



# Evaluation of potential impact of Grand Ethiopian Renaissance Dam on Seawater Intrusion in the Nile Delta Aquifer

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## Abstract

The Nile Delta aquifer in Egypt is one of the largest groundwater reservoirs worldwide. It contributes significantly to the water budget of the country and acts as the main source of freshwater apart from the Nile River. Due to excessive pumping to meet the increasing water demands, the seawater intrusion from the Mediterranean Sea has been triggered affecting the groundwater quality in the northern and middle zones of the Nile Delta aquifer. This paper investigates the possible adverse impact of reducing the flow in the Nile River due to the construction of the Grand Ethiopian Renaissance Dam on the Nile Delta aquifer and considers possible measures to adapt with such impacts. A numerical model is developed using SEAWAT to simulate the groundwater flow and solute transport considering the operation of the new dam. Two scenarios of filling the reservoir during 3 and 6 years were considered. The maximum groundwater drawdown in the middle Delta will reach 2.65 m under the conditions of scenario one and 1.4 m under the conditions of scenario two. Equi-concentration lines 1000 and 35,000 ppm would advance to a distance of 110.2 and 70.85 km, respectively, under the first scenario and 108.25 and 67.3 km, respectively, under the second scenario. Results indicated that filling the reservoir in 3 and 6 years would require reducing groundwater abstraction rates from the Nile Delta aquifer by 60 and 40%, respectively, to maintain the freshwater body in the Nile Delta aquifer.

**Keywords** Ethiopian Renaissance Dam · Nile Delta Aquifer · Recharge · Seawater intrusion · SEAWAT

## Introduction

Excessive groundwater pumping in coastal areas, associated with the lack of natural recharge in arid and semi-arid regions, has accelerated the seawater intrusion problem in coastal aquifers. The degree of intrusion may vary from few hundreds of meters in small-undisturbed aquifers to more than hundreds of kilometers in large disturbed aquifers

(Sherif and Singh 2002; Sherif et al. 2012). Due to the direct hydraulic contact between freshwater bodies in coastal aquifers and seawater bodies, and the density difference of the two water bodies, seawater migrates through the bottom layers of the coastal aquifers causing the seawater intrusion problem. Under natural conditions, a transition zone between the two water bodies would develop in which the salt concentration and density vary gradually. The delicate balance between freshwater and seawater bodies might be affected by manmade activities such as pumping and recharge activities and alteration of land use and irrigation practices. Construction and operation of dams would also change the flow regime in rivers and canals and would affect the groundwater recharge temporary and spatially.

Since the construction of the High Aswan Dam (HAD), the population of Egypt has increased from 27.9 million in 1960 to 88.8 million in 2015, while Egypt's share of the Nile Water has remained constant at 55.5 BCM/y. The HAD was built to accommodate water surplus and floods, that might be generated during rainy seasons, and to regulate the flow and maintain Egypt's share of the Nile water (El-Atfy 2007).

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The total water storage capacity of the HAD is 121 BCM, including 90 BCM as life storage, 31 BCM as dead storage (Moussa et al. 2001).

A number of international agreements between all Nile basin countries were signed for the allocation of the water share of each country. Egypt and Sudan signed an agreement for the utilization of the Nile water that enters the territories of Sudan and Egypt with a share of 55.5 BCM/y for Egypt and 18.5 BCM/y for Sudan. The agreement constituted the basis on which Sudan would construct the Roseires Dam on the Blue Nile and Egypt construct the HAD on the Main Nile (Whittington et al. 2014).

In 2011, Ethiopia began constructing the Grand Ethiopian Renaissance Dam (GERD) on the Blue Nile at Guba, 60 km from Sudan boundary to generate electricity. The dam has a storage capacity of 74 BCM, of which 60 BCM is a life storage, and is expected to produce 6000 Megawatt (MW) electricity (Tesfa 2013). The project spans an area of 1800 km<sup>2</sup> and once completed it will be Africa's largest hydropower dam with an approximate height of 140 m. Although the dam will mostly be used for electricity generation (as announced by the Ethiopian government), a huge volume of water (74 BCM) will be diverted to its reservoir to develop the required head for power generation. This will seriously affect the discharge in the Nile River at the downstream side of the GERD extending within the territories of Sudan and Egypt. Based on the required time to fill the reservoir, Egypt's water share (55.5 BCM) will be affected and the water discharge and levels in the Nile River will decline causing a significant reduction in the recharge of the Nile Delta aquifer. This would induce further seawater intrusion in the Nile Delta aquifer.

A limited number of studies were carried out recently to assess the possible impacts of constructing GERD on Egypt. Abdelkader and Elsanabary (2015) conducted a numerical study on the hydrological and environmental impacts of GERD on the River Nile. Four scenarios of filling the GERD reservoir over durations of 2, 5, 10 and 20 years were considered. The annual water volumes that should be diverted to fill the GERD reservoir to the desired water level (146 m) were 39.5, 15.8, 7.9 and 3.95 BCM/y, respectively. Negm et al. (2014) used a mathematical model (MODSIM) to study the possible impacts of building GERD on the flow conditions in the Nile River considering three scenarios of filling the reservoir over a time period of 2, 3, and 6 years. The results indicated that the flow in the Nile River at HAD will be reduced by 37.263, 25.413, and 13.287 BCM, respectively. As a result, water levels in the Nile River and irrigation canals will decline, causing a reduction of the groundwater recharge in the Nile Delta aquifer. Consequently, the seawater intrusion from the Mediterranean Sea would be accelerated. Armanuos et al. (2017)

presented an evaluation to the potential impact of GERD and pumping scenarios on groundwater levels using MODFLOW. Three scenarios were studied including: reduction of water depth in canals, increasing pumping from the aquifer and a combination of both. The results revealed that the effect of increasing pumping on groundwater levels in the Nile Delta aquifer is more significant than decreasing the water depth of the canals network. The third scenario presented the worst case as the average drawdown reached 1.7 m in the middle part of the Delta aquifer. Such a drawdown would cause a significant inland movement of the saline water body.

A number of researchers investigated the seawater intrusion problem in the Nile Delta aquifer (Amer and Sherif 1996; Sherif and Singh 1997; Roger et al. 2009). The Nile Delta aquifer is a semi-confined aquifer, and its thickness varies from 200 m in the south to more than 900 m at the Mediterranean Sea (Serag El Din 1989). Sherif et al. (2012) discussed the concept of equivalent freshwater head in successive horizontal simulations of seawater intrusion in Nile Delta aquifer using a 3-D finite element variable density model (FEFLOW). Abd-Elaty et al. (2014a, b) used MODFLOW and SEAWAT to study the possible impacts of climatic change on seawater intrusion in Nile Delta aquifer using SEAWAT and concluded that the aquifer would be subjected to additional seawater intrusion under the conditions of climate change and seawater level rise.

This study discusses the possible impacts of the construction of GERD on groundwater quantity and quality in the Nile Delta aquifer. The impacts are assessed under the conditions of filling the GERD reservoir in 3 and 6 years, respectively. The two scenarios consider a water deficit in the Nile River of 24.60 and 12.30 BCM/y, respectively. Possible means for the alleviation of the adverse impacts and maintaining the quality of the groundwater resources in the Nile Delta aquifer are also discussed. This study has been carried out at the Faculty of Engineering, Zagazig University, Zagazig, Egypt, in the period from 2014 to 2017 as a part of Ph.D. study.

## Description of the study area

The Nile Delta aquifer is among the largest groundwater reservoirs in the world. Due to its strategic importance in Egypt's water budget, the middle area of the Nile Delta is considered in this study. It is bounded by the Mediterranean Sea at the north, Nile River at the south and the two branches of Nile River in the east and the west, as shown in Fig. 1a. The study domain has a total area of 9000 km<sup>2</sup> and is located between latitudes 30°20' and 31°50'N, and longitudes 30°10' and 31°35'E. The average rainfall is relatively small and varies from 25 mm/year in the south to 200 mm/year in the north (RIGW 1992). The evaporation rate ranges between 7 mm/day in the south to 4 mm/day in the north



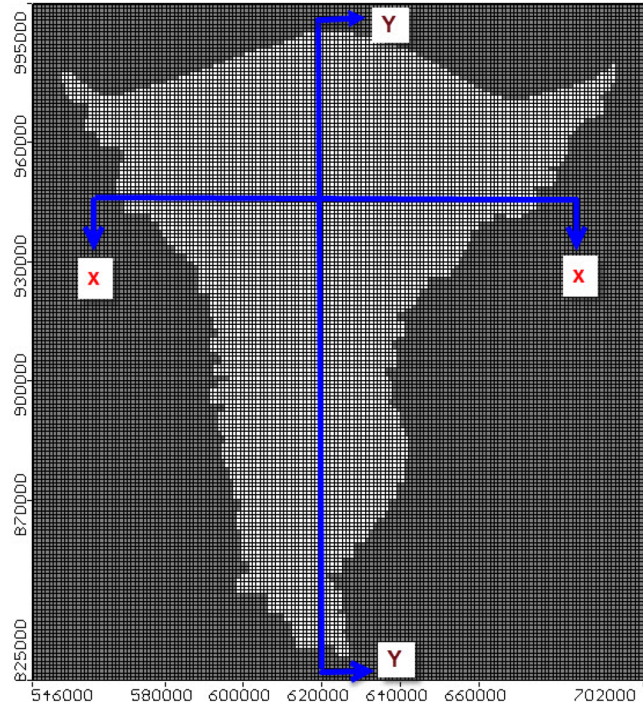
(WMRI-NWRC 2002). The average daily temperature ranges from 17 to 20 °C in the northern zone to more than 25 °C in the southern parts of the study domain (SNC-2010).

The middle zone of the Nile Delta aquifer can be differentiated into two main aquifer systems. The tertiary aquifer system

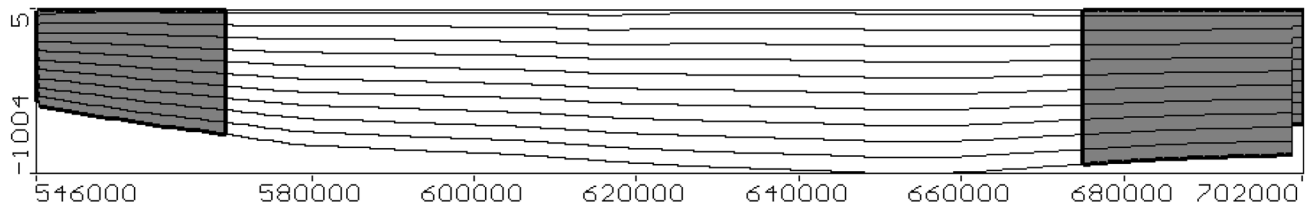
which is represented by the Pliocene clay as an aquiclude, with the Miocene and Oligocene aquifers (Nosair 2011) and the Quaternary aquifer system with a thickness of 250 m at the south and approximately 1000 m north (El Fayoumy 1968; Rizzini et al. 1978; Said 1981). The aquifer is mainly composed



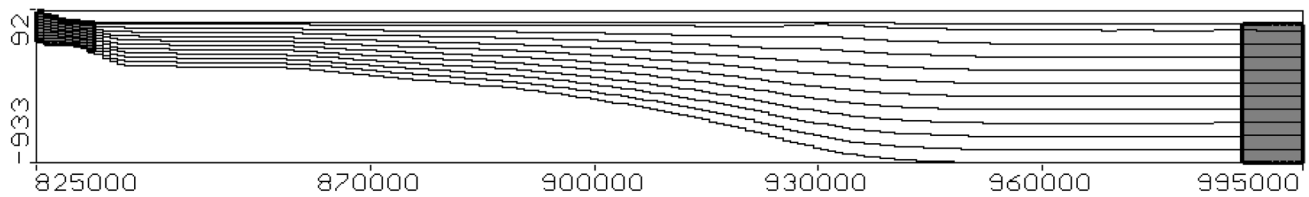
(a) Location map



(b) Discretization of the study domain in the horizontal view



(c) Discretization of the lateral cross section X-X



(d) Discretization of the longitudinal cross section Y-Y

**Fig. 1** Location map of the middle area of the Nile Delta aquifer and Domain discretization. **a** Location map. **b** Discretization of the study domain in the horizontal view. **c** Discretization of the lateral cross section X-X. **d** Discretization of the longitudinal cross section Y-Y

of loose quartzitic sands with pebbles and gravels in different proportions related to the old litho-facies (Hefny (1980), Sallouma (1983) and Serag El Din (1989)). The Nile Delta aquifer is recharged through rainfall with an average recharge of 25 mm/year. It is also recharged from the Nile River and the irrigation system which may vary between 0.25 and 0.80 mm/day (RIGW 1980 and Morsy 2009). The abstraction rate from the entire Nile Delta aquifer increased during the period 1992 to 2008 from 3.03 to 4.90 Mm<sup>3</sup>/year (Morsy 2009). The aquifer is classified as semi-confined (Ball 1939) and the depth to the groundwater table ranges from 1 m in the northern parts to 5 m in the southern parts near Cairo (RIGW 2002 and Morsy 2009).

## Materials and methods

### Numerical model

SEAWAT code was employed in the current study to assess the possible impacts of the construction of GERD on the groundwater and SWI in the middle zone of the Nile Delta aquifer. SEAWAT combines MODFLOW and MT3DMS into a single computer code to solve groundwater flow and solute transport equations iteratively. The code has been tested and verified against several benchmark problems involving variable density groundwater flow including, among others, Henry problem, Elder problem and HYDROCOIN problem. The variable density flow (VDF) process of SEAWAT uses the well-established MODFLOW methodology to solve the variable density groundwater flow equation (Langevin et al. 2003). The MT3DMS module of SEAWAT, utilizes the integrated MT3DMS transport (IMT) process to solve the solute transport equation. The VDF process solves the following variable density groundwater flow equation (Langevin et al. 2008):

$$\nabla \left[ \rho * \frac{\mu_o}{\mu} * K_o \left( \nabla * h_0 + \frac{\rho - \rho_f}{\rho_f} * \nabla Z \right) \right] = \rho * S_{s,0} \left( \frac{\partial h_0}{\partial t} \right) + \theta * \left( \frac{\partial \rho}{\partial C} \right) \left( \frac{\partial C}{\partial t} \right) - \rho_s * q'_s \quad (1)$$

where  $\rho_o$  is the fluid density (ML<sup>-3</sup>) at the reference concentration and reference temperature;  $\rho$  is density of saline ground water (ML<sup>-3</sup>);  $\mu_o$  is dynamic viscosity of the fresh ground water (ML<sup>-1</sup> T<sup>-1</sup>);  $\mu$  is dynamic viscosity of saline ground water (ML<sup>-1</sup> T<sup>-1</sup>);  $K_o$  is the hydraulic conductivity tensor of material saturated with the reference fluid (LT<sup>-1</sup>);  $h_0$  is the hydraulic head (L);  $S_{s,0}$  is the specific storage (L<sup>-1</sup>);  $t$  is time (T);  $\theta$  is porosity (-);  $C$  is salt concentration (ML<sup>-3</sup>); and  $q'_s$  is a source or sink (T<sup>-1</sup>) of fluid with density  $\rho_s$ .

The IMT process solves the following solute transport equation (Langevin et al. 2008):

$$\left( 1 + \frac{\rho_b * K_d^k}{\theta} \right) \frac{\partial(\theta * C)}{\partial t} = \nabla(\theta D * \nabla C^k) - \nabla(q * C^k) - (q'_s * C_s^k) \quad (2)$$

where  $\rho_b$  is the bulk density (mass of the solids divided by the total volume) (ML<sup>-3</sup>),  $K_d^k$  is the distribution coefficient of species  $k$  (L<sup>3</sup> M<sup>-1</sup>),  $C_k$  is the concentration of species  $k$  (ML<sup>-3</sup>),  $D$  is the hydrodynamic dispersion coefficient tensor (L<sup>2</sup>T<sup>-1</sup>),  $q$  is specific discharge (LT<sup>-1</sup>), and  $C_s^k$  is the source or sink concentration [ML<sup>-3</sup>] of species  $k$ .

### Model geometry and discretization

The study domain was divided into 141 columns and 157 rows with 1 km<sup>2</sup> cells as shown in Fig. 1b. The depth of the aquifer is divided into eleven layers with a maximum layer thickness of about 90 m at the seaside. The first layer represents the clay cap with a thickness ranging between 20 and 50 m. The other layers represent the Quaternary aquifer and of equal thicknesses. Figure 1c, d presents the discretization in the lateral and longitudinal directions of the study domain.

### Boundary conditions

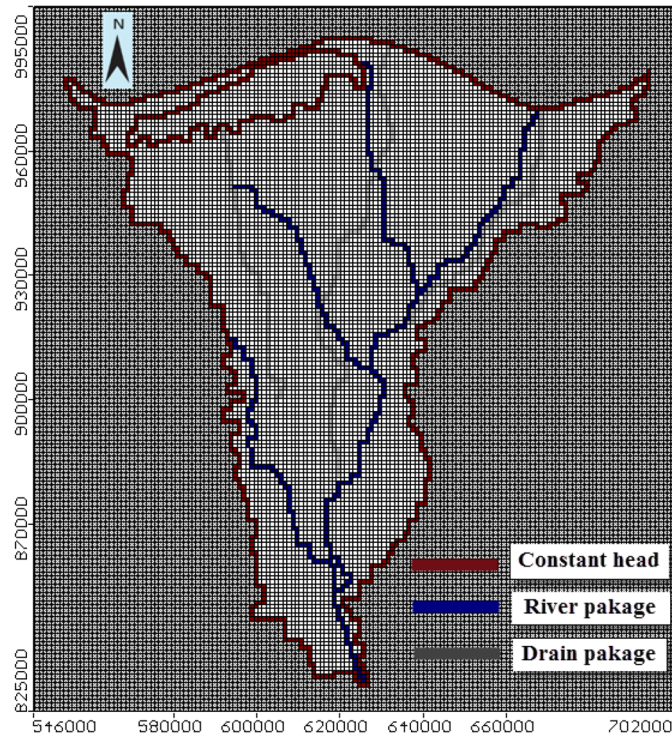
A specified head boundary condition, with constant head of 16.96 m above mean sea level at southern boundary and a zero level at the shoreline of the Mediterranean Sea, was considered. The conceptual model setup and boundary conditions are shown in Fig. 2a. The southeastern side of the study domain is bounded by Damietta branch with a constant head that varies in space from 13.66 at the south to 0.50 m at the north. The southwestern side of the domain is bounded by Rosita branch with constant head boundary that varies along the branch from 13.17 at the south to 0.50 m at the north. A solute concentration of 35,000 ppm is defined along the coastal line along the Mediterranean Sea, and the initial concentration of groundwater was set 200 ppm. The main lakes in the study area were assigned zero head and a concentration of 35,000 ppm due to the direct contact with the Mediterranean Sea.

## Results and discussion

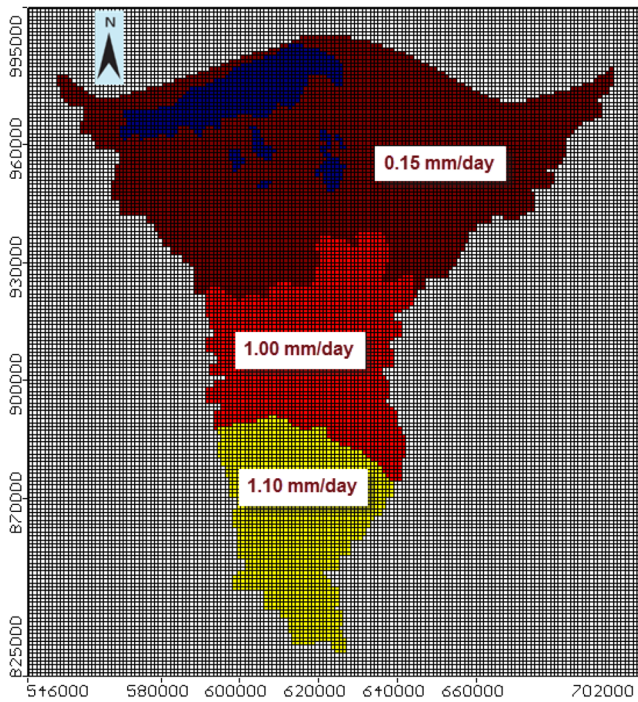
### Hydraulic parameters

The hydraulic parameters of each layer of the aquifer system, including hydraulic conductivity ( $K$ ), specific storage ( $S_s$ ), specific yield ( $S_y$ ), and total porosity, are presented in Table 1. Figure 2b shows the distribution of net recharge in the study area which depends on seepage from irrigation and

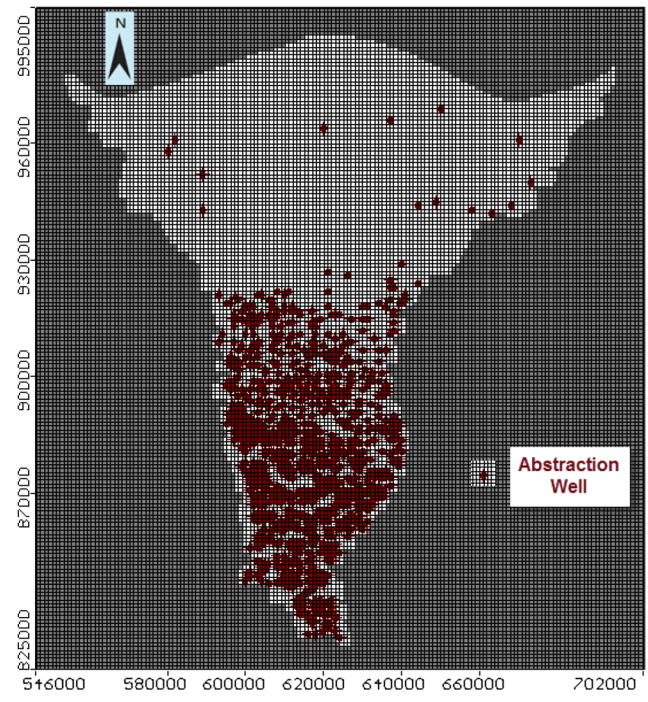




(a) Conceptual model setup and boundary condition



(b) Net recharge in the study domain



(c) Abstraction wells in the middle area of the Nile Delta

**Fig. 2** Conceptual model setup, boundary condition, net recharge and location of abstraction wells in the study area. **a** Conceptual model setup and boundary condition. **b** Net recharge in the study domain. **c** Abstraction wells in the middle area of the Nile Delta

drainage canals, excess water from irrigation practices and rainfall (Morsy 2009). The total abstraction from the Middle Nile Delta (MND) aquifer for irrigation and domestic purposes is estimated as  $0.81 \times 10^9 \text{ m}^3/\text{year}$  (Morsy 2009). The distribution of abstraction wells is shown in Fig. 2c.

The longitudinal dispersivity ( $\alpha_L$ ) was taken as 250 m, and the lateral dispersivity ( $\alpha_T$ ) and the vertical dispersivity ( $\alpha_V$ ) were set equal to 25.0 and 2.50 m, respectively. The diffusion coefficient was set equal to  $10^{-4} \text{ m}^2/\text{day}$  (Sherif et al. 1988). The two Nile branches, Damietta and Rosita, and the main canals were introduced in the conceptual model using the river package interface. The information included river stage level, bottom level, riverbed vertical hydraulic conductivity, riverbed thickness and riverbed conductance. Information related to the main drains within the study domain was also incorporated in the model.

### Model calibration

The model was calibrated through comparing the simulated and the measured water levels in many observation wells scattered in the study area. Field records of water levels were obtained from the GIS groundwater resources database of the Groundwater Research Institute, Ministry of Water Resources. Based on the results, the residual varied between  $-0.035$  and  $0.269 \text{ m}$  with root-mean-square (RMS) of  $0.172 \text{ m}$  and a normalization root-mean-square of  $1.719\%$ . The maximum difference between the simulated and measured groundwater levels was  $1.4 \text{ m}$  which is within the range of  $10\%$  of the measured levels, as shown in Fig. 3. Under the steady-state conditions, the total water influx was equal to the total water out flux from the study domain ( $4,439,500 \text{ m}^3/\text{day}$ ).

### Simulation of groundwater flow and saltwater intrusion

The numerical model SEAWAT was then employed to simulate the groundwater flow and seawater intrusion in the middle zone of the Nile Delta aquifer. Figure 4a shows the simulated groundwater levels in the study area which vary

from  $14.00 \text{ m}$  (amsl) in the south (near Cairo) to zero at the shoreline of the Mediterranean sea. Figure 4a also shows the velocity vectors in the study domain at the upper layer of the Quaternary aquifer with an average horizontal velocity of  $0.0668 \text{ m/day}$ . The average horizontal velocity in the semi-pervious clay layer was  $0.0019 \text{ m/day}$ . It should be noted, however, that in the deeper layers of the Quaternary aquifer, the velocity vectors in the vicinity of the shoreline are reversed. Due to the density difference between the seawater and freshwater bodies, the seawater intrudes the Nile Delta aquifer from the lower layers at the shore boundary and rotates back to the sea through the upper layers.

The resulted salinity distribution and dispersion zone in the horizontal view are demonstrated in Fig. 4b. On the other hand, Fig. 4c depicts the groundwater salinity distribution and the dispersion zone in the vertical view at the middle of the Nile Delta aquifer (Fig. 1d). Equi-concentration line  $1000 \text{ ppm}$  reached  $101.95 \text{ km}$ , while and Equi-concentration line  $35,000 \text{ ppm}$  reached  $63.90 \text{ km}$ , measured from the shoreline and at the bottom of the aquifer system.

### Impact of GERD on groundwater conditions in the Nile Delta aquifer

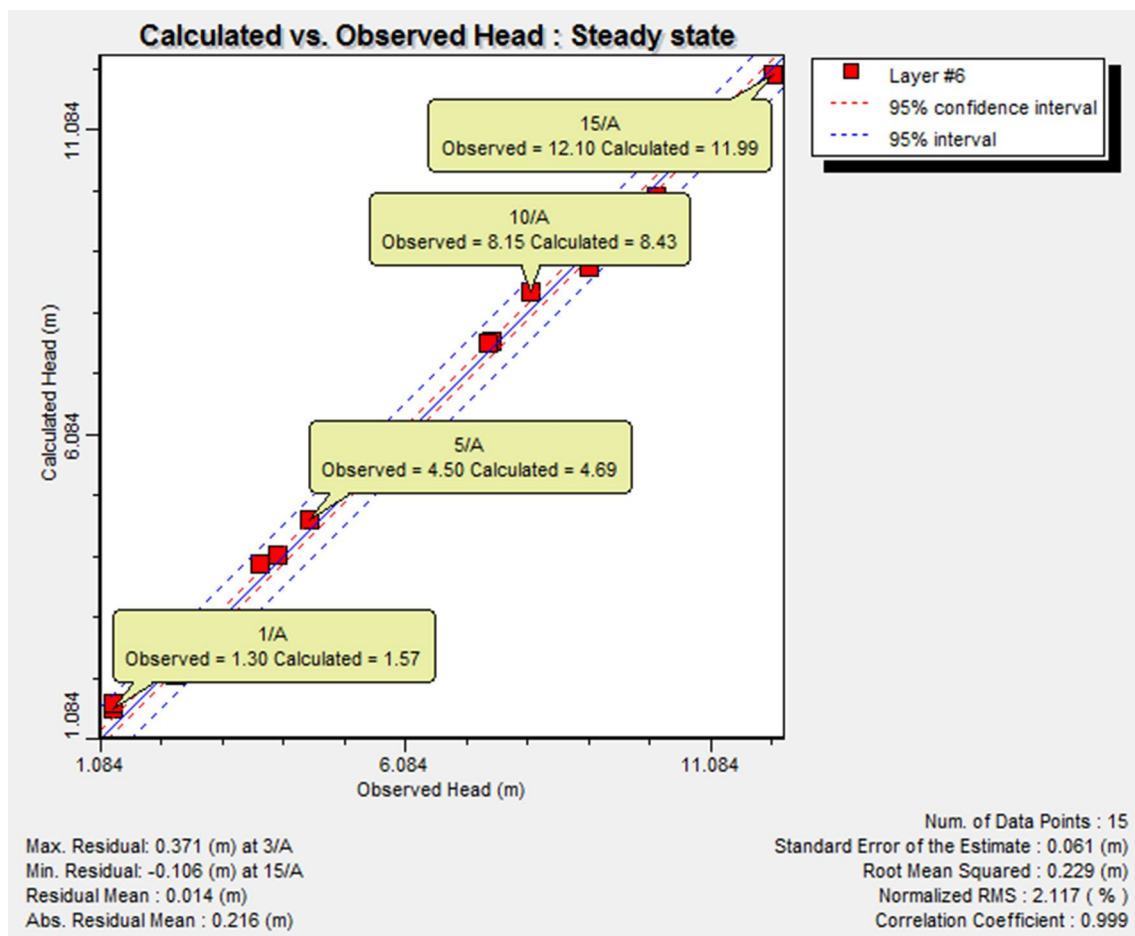
Under the normal circumstances and based on Egypt's share according to international agreements, the annual water flux at the HAD is  $55.5 \text{ BCM}$ . Assuming that the water storage in the reservoir of the HAD remains constant, any storage in the GERD would affect the annual volume of water that is released from the HAD. Table 2 elaborates the relationship between the volume of water stored in the GERD and the volume of water that would reach, and could be released from, the HAD considering different filling times of the GERD reservoir.

Filling the reservoir of GERD in 3 years would reduce the annual average flow in the Nile River from  $55.5$  to  $30.90 \text{ MCM}$  and hence would cause a reduction of  $44.32\%$  in the annual flow of the Nile River. If the filling time is extended to 6 years, the average annual flow in the Nile River would be reduced to  $43.20 \text{ BCM}$ , causing a reduction of  $22.16\%$  of its annual flow. It should also be noted that the Nile River

**Table 1** Hydrogeological parameters in the Nile Delta aquifer

Main hydraulic units	Layer no	Hydraulic conductivity		Storage coefficient	Specific yield	Effective porosity
		$K_h$ m/day	$K_v$ ( $\text{m}^2/\text{day}$ )			
Clay	1	0.10–0.25	0.01–0.025	$10^{-3}$	0.10	50–60
Fine sand with lenses of clay	2, 3, 4 and 5	5–20	0.5–2	$5 \times 10^{-3}$	0.15	30
Course sand Quaternary	6, 7, 8 and 9	20–75	2–7.50	$2.50 \times 10^{-3}$	0.18	25
Graded sand and gravel	10 and 11	75–100	7.50–10	$5 \times 10^{-4}$	0.20	20





**Fig. 3** Model calibration: calculated versus observed heads

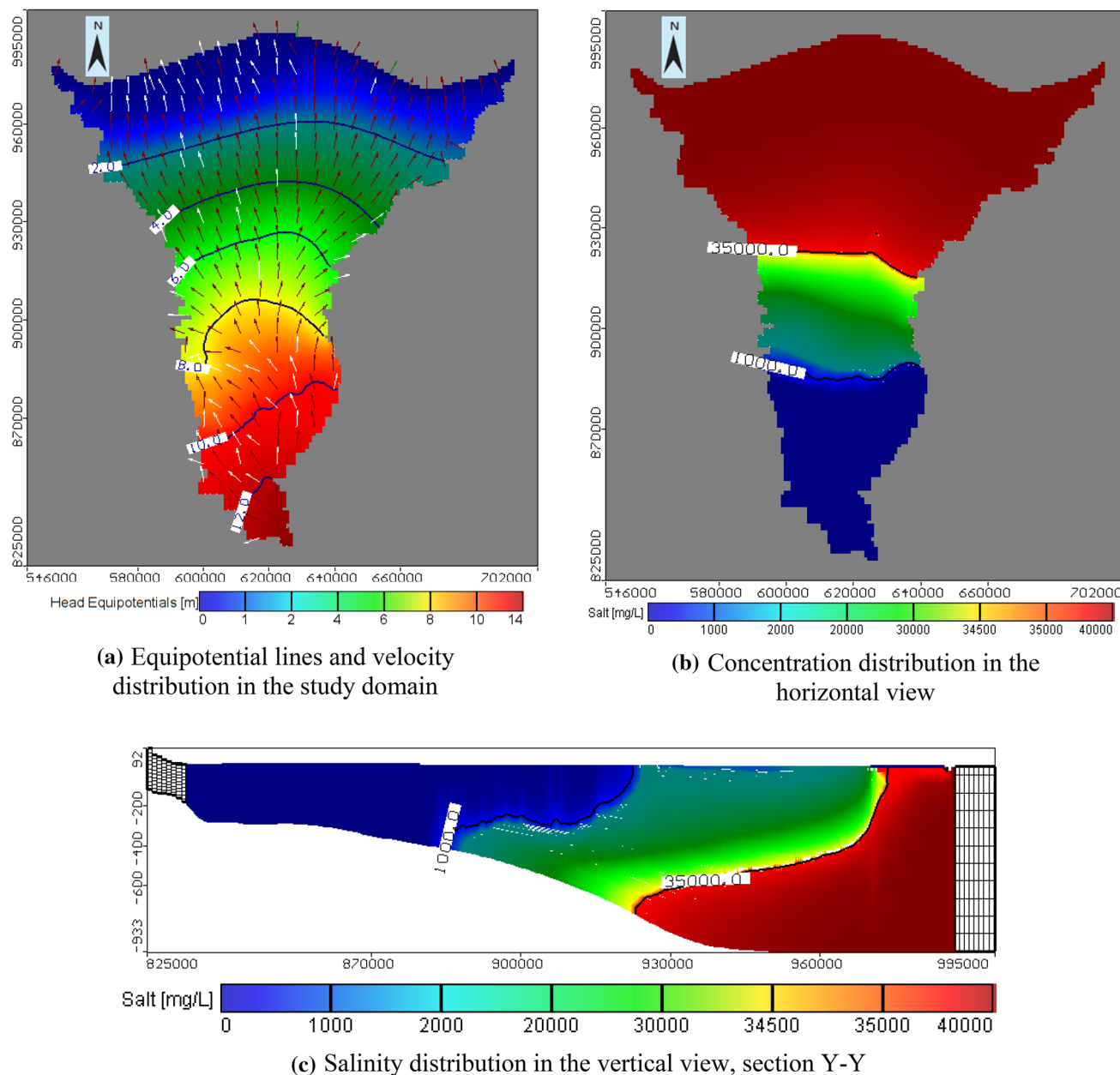
will be completely drained if the GERD is filled in 1 year as all the flow will be diverted to the reservoir of the GERD. It is therefore evident that during the filling phase of the GERD, the water levels in the Nile River, its two main branches, and the extensive irrigation network of the middle Delta region, will be reduced. This will have a direct impact on the groundwater recharge in the Nile Delta aquifer.

The developed model was used to assess the possible impacts of the construction of the GERD on the groundwater conditions in the middle zone of the Nile Delta aquifer. Two scenarios of filling the reservoir of the GERD were considered. In the first scenario, the reservoir is filled in 3 years and in the second scenario the reservoir is filled in 6 years. As such, the water levels in the surface water network system should be reduced to accommodate for the reduction in discharge as given in Table 2.

Figure 5 provides the decline of the groundwater levels in the middle Delta for the two scenarios. Under the first scenario, where the reservoir is filled in 3 years, the maximum drawdown in the groundwater level (2.65 m) will be encountered at a distance of about 100 km from the shoreline.

Under the second scenario, where the reservoir is filled in 6 years, the maximum drawdown will be equal to 1.4 m and will be encountered at the same distance from the shoreline. It is also concluded that the impacts of filling the reservoir of the GERD on groundwater levels will mostly be in the middle zone of the Nile Delta aquifer. This observation is consistent with the results of Armanuos et al. (2017).

Figure 6a and b provides the vertical view of the salinity distribution and the dispersion zone in the middle Delta along section Y–Y (Fig. 1d) under the two scenarios, respectively. Under the first scenario, equi-concentration line 35,000 ppm migrated inland to a distance of 70.85 km measured from the shoreline along the bottom boundary, while equi-concentration line 1000 ppm migrated inland to a distance of 110.2 km measured from the shoreline and along the same boundary. In the second scenario, in which the filling time of the reservoir of GERD extended to 6 years, equi-concentration lines 35,000 and 1000 ppm migrated to a distance of 67.30 and 108.25 km, respectively, measured from the shoreline along the bottom boundary. It is therefore concluded that the filling time



**Fig. 4** Equipotential lines and concentration distribution in the middle area of the Nile Delta. **a** Equipotential lines and velocity distribution in the study domain. **b** Concentration distribution in the horizontal view. **c** Salinity distribution in the vertical view, section Y–Y

**Table 2** Relationship between water storage in the reservoir of GERD and water flow at HAD

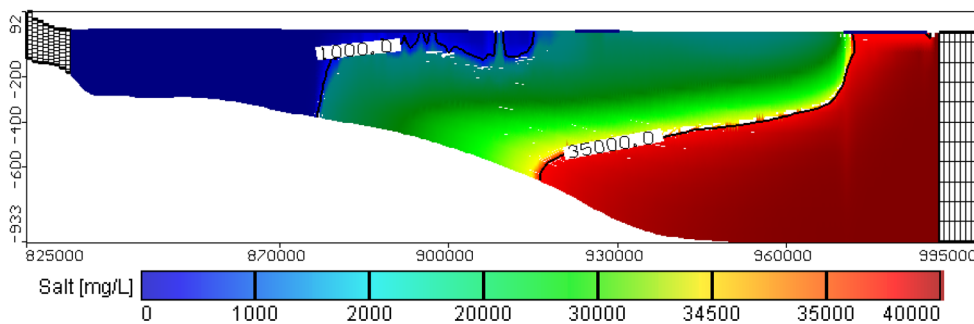
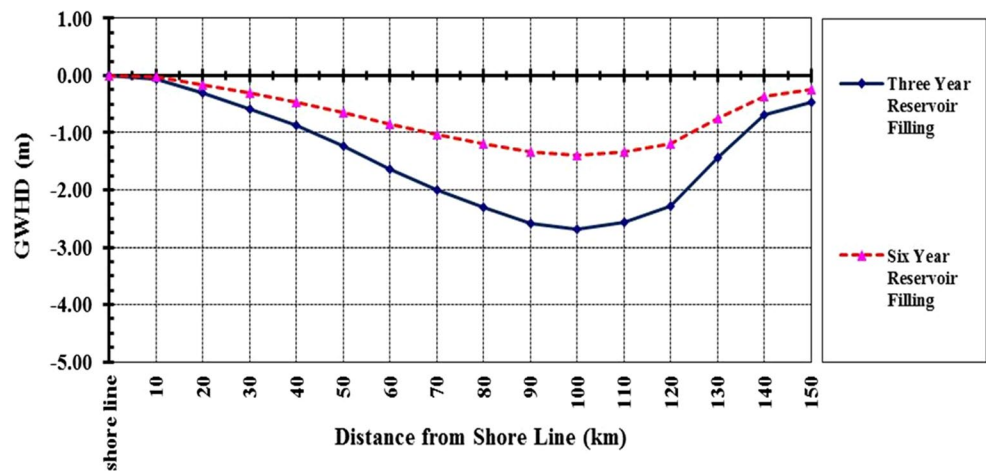
Time of filling (year)	1	2	3	4	5	6	7	8	9	10	11	12
Storage at GERD (BCM/year)	74.00	37.00	24.60	18.50	14.80	12.30	10.60	9.25	8.20	7.40	6.70	6.15
Water flow at HAD (BCM/year)	0.00	18.50	30.90	37.00	40.70	43.20	44.90	46.25	47.30	48.10	48.80	49.35
% of reduction in flow at HAD	0.00	66.67	44.32	33.33	26.67	22.16	19.10	16.67	14.77	13.33	12.07	11.08

of the reservoir of GERD will have a significant impact on the groundwater levels and quality in the Nile Delta aquifer. As anticipated, filling the reservoir of GERD in a

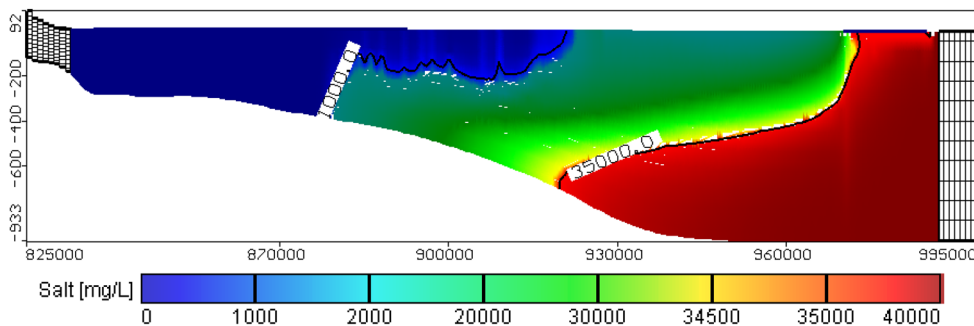
short period of time will have more adverse impacts on the groundwater levels and quality in the Nile Delta aquifer.



**Fig. 5** Decline of the ground-water levels in the middle Delta under the two scenarios of filling the GERD reservoir



**(a)** Scenario one (filling the GERD reservoir in 3 years)



**(b)** Scenario two (filling the GERD reservoir in 6 years)

**Fig. 6** Salinity distribution in the vertical view for scenarios one and two. **a** Scenario one (filling the GERD reservoir in 3 years). **b** Scenario two (filling the GERD reservoir in 6 years)

### Mitigation of the adverse impacts of the construction of the GERD

To mitigate the adverse impacts of the construction of the GERD, it is proposed to reduce the groundwater abstraction rates from the middle zone of the Nile Delta aquifer. To that end, the developed model was employed to study

the impact of decreasing the groundwater abstraction by 20, 40, 60, 80 and 100%, in association with the first and second scenarios of filling the reservoir of GERD.

Table 3 presents the inland migration distances of equi-concentration lines 1000 and 35,000 ppm under the two scenarios of filling the reservoir of GERD. The base case represents the current conditions prior to the start of the filling of the GERD dam. Under such conditions, equi-concentration

lines 1000 ppm and 35,000 ppm migrated inland to 101.95 and 63.90 km, respectively, measured from the shoreline. Case 1 represents the conditions without any reduction of groundwater pumping, while cases 2, 3, 4, 5, and 6, represent the conditions with a pumping reduction of 20, 40, 60, 80, and 100%. Figure 7 represents the relation between intrusion length for equi-concentration lines 1000 and 35,000 ppm in the middle of the Nile Delta aquifer and two scenarios of filling the reservoir of GERD (6 and 3 years). The intrusion distance of both equi-concentration lines 1000 ppm and 35,000 ppm has increased when the reservoir is filled in 3 years as compared to that when the reservoir is filled in 6 years. In addition, a 60% reduction of groundwater pumping has reduced the intrusion of both equi-concentration

lines 1000 ppm and 35,000 ppm in the case of filling the reservoir in 6 years but did not fully mitigate the additional intrusion when the GERD reservoir is filled in 3 years. The 60% reduction of groundwater abstraction has had a significant effect on equi-concentration line 1000 ppm but nominal effect on equi-concentration line 35,000 ppm. Overall, the 60% reduction in groundwater abstraction caused a clear reduction in the width of transition (dispersion) zone.

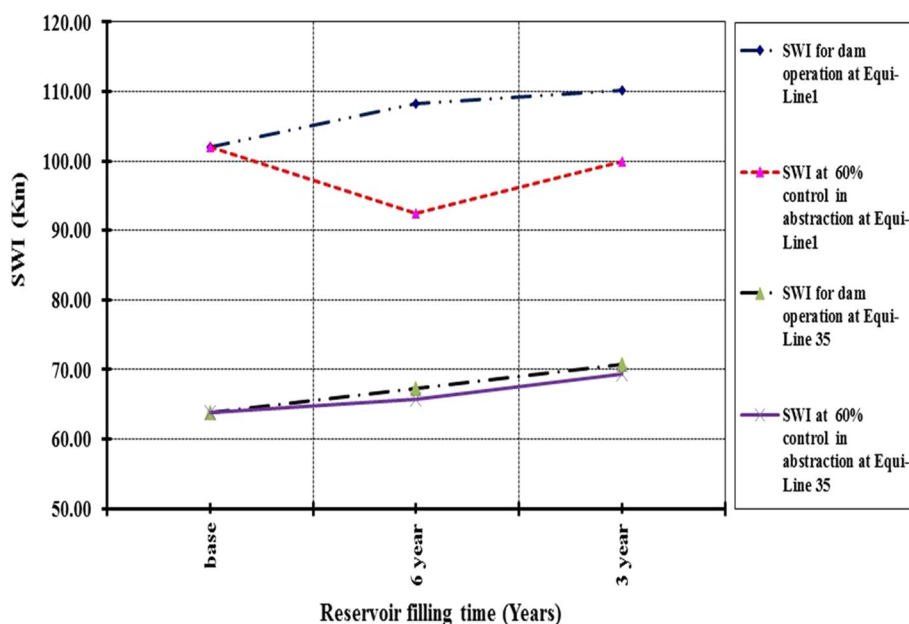
It is observed that, in all cases, equi-concentration line 35,000 ppm will migrate further inland beyond its current location. Even with the full termination of groundwater pumping from the middle area of the Nile Delta aquifer, it will not be possible to maintain the equi-concentration line 35,000 ppm at its current location (63.90 km from the shoreline measured along the bottom boundary) under the two scenarios of filling the reservoir of GERD. This means that the total volume of the seawater body in the northern parts of the Nile Delta aquifer will increase.

However, the freshwater body (with a salinity of less than 1000 ppm) can be preserved, and indeed enhanced, if the pumping from the middle is reduced by about 60% for the 3 years filling scenario and by about 30–40% for the 6 years filling scenario. As indicated in Table 3, equi-concentration line 1000 ppm should retard toward the seaside by 2 km (from 101.95 to 99.95 km) if the pumping is reduced by 40% under the conditions of scenario one. Under the conditions of scenario two, equi-concentration line 1000 will retard toward the seaside by 4 km (from 101.95 to 97.95 km) if the pumping is reduced by 60%, as shown in Table 3. In general, lower equi-concentration lines are more sensitive to the reduction of pumping as compared to higher equi-concentration lines.

**Table 3** Intrusion length of equi-concentration lines 1000 and 35,000 ppm under different abstraction rates for the two scenarios of filling the GERD reservoir

Time of filling the reservoir	3 years		6 years	
	Intrusion length (km)		Intrusion length (km)	
	Equi-concentration line 1	Equi-concentration line 35	Equi-concentration line 1	Equi-concentration line 35
Base	110.20	70.85	108.25	67.30
20%	108.75	70.40	104.95	67.05
40%	105.80	70.00	97.95	66.75
60%	99.95	69.40	92.55	65.75
80%	94.30	68.75	88.35	65.25
100%	89.95	68.30	84.80	65.20

**Fig. 7** Relation between intrusion length in the Nile Delta aquifer and different scenarios of filling the reservoir



The shortage in the water budget due to the proposed reduction in groundwater pumping can be substituted from the live storage of the HAD reservoir. It is also recommended to consider changing the crop pattern to reduce the water consumption in the agriculture sector and use modern irrigation systems to improve the irrigation efficiency and reduce the groundwater pumping from the Nile Delta aquifer.

## Conclusion

The renewable water resources in Egypt are mostly limited to its share from Nile River water (55.5 billion m<sup>3</sup>/year). The construction and operation of GERD within Ethiopian territories will reduce the flow in the Nile River and in the irrigation network of the Nile Delta during the filling stage of its reservoir and hence the groundwater recharge in the Nile Delta aquifer will decline. Maintaining the current groundwater pumping, under the conditions of reduced recharge, would accelerate the seawater intrusion problem and deteriorate the groundwater quality in the Nile Delta aquifer. SEAWAT is used to assess the adverse impacts of the construction of GERD and delineate the additional seawater intrusion in the middle zone of the Nile Delta aquifer. Currently, equi-concentration lines 1000 and 35,000 ppm intersect the bottom of the aquifer at a distance of 101.95 and 63.9 km, respectively, measured from the shore boundary. If the GERD is filled in 3 years (first scenario), equi-concentration lines 1000 and 35,000 ppm would advance inland to a distance of 110.2 and 70.85 km, respectively, measured along the bottom boundary. If the GERD is filled in 6 years (second scenario), the same equi-concentration lines would advance to a distance of 108.25 and 67.3 km, respectively. The maximum groundwater drawdown in the middle Delta will reach 2.65 m under the conditions of scenario 1 and 1.4 m under the conditions of scenario two. To avoid the adverse impacts and maintain the freshwater volumes in the Nile Delta aquifer, the groundwater pumping from the middle zone should be reduced by 60% under the conditions of scenario 1 and by 30–40% under the conditions of scenario two.

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