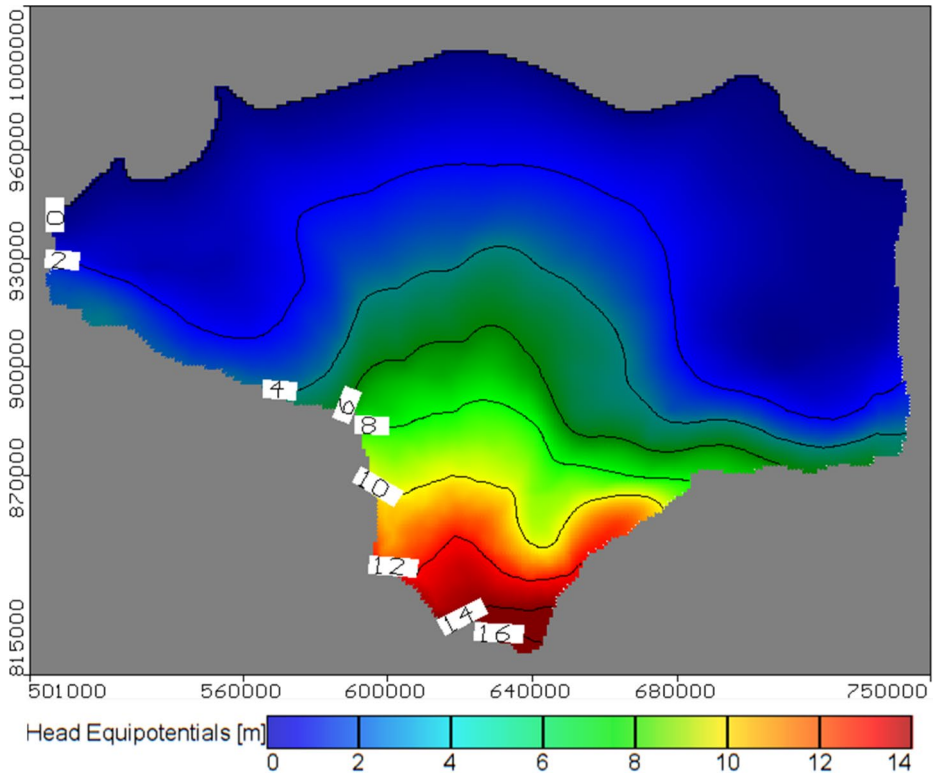


Fig. 4 A real view of the groundwater heads in the NDA study area

Because climate changes utilize increasing temperatures, which will lead to an increase in water demand for surface irrigation and increasing extraction rate on the Nile delta aquifer and the next operation of new structures in the Nile as the Grand Ethiopia Renaissance Dam, a combination of these scenarios will affect water supplies, so four scenarios of MIS were analyzed in this study. Four scenarios were applied: sprinkler, subsurface, and drip irrigation systems. The flow to the aquifer was reduced by 60%, 40%, and 20% relative to the baseline case.

3.2 Effect of Modern Irrigation System on Groundwater Drawdown (Scenario A)

In this scenario, the Impact of changing the irrigation system from the current technique (i.e., surface irrigation) to applying MIS for the sprinkler, subsurface, and drip irrigation systems was simulated.

Figure 5 shows groundwater drawdown, which reached 2.60, 4.20, and 6.50 m for applying sprinkler, subsurface, and drips irrigation systems. This indicated that the MIS damages coastal aquifers. Therefore, it must be considered for future design and development.

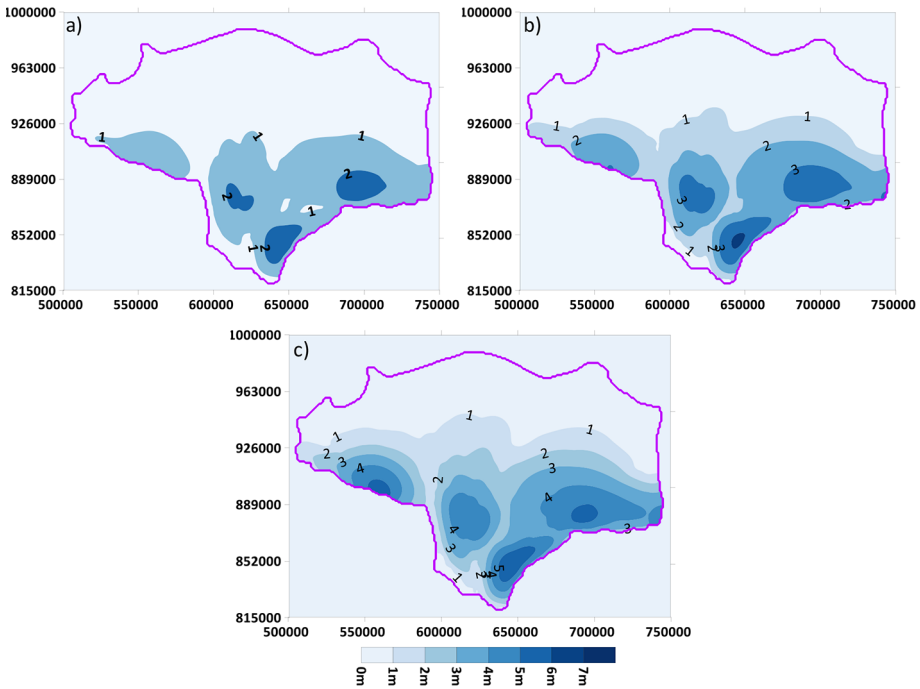


Fig. 5 Drawdown for different irrigation methods in NDA for a) sprinkler irrigation, b) subsurface irrigation, and c) drip irrigation

3.3 Effect of Modern Irrigation System on land Subsidence (Scenario B)

Changing the current irrigation system from surface to sprinkle, subsurface, and drip system is considered. Figure 6 illustrates the land subsidence rates in the NDA due to the changing irrigation system. Scenario B showed that the land subsidence reached 26, 44, and 65 cm for applying sprinkle, subsurface, and drip irrigation.

According to previous findings, the drip irrigation system caused the highest land subsidence rate due to the fall in groundwater heads to low aquifer recharge rates (El Shinawi et al. 2022; Gabr and Fattouh 2021).

4 Discussion

The current study discussed the impact of modern irrigation systems on groundwater resources and land subsidence in the Nile delta's arid and semi-regions. Different MIS were applied to the study area to assess their Impact on groundwater drainage and land subsidence compared to the current surface irrigation method utilized in the old delta of the Nile River. Concerning Fig. 7, the maximum groundwater drawdown touched 2.60, 4.20, and 6.50 m; correspondingly, these results for groundwater heads are satisfied with Abd-Elaty et al. (2021a), which studied the Impact of over-pumping on groundwater heads in Nile delta.

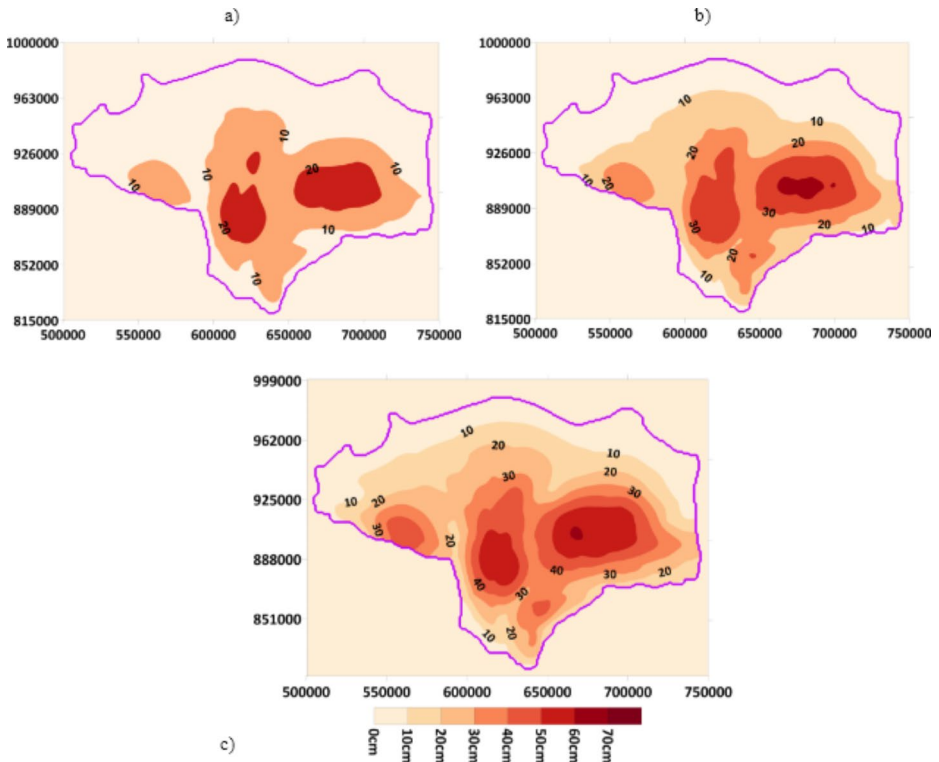


Fig. 6 Land subsidence for different irrigation methods in NDA for a) sprinkler irrigation, b) subsurface irrigation, and c) drip irrigation

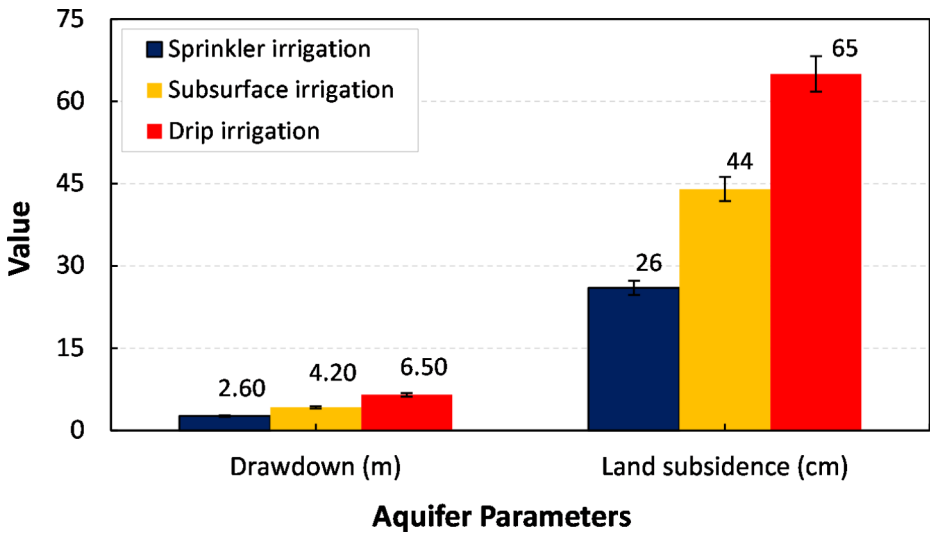


Fig. 7 Maximum groundwater withdrawal and land subsidence rates for using different irrigation methods in NDA

Moreover, reducing groundwater heads using the MIS will affect aquifer drawdown and land subsidence in the study area. In contrast, the land subsidence moved to 26, 44, and 65 cm using sprinkle, sub-surface, and drip irrigation in the study area due to reduced aquifer recharge. Overall, drip irrigation requires much less water than other irrigation methods. As a result of the previous scenarios, using MIS (i.e., sprinkle, sub-surface, and drip irrigation) instead of surface irrigation (i.e., base case) increases groundwater drawdown and land subsidence rates. The results of land subsidence are close to the study developed by El Shinawi et al. (2022). The study is important for the decision-maker to consider the influence of MIS on groundwater resources and land subsidence in old land at the Nile delta and similar study areas where the waterway, roads, buildings, infrastructures, water structures as culverts, bridges, and regulators will influence by the using of MIS. Also, future design and planning must consider the application of MIS in these old lands to balance water management and natural hazards caused by land subsidence.

5 Conclusion

Land subsidence is an environmental geohazard problem that affects human life. This study investigated the modern irrigation systems (MIS) and their Impact on land subsidence in coastal aquifers in the Nile delta, Egypt. Changing the irrigation methods to ensure food security from surface irrigation in the current situation to MIS using sprinkle, sub-surface, and drip irrigation to manage the water shortage in the Nile delta due to overpopulation. The current study results showed that changing the irrigation method has increased the groundwater drawdowns of 2.60 m, 4.20 m, and 6.50 m using sprinkle, sub-surface, and drip irrigation, respectively. At the same time, the maximum land subsidence reached 26 cm, 44 cm, and 65 cm. The decision-makers should consider the Impact of land subsidence on the future design of infrastructures and waterworks, considering the preferable irrigation methods for water resources management.

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Authors' Contributions **Ismail Abd-Elaty, Ismail Fathy and Elsayed Ramadan:** Conceptualization, Methodology, Investigation, Formal analysis, Data curation. **Ismail Abd-Elaty, Ismail Fathy, Alban Kuriqi, Am Pris John, Salvatore Straface, and Elsayed Ramadan:** Visualization, writing—original draft, Writing—review & editing, Resources. **Alban Kuriqi, Am Pris John and Salvatore Straface:** Supervision.

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Declarations

Conflicts of interest/Competing Interests (The authors declare that they have no conflict of interest.)

Ethics Approval (Not applicable)

Consent to Participate (Yes)

Consent for publication (Yes)

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