Evaluation of the potential impact of Grand Ethiopian Renaissance Dam and pumping scenarios on groundwater level in the Nile Delta aquifer

Asaad M. Armanuos, Mona G. Ibrahim, Wael Elham Mahmod, Abdelazim Negm, C. Yoshimura, Jiro Takemura and Bakenaz A. Zidan

ABSTRACT

The main objective of this study is to evaluate the potential impact of Grand Ethiopian Renaissance Dam (GERD) and pumping scenarios on groundwater level by a three-dimensional groundwater model of the Nile Delta using MODFLOW software. The Nile Delta has highly intensive irrigation canal networks that share yearly about 35.5 km^3 of water. In this study, an integrated three-dimensional groundwater model is built considering the actual condition of the irrigation canals and their recharges of the Nile Delta aquifer. The model was calibrated for estimating the vertical and hydraulic conductivity. The model was run for three scenarios: (1) reduction of water depth in canals, (2) increasing pumping discharge from the aquifer and (3) combination between the first and second scenarios. Results reveal that the effect of increasing the pumping discharge on groundwater level in the Nile Delta is more significant than decreasing the water depth of the canals network due to the fact of the existence of the upper clay layer which reduces the amount of water penetrating and reaching the groundwater in the aquifer. The last scenario presents the worst case as the average drawdown reached 1.26 m, 1.7 m and 1.35 m in the western, central and eastern parts of the Nile Delta respectively. The study results should be taken in account for studying the saltwater intrusion and climate change impacts on the Nile Delta region.

Key words | GERD, groundwater, irrigation canal networks, Nile Delta aquifer, recharge

Asaad M. Armanuos (corresponding author)
Egypt-Japan University of Science and Technology, Alexandria,
Egypt Tanta University and Tokyo Institute of Technology,
Tokyo, Japan
E-mail: *asaad.matter@ejust.edu.eg*; *armanuos.a.aa@m.titech.ac.jp*

Mona G. Ibrahim
Egypt-Japan University of Science and Technology, Alexandria, Egypt
and
Environmental Health Department, High Institute of Public Health, Alexandria University,
Alexandria, Egypt

Wael Elham Mahmod
Egypt-Japan University of Science and Technology, Alexandria, Egypt
and
Civil Engineering Department, Faculty of Engineering,
Assiut University
Assiut, Egypt

Abdelazim Negm
Faculty of Engineering,
Zagazig University, Zagazig, Egypt

C. Yoshimura
Department of Civil Engineering,
Tokyo Institute of Technology,
2-12-1Oookayama, Meguro,
Tokyo 152-0033, Japan

Jiro Takemura
Department of Civil Engineering,
Tokyo Institute of Technology,
2-12-1 Oookayama, Meguro,
Tokyo 152-8552, Japan

Bakenaz A. Zidan
Faculty of Engineering,
Tanta University, Tanta, Egypt

INTRODUCTION

The Nile Delta receives almost 35.5 km^3/year of the surface water from the Nile River. This also recharges the aquifer through the infiltration of excess irrigation water and seepage from canals (Anon 1980; Shahein 1985; Kashef 1983), which is the main source of recharge for the Nile Delta aquifer (Wahaab & Badawy 2004; El Ramly 1997). According to El Ramly (1997), the rate of groundwater recharge from the excess irrigation water ranges from 0.25 to 1.1 mm/day. The agricultural recharge to the Quaternary aquifer ranges from 0.8 to 1.1 mm/day for old lands and

doi: 10.2166/ws.2017.037

from 1.9 to 2.1 mm/day for the reclaimed area (Shamrukh *et al.* 2001). The groundwater recharge in the Nile Delta aquifer was studied by different authorities based on water balance equations, it ranges from 5 to 10% of the input value from about 2 to 4 km^3/year (Shahein 1985). Armanuos *et al.* (2016a) estimated the groundwater recharge from rainfall in the Nile Delta aquifer for six different years by using the WetSpass model. The model was calibrated for the Nile Delta parameters based on crop classification. The groundwater recharge ranged from 0.0 to 134 mm/winter season in the years 2000 and 2010.

The water levels in the Nile River and 10 main canals have been assigned in building a three dimensional (3-D) model to study saltwater intrusion and climate change impacts on the Nile Delta. The freshwater recharge effect on the seawater intrusion in the Nile Delta aquifer is noticed in the upper layer around the Nile River and its branches (Sherif *et al.* 2012). The water and bed levels of only eight canals were taken in account for the Nile Delta groundwater modeling by Abdelaty *et al.* (2014). The seawater moved towards the Nile Delta aquifer with the decline of water levels in canals, Abdelaty *et al.* (2014). Armanuos *et al.* (2016b) used Google Earth Pro software to estimate the bank levels and upper water width of irrigation canals in the Nile Delta region.

The construction of the Grand Ethiopian Renaissance Dam (GERD) will affect the water quota of Egypt, as it will decrease the Aswan High Dam (AHD) discharges (International Panel of Experts (IPOE) 2013). The GERD construction will have negative impacts on Sudan and Egypt. Ramadan *et al.* (2015) used mathematical modeling to develop different operational scenarios of GERD and investigated its impacts on the security of Egypt water resources. The results showed that the negative effects on Egypt's water resources will be dominant. In cases of GERD impounding during 6, 3, and 2 years for the normal flow case, the Lake Nasser active storage (90.7 BCM) will be decreased by 13.287, 25.413 and 37.263 BCM per year. At minimum flow from the Blue Nile, Lake Nasser active storage (90.7 BCM) will be decreased by 44.398, 54.415 and 55.138 BCM per year. At minimum average flow from the Blue Nile, Lake Nasser active storage (90.7 BCM) will be decreased by 25.963, 37.814 and 45.105 BCM per year. The impacts of the GERD construction on the performance of AHD were assessed (Mulat & Moges 2014). In the case of 6 years of filling; yearly outflows of the GERD through the impounding period will not decrease more than 28.9 BCM per year (about 58% of the mean flow).

Previous studies have considered groundwater recharge depending on 10 canals in groundwater modeling in spite of the actual irrigation network in Nile Delta region consisting of about 200 canals (MWRI 1954). Based on Ramadan *et al.* (2015) and Mulat & Moges (2014), the GERD construction will decrease the active storage of AHD by 14.8 to 60.7% and decrease the outflow from AHD to the Nile River and the Nile Delta irrigation canals network. This paper aims to evaluate the potential impacts of GERD and pumping scenarios on groundwater level by building a three dimensional model of the Nile Delta using MODFLOW software including the actual irrigation canals.

STUDY AREA DESCRIPTION

The Nile Delta is located in the Northern part of Egypt between latitudes 30°05′and 31°30′ N and longitudes 29°50′ and 32°15′E. It is about 25,000 km^2 (MWRI 2013). It is bounded by the Mediterranean Sea in the north, the Nile River in the south, the Suez and Ismailia Canals in the east and the El Nubaria Canal in the west (MWRI 2013), as shown in Figure A1 in the Supplementary Material (available with the online version of this paper).

Much geological, hydrochemical and hydrological research has extensively studied the Nile Delta aquifer in order to identify the characteristics of the Nile Delta aquifer (e.g., Mabrouk *et al.* 2013). Figure A2(a) and A2(b) in the Supplementary Material show the key map for the Nile Delta region and the hydrogeological section A-A in the Nile Delta aquifer respectively (Elewa 2010). The thickness of Nile Delta Quaternary aquifer increases from 200 m in the south near Cairo city towards the north directions to reach about 1,000 m, at the Mediterranean Sea (RIGW 1992). Table A1 in the Supplementary Material describes the coordinates of four points A, B, C and D in the model, see Figure 1. The depth to the groundwater level in the Nile Delta aquifer increases from the north towards the south. It varies between 1 and 2 m in the north, increases to vary from 3 to 4 m in the middle and reaches a maximum value of 5 m in the south, RIGW (2002) and Morsy (2009). The Quaternary aquifer is

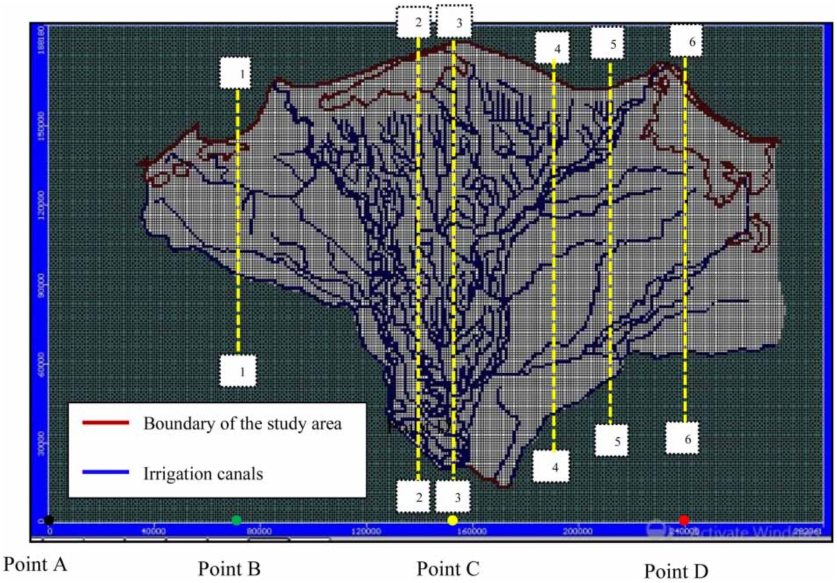

Figure 1 | Model geometry and discretization.

considered a semi-confined aquifer where it is covered by an impervious clay layer in the top (Wilson *et al.* 1979). The clay layer in the southern part of the Nile Delta aquifer acts as an aquitard and its thickness ranges from 5 to 25 m while in the northern parts it reaches about 50 m and acts as an aquiclude (Said 1962). Table A2 in the Supplementary Material summarizes the estimated values of the vertical and horizontal hydraulic conductivity of the top clay layer by different studies. The horizontal hydraulic conductivity in the Quaternary Nile Delta aquifer ranges between 0.05 and 0.5 m/day (RIGW 1992). The value range between 10^{-4} and 10^{-3} represents the storage coefficient of the Nile delta aquifer while 0.3 represents the porosity of the aquifer medium (Abdelaty *et al.* 2014). Table A3 in the Supplementary Material summarizes the hydraulic parameter estimations of the Quaternary Nile Delta aquifer estimated by various studies.

METHODOLOGY

The following four steps were considered to achieve the objectives: (1) identifying model parameters and data collection, (2) model building, model calibration, (3) the model testing for the studied scenarios and (4) analysis of results. The following sections describe briefly the different steps of methodology.

Identifying Nile Delta aquifer hydraulic parameters

The hydraulic parameters of the Nile Delta aquifer were identified based on previous research (see Tables A2 and A3 in the Supplementary Material, available with the online version of this paper). The directions of the irrigation canals and their names in the Nile Delta were identified based on MWRI (1954) and Roest (1999). The water level of El Raiah, the main canals and drains for the year 2008 in the Nile Delta were collected from previous studies (Morsy 2009; Abdelaty *et al.* 2014; RIGW 2015), see Table A4 in the Supplementary Material. The topography map of the Nile Delta and the base level of the Quaternary aquifer were collected from EGSA (1997).

Model building

A 3-D model was built for the Nile Delta aquifer by using MODFLOW software. The governing equations of the groundwater flow are derived by mathematical combination of the water balance equation and Darcy's law (Anderson & Woessner 1992). The MODFLOW model describes the groundwater flow in anisotropic and nonhomogeneous and medium according to the following equation (Bear 1979):

$$\frac{d}{dx}\left(K_{xx}\frac{dh}{dx}\right)+\frac{d}{dy}\left(K_{yy}\frac{dh}{dx}\right)+\frac{d}{dz}\left(K_{zz}\frac{dh}{dz}\right)-W=S_s\frac{dh}{dt}$$

where K_{xx}, K_{yy}, K_{zz} are values of hydraulic conductivity in x, y and z directions (LT^{-1}); h is the piezometric head (L); W is a volumetric flux per unit volume of aquifer representing sources and/or sinks of water (T^{-1}); S_s is the specific storage (L^{-1}) and t is time (T).

The 3-D model of the Nile Delta aquifer was built by a grid system consisting of 292 columns and 190 rows with cell dimensions 1.0 km × 1.0 km with variation in depth from 1,000 m at the shore line of the Mediterranean Sea in the north to 200 m in the south. The built model is divided into eleven layers, the upper clay layer is represented by layer number one; the following layers from two to eleven represent the Quaternary layer. Figure A3(a) to A3(c) in the Supplementary Material show the three vertical cross sections 1–1, 3–3 and 6–6 in the Nile Delta model respectively. The groundwater flow in the Nile Delta aquifer is from the south towards the north with hydraulic gradient about 11.0 cm/km and the gradient is mild in the north about 7.0 cm/km. Based on the literature, the south boundary condition of the Nile Delta model defined a constant head equal to 16.96 + msl (Morsy 2009; Abdelaty et al. 2014). The upper boundary condition in the north defined a zero value along the shore line of the Mediterranean Sea. The east boundary is left free at the Suez Canal. In the south east, the model is bounded by the Ismailia Canal where the water level starts at 16.17 amsl in the south and ends at 7.01 amsl in the east. In the southwest the model is bounded by El Rayah, El Behery and El Nubaria Canals where the water level in field starts at 16.00 m amsl in the south and ends at 0.50 m amsl in the north. The four main lakes of the Nile Delta are Mariot, Idku, Burullus, and Manzala and they were assigned to the model as a constant head, as they are directly connected to the Mediterranean Sea. The river package in the MODFLOW was used to assign the hydraulic properties of the Damietta and Rosetta branches and also the Rayahs and the main canals of the model. The drain package in the MODFLOW was used to simulate the main drains of the Nile Delta. The bank level and upper canal width of the irrigation canal networks which were estimated by Armanuos et al. (2016b) were used to build the model, see Table A5 in the Supplementary Material. The average water depth in the main and branch canals in the Nile Delta equal 2.0 and 3.0 m respectively (Dahab 1993). Figure 1 shows the canal distribution which was considered to build the model. The recharge from excess irrigation water depends on the soil type, irrigation and drainage practices assigned to the model based on reported values by Morsy (2009), as shown in Figure 2. The annual extraction rate per governorate in the Nile Delta region in the year 2008 was assigned to the model. Where, the total volume rate of extraction from the total area of the Nile Delta was 2.78 Mm^3/year in the year 2008 (Morsy 2009). The free board between the bank and water level in the

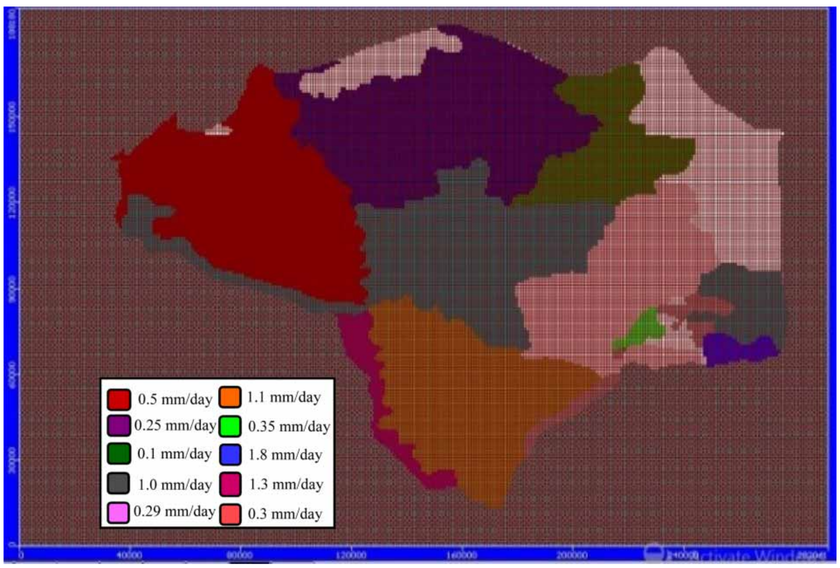

Figure 2 | Recharge from excessive irrigation water.

irrigation canals based on the Egyptian code of water resources and irrigation works equals 0.5, 0.75 and 1.0 m for distributed, branch and main canals respectively (NWRC 2003).

Model calibration and validation

In the calibration process, the model was run many times to minimize the difference between the measured hydraulic head by RIGW in 2008 and the simulated head by the model. Sixty distributed observation wells have been selected in the study area for the calibration process until the maximum difference between the measured and simulated hydraulic head level became 0.60 m, as shown in Figure A4 in the Supplementary Material. For model validation, the observed hydraulic heads were compared to the simulated ones for an other 60 records, as shown in Figure A4 in the Supplementary Material. Table A6 in the Supplementary Material shows the calibrated values of the Nile Delta aquifer model parameter.

Studied scenarios and assumptions

To study the impact of flow reduction to the Nile Delta, due to filling the reservoir of GERD, on groundwater level in the Nile Delta aquifer, three scenarios were studied based on three assumptions. The first assumption is that the flow from High Aswan Dam to the Nile Delta will decrease with the same percentage of active water in Lake Nasser reservoir due to GERD construction. The second assumption is that the crop pattern in the Nile Delta is constant, so the water depth will be decreased with the same percentage in the canals according to the studied scenarios. Finally the decrease of the total surface water through the canals will lead to a further pressure on groundwater storage in the Nile Delta aquifer and increasing the groundwater pumping will be expected to compensate the reduction in surface water.

Ethiopia is planning to end the work in GERD by 2018. In case of impounding GERD in 2 and 6 years, the active storage of AHD will decrease by about 50 and 25%; as a result of that the outflow from AHD to the Nile River and the Nile Delta irrigation canals network will decrease (Ramadan *et al.* 2015). Two separate simulations of decrease in the water depths in canals were done by 50 and 25% in the years 2020 and 2024 respectively and two other separate simulations were done for increasing the pumping discharge from the wells by 50 and 25% in the same years consequently.

The total annual groundwater abstraction from the Nile Delta aquifer has increased dramatically throughout the last 30 years. Research Institute of Groundwater in Egypt (RIGW) reported its increase from 1.6×10^9 m^3/year in 1980 to 3.5×10^9 m^3/year in 2003 and reached 4.6×10^9 m^3/year in 2010 (RIGW 2003; Mabrouk *et al.* 2013). It is expected that the annual abstraction rate will exceed 0.20×10^9 m^3 per year through the coming years (Mabrouk *et al.* 2013). Recent studies in simulating the saltwater intrusion in the Nile Delta by Sherif (2003) and Abdelaty *et al.* (2014) conducted different scenarios of pumping discharges increasing from the Nile Delta aquifer by 25, 50, 75 and 100% based on RIGW measurements (RIGW 2003) and (Mabrouk *et al.* 2013). The current model was run for three scenarios: reduction of water depth in canals by percentage 25 and 50%, increasing pumping discharges by percentage 25 and 50%, and the third scenario presents the combination between the first and second scenarios.

RESULTS AND DISCUSSION

Calibration and validation results

The root-mean-square error (RMSE) between the observed and simulated groundwater head was constant for different values of horizontal hydraulic conductivity of the first clay layer. The percentage of the vertical to horizontal hydraulic conductivity equals 10%. Figure 3(a) presents the calibrated values of the vertical hydraulic conductivity of the first layer; it ranges between 0.01 to 0.025 m/day. Figure 3(b) presents the values of the calibrated horizontal hydraulic conductivity of the second layer; it ranges from 50 to 240 m/day. Figure 4(a) and 4(b) present the observed and simulated groundwater levels consequently. The comparison between the observed and simulated groundwater levels for 60 records from different observation wells by RIGW in 2008, Morsy (2009), and the histogram of the frequency range of residuals are shown in Figure 5(a). The correlation factor R^2 and RMSE between the observed and simulated groundwater levels were 0.9763 and 0.60 m respectively. Figure 5(b) shows the comparison

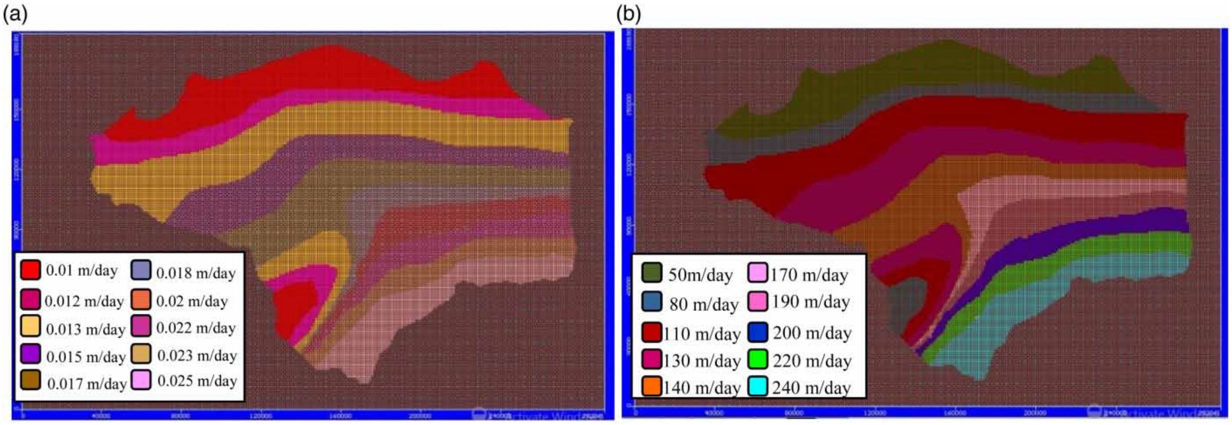

Figure 3 | Calibrated range of characteristics of Nile Delta aquifer. (a) Calibrated vertical hydraulic conductivity of the first layer. (b) Calibrated hydraulic horizontal conductivity of the second layer.

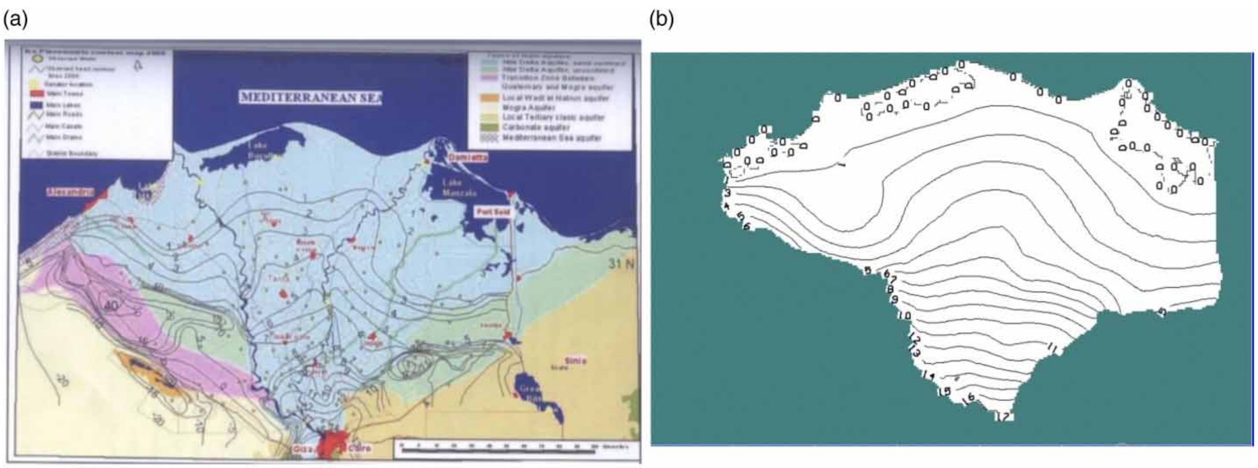

Figure 4 | Groundwater head in the Nile Delta aquifer 2008. (a) Observed groundwater level, Morsy (2009). (b) Simulated groundwater level.

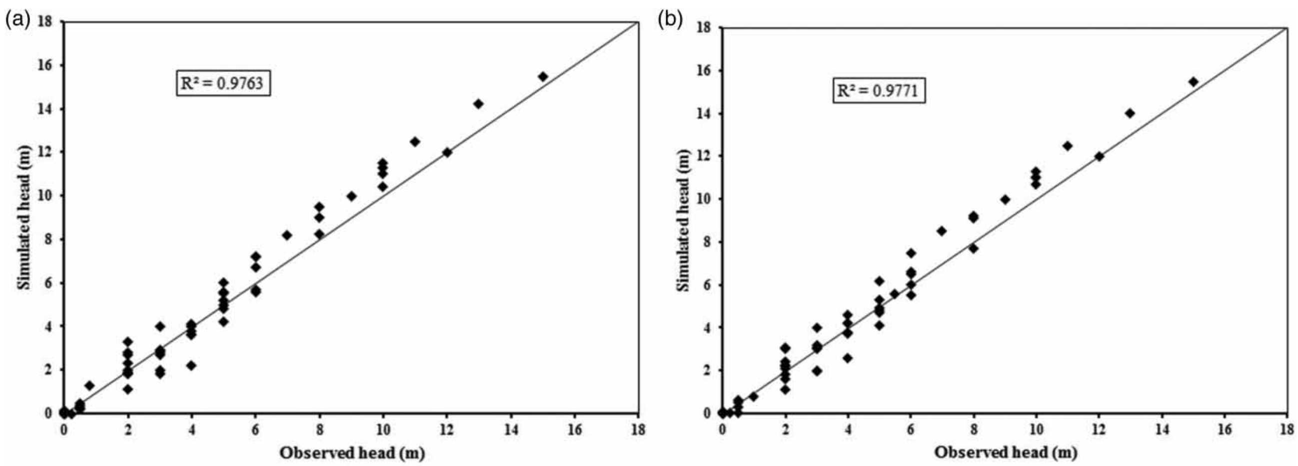

Figure 5 | Relationship between observed and simulated groundwater levels for (a) calibration and (b) validation process.

between the observed and simulated groundwater levels for an other 60 well records chosen for model validation. The correlation coefficient R^2 between the simulated and observed head equals 0.9771 and the RMSE equals 0.60 m.

Scenario 1: Decreasing water depth of canal networks

Figure 6(a) and 6(b) present the groundwater level for the first scenario by decreasing the water depth of the canals by 25% and 50% respectively. Figure 7(a)–7(f) show the variations of the groundwater level in the Nile Delta aquifer for six cross sections consequently. By decreasing the water depth of canals by 25% (scenario 1.a) the groundwater level inclined to range between 0.0 to 5.6 above mean sea level (amsl) in the west, from 0.0 to 16.0 amsl in the central part and reached from 0.0 m to 5.0 amsl in the eastern area, as shown in Figure 6(a). By decreasing the water depth of canals by 50% (scenario 1.b) the groundwater level ranged between 0.0 to 5.0 amsl in the west, from 0.0 to 15.6 amsl in the central part and reached from 0.0 m to 4.4 amsl in the eastern area, as shown in Figure 6(b). Decreasing the water depth by 25 and 50% led to decrease in groundwater level in the Nile Delta aquifer. In respect to section 1, at distance 50 km from the shore line, the hydraulic head in the south declined from 6.2 in 2008 to 5.6 and 5.0 m amsl in scenarios 1.a and 1.b respectively, as shown in Figure 7(a). In cross section 2, at distance 146 km from the shore line, the drawdown increased towards the south reaching maximum values of about 0.5 and 1.0 m while it increased to reach 1.0 and 1.4 m in cross section 3, at distance 160 km from the shore line, for scenarios 1.a and 1.b consequently, as shown in Figure 7(b) and 7(c). In the west, in cross sections 4 and 5, the groundwater level decreased by 0.2 and 0.4 m in scenarios 1.a and 1.b consequently, as shown in Figure 7(d) and 7(e). In cross section 6, the drawdown increased from north towards the south and equals 0.1 m and 0.2 m from the current situation in scenarios 1.a and 1.b respectively, as shown in Figure 7(f).

Scenario 2: Increasing discharges of pumping wells

Figure 8(a) and 8(b) present the groundwater level for the second scenario by increasing the pumping discharges in the wells by 25% and 50% respectively. Figure 9(a)–9(f) show the variations of groundwater level for six cross sections consequently for pumping scenarios. By increasing the pumping discharges in wells by 25% (scenario 2. a) the groundwater level decreased to range between 0.0 to 5.5 amsl in the west, from 0.0 to 15.8 amsl in the central part and ranged between 0.0 m and 3.3 amsl in the eastern area, as shown in Figure 8(a). By increasing the pumping discharges in wells by 50% (scenario 2. b) the groundwater level ranged between 0.0 to 4.8 m amsl in the west, from 0.0 to 14.0 amsl in the central part and between 0.0 m and 2.1 amsl in the eastern area, as shown in Figure 8(b). Increasing the pumping discharges in wells by 25 and 50% leads to decrease in the groundwater level. In respect to section 1, at distance 50 km from the shore line, the head in the south declined from 6.2 amsl in 2008 to 5.5

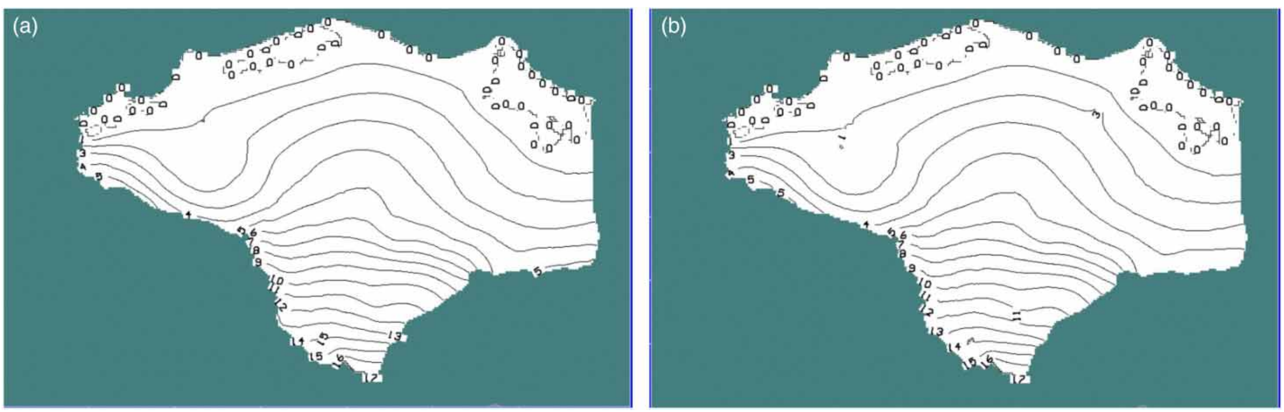

Figure 6 | Groundwater level in the Nile Delta aquifer for scenario 1. (a) Scenario 1.a: canal water depth decrease by 25%. (b) Scenario 1.b: canal water depth decrease by 50%.

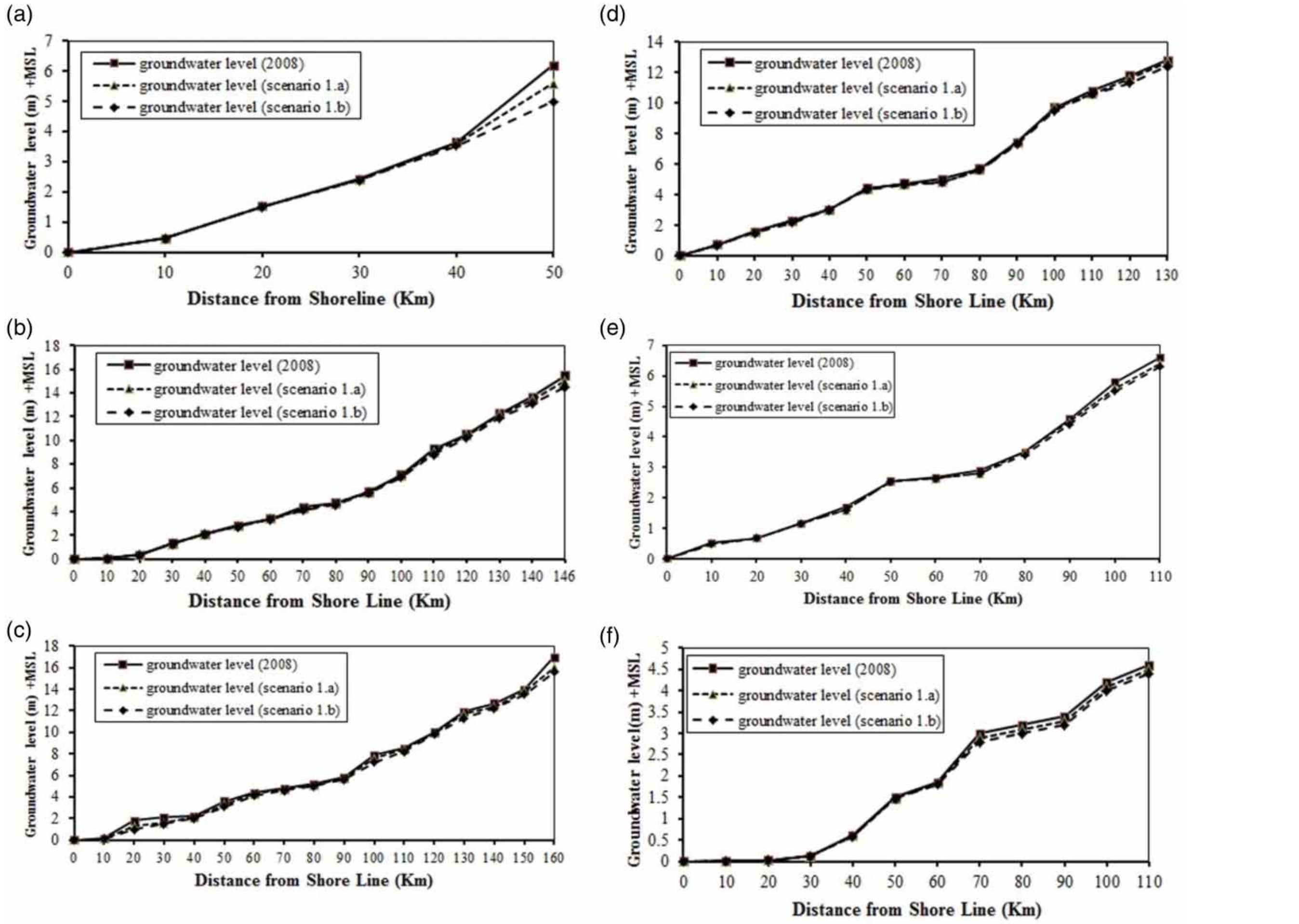

Figure 7 | Groundwater level in the Nile Delta aquifer at different cross sections for scenario 1. (a) Cross section 1. (b) Cross section 2. (c) Cross section 3. (d) Cross section 4. (e) Cross section 5. (f) Cross section 6.

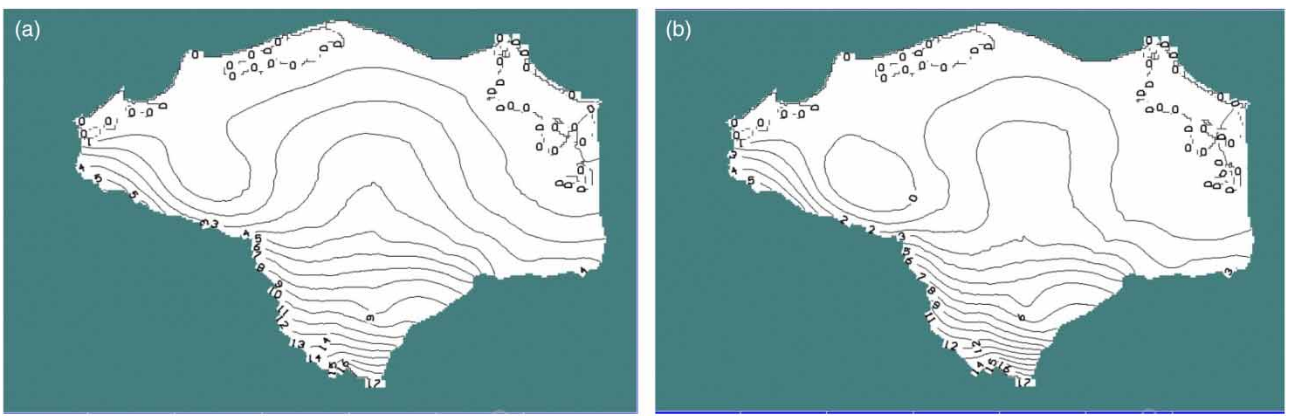

Figure 8 | Groundwater level in the Nile Delta aquifer for different pumping activities (scenario 2). (a) Scenario 2.a: well discharges increased by 25%. (b) Scenario 2.b: well discharges increased by 50%.

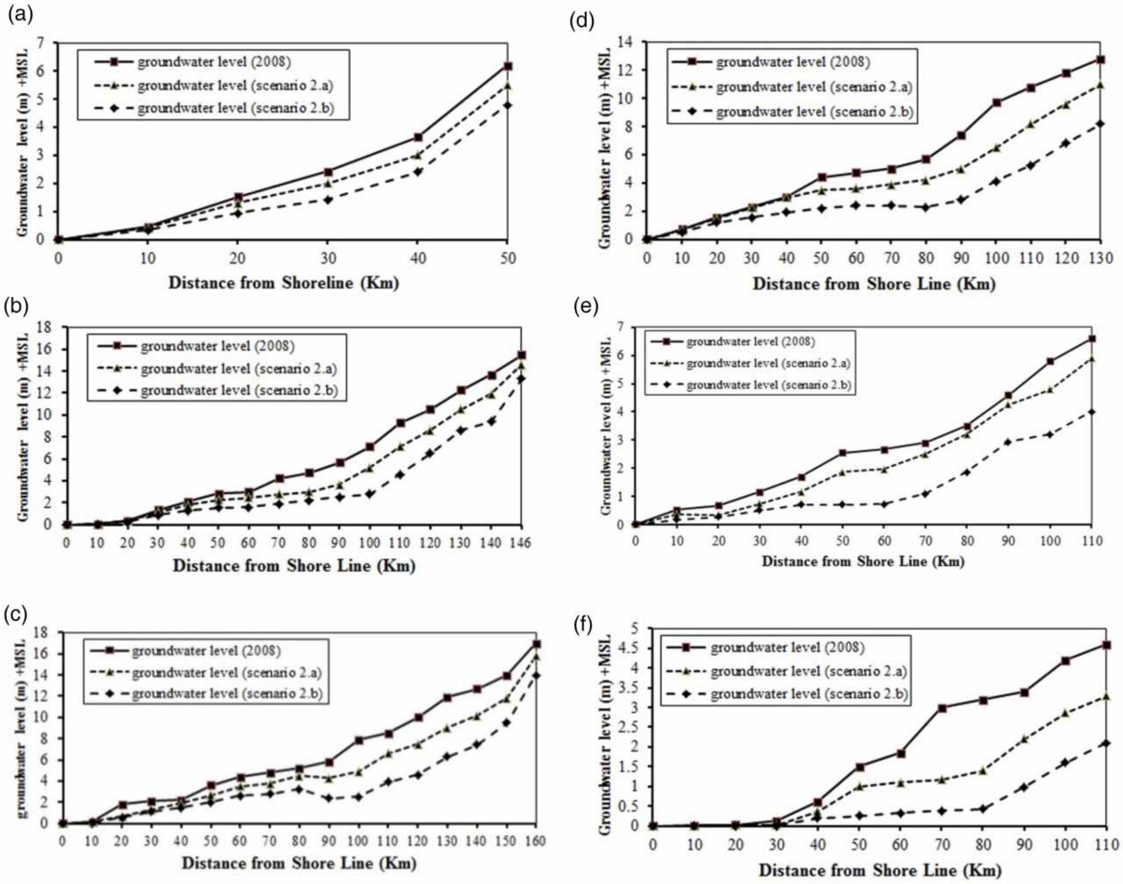

Figure 9 | Groundwater level in the Nile Delta aquifer at different cross sections for scenario 2. (a) Cross section 1. (b) Cross section 2. (c) Cross section 3. (d) Cross section 4. (e) Cross section 5. (f) Cross section 6.

and 4.8 m amsl in scenarios 2.a and 2.b respectively, as shown in Figure 9(a). In cross section 2, at distance 146 km from the shore line, the drawdown increased towards the south reaching maximum values of about 0.9 and 2.2 m while it reached 2.2 and 3 m in cross section 3, at distance 160 km from the shore line, for scenarios 2.a and 2.b consequently, as shown in Figure 9(b) and 9(c). In the west, in cross section 4, the groundwater level decreased by 2.8 and 3.6 m in scenarios 2.a and 2.b consequently, as shown in Figure 9(d). In cross section 5, the groundwater level decreased by 0.7 and 2.6 m in scenarios 2.a and 2.b consequently, as shown in Figure 9(e). In cross section 6, the drawdown increased from the north towards the south and equalled 1.3 m and 2.5 m from the current situation in scenarios 2.a and 2.b respectively, as shown in Figure 9(f).

Scenario 3: Combination between scenario 1 and scenario 2

Figure 10(a) and 10(b) present the groundwater level in the combination between scenarios 1 and 2. Figure 11(a)–11(f) show the variations of groundwater level for six cross sections consequently for combining scenarios. By increasing the pumping discharges in wells by 25% and decreasing the water depth in canals by 25% (scenario 3. a) the groundwater level decreased to range between 0.0 to 5.36 amsl in the west, from 0.0 to 15.4 amsl in the central part and from 0.0 m to 3.7 amsl in the eastern area, as shown in Figure 10(a). By increasing the pumping discharges in wells by 50% and decreasing the water depth in the canals by 50% (scenario 3. b) the groundwater level ranged between 0.0 to 3.68 m amsl in the west, from 0.0 to

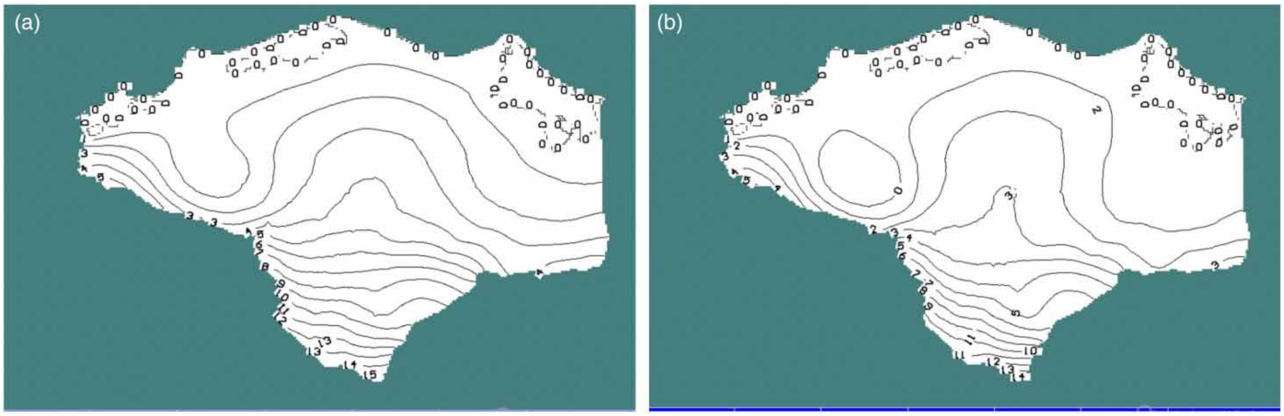

Figure 10 | Groundwater level in the Nile Delta aquifer for combination scenario 3. (a) Scenario 3.a: combination between scenario 1.a + scenario 2.a. (b) Scenario 3.b: combination between scenario 1.b + scenario 2.b.

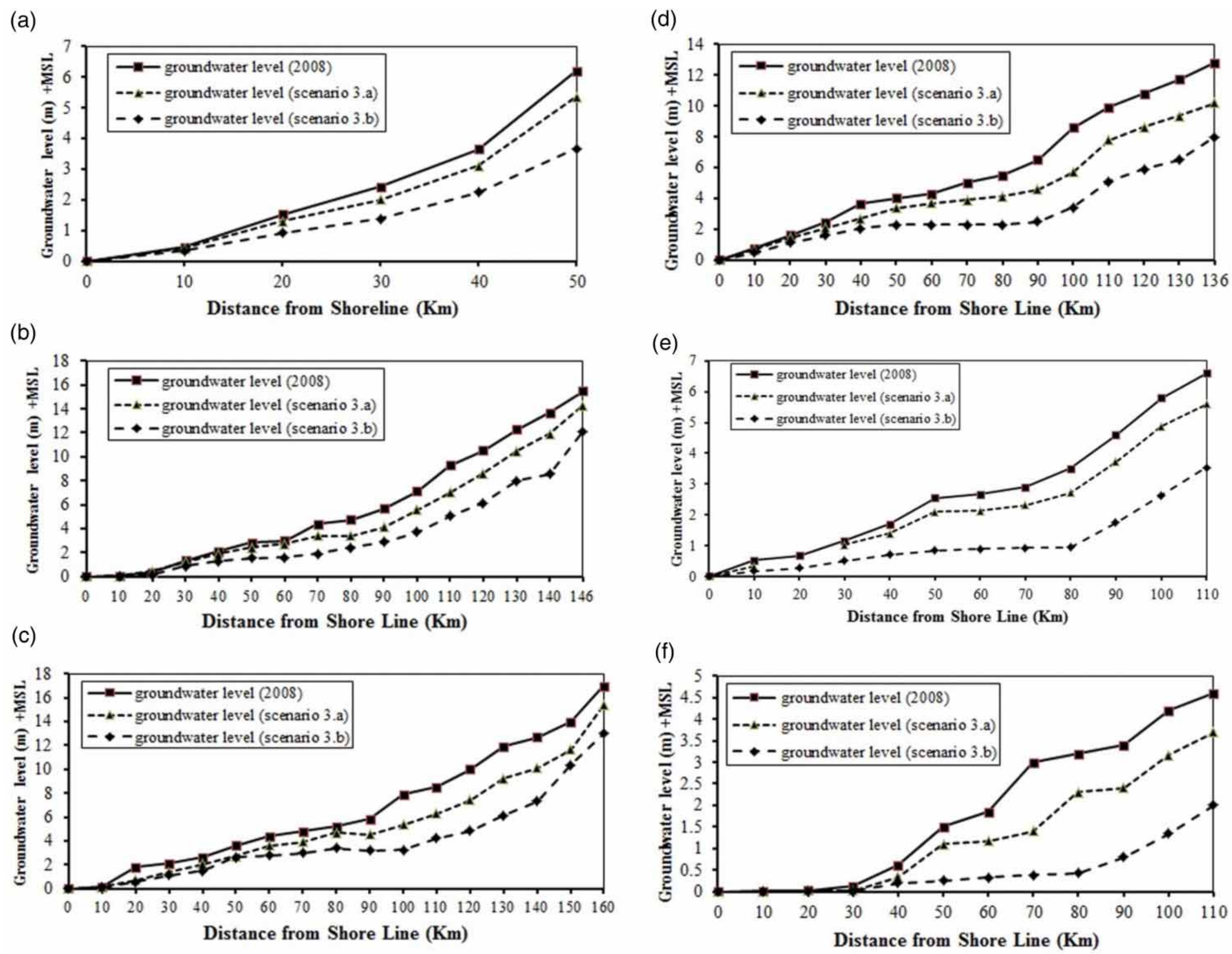

Figure 11 | Groundwater level in the Nile Delta aquifer at different cross sections for scenario 3. (a) Cross section 1. (b) Cross section 2. (c) Cross section 3. (d) Cross section 4. (e) Cross section 5. (f) Cross section 6.

13.0 amsl in the central part and from 0.0 m to 2.0 amsl in the eastern area, as shown in Figure 10(b). Increasing the pumping discharges and decreasing the water depth in canals leads to more drawdown in groundwater level compared with the first and second scenarios. In respect to section 1, at distance 50 km from the shore line, the head in the south declined from 6.2 amsl in 2008 to 5.36 and 3.68 m amsl in scenarios 3.a and 3.b respectively, as shown in Figure 11(a). In cross section 2, at distance 146 km from the shore line, the drawdown increased towards the south reaching maximum values of about 2.2 and 3.4 m while it reached 2.2 and 3.6 m in cross section 3, at distance 160 km from the shore line, for scenarios 3.a and 3.b consequently, as shown in Figure 11(b) and 11(c). In the west, in cross section 4, the groundwater level decreased by 2.6 and 3.8 m in scenarios 3.a and 3.b consequently, as shown in Figure 11(d). In cross section 5, the groundwater level decreased by 1.0 and 2.9 m in scenarios 3.a and 3.b consequently, as shown in Figure 11(e). In cross section 6, the drawdown increased from north towards the south and equals 1.3 m and 2.6 m from the current situation in scenarios 3.a and 3.b respectively, as shown in Figure 11(f).

This paper presents the first study to build a 3-D model for the Nile Delta aquifer where the high intensive irrigation canal networks were included for accurate simulation of groundwater recharge from the canals network by using MODFLOW software. The impact of increasing pumping discharge from wells on groundwater level in the Nile Delta is much more significant than the impact of decreasing water depths of canals; this is due to the fact of the existence of the upper clay layer, which reduces the ability of the water to penetrate and reach the groundwater in the aquifer. The drawdown increases from the north towards the south. The reasons behind this are that the southern part of the Nile Delta has high pumping discharge values compared with the northern area and the effect of the constant head model boundary at the northern area along the shore line of the Mediterranean Sea. The last scenario presents the worst one where combination between increasing the drawdown related to increasing the pumping and decreasing groundwater recharge with respect to decreasing water depths of the canals.

CONCLUSIONS

The paper presents simulation of the effect of decreasing the water depth in the canal networks in the Nile Delta due to the impact of GERD and of increasing the pumping discharges on groundwater level by using MODFLOW software where the intensive irrigation network canals of the Nile Delta were included for more accurate simulation of groundwater recharge. The model was calibrated for hydraulic conductivity of the first and second layer using the observed head by RIGW (Morsy 2009). The model was tested for three scenarios: (1) reduction of water depth in canals due to the impact of GERD, (2) increasing pumping discharges of groundwater wells and (3) combination of the first and second scenarios. Under the conditions assumed in these scenarios, the effect of increasing the pumping discharges is much more significant than the effect of decreasing the water depth in canals network compared with the situation in 2008. The drawdown of groundwater head increases from the north towards the south in the Nile Delta region. Decreasing the water depth by 25% leads to drawdowns of 0.30 m, 0.5 m and 0.2 m in average in the western, central area and eastern parts of the Nile Delta while a further drawdown is expected to reach 0.6 m, 0.7 m and 0.4 m in average in case of decreasing the water depth by 50%. Increasing the pumping discharges by 25% leaded to drawdowns of 0.35 m, 1.0 m and 0.5 m in average in the western, central area and eastern parts of the Nile Delta while a further drawdown is expected to reach 0.7 m, 1.5 m and 1.27 m in average in case of increasing the pumping discharges by 50%. It is highly recommended to re-investigate the saltwater intrusion in the Nile Delta aquifer taking into considerations the different filling scenarios of the GERD reservoir.

ACKNOWLEDGEMENTS

The first author would like to thank the Egyptian Ministry of Higher Education (MoHE) for providing him with the financial support (PhD scholarship) for this research as well as the Egypt Japan University of Science and Technology (E-JUST) for offering the facility and tools needed to conduct this work.

REFERENCES

Abdelaty, I. M., Abd-El hamid, H. F., Fahmy, M. R. & Abdelaal, G. M. 2014 Investigation of some potential parameters and its impacts on saltwater intrusion in Nile Delta aquifer. *Journal of Engineering Sciences, Assiut University, Faculty of Engineering* **42** (4), 931–955.

Anderson, M. P. & Woessner, W. W. 1992 *Applied Groundwater Modeling: Simulation of Flow and Advection Transport*. Academic Press, San Diego, New York, Boston, p. 318.

Anon 1980 *Investigation Project of Sustained Yield of Aquifers, Part 1*, Groundwater Research Institute, Cairo, p. 342.

Armanuos, A. M., Negm, A., Yoshimura, C. & Valeriano, O. C. S. 2016a Application of WetSpass model to estimate groundwater recharge variability in the Nile Delta aquifer. *Arab Journal of Geosciences* **9**, 553. DOI: 10.1007/s12517-016-2580-x

Armanuos, A. M., Negm, A., Yoshimura, C. & Valeriano, O. C. S. 2016b Estimation of bed and bank levels of an irrigation canal network towards accurate groundwater modeling of the Nile Delta aquifer. *International Water Technology Journal* **6** (1), 74–84.

Bear, J. 1979 *Hydraulics of Groundwater*. McGraw-Hill, New York.

Dahab, K. A. 1993 Hydrological evaluation of the Nile Delta after the High dam construction, PhD thesis, Faculty of science, Monofia University, Egypt, 30.

EGSA (Egyptian General Survey and Mining) 1997 Topographical maps cover Nile Delta, Scale 1:1500000 and 1:10000.

Elewa, H. H. 2010 Potentialities of water resources pollution of the Nile River Delta, Egypt. *Open Hydrology Journal* **4**, 1–13. DOI: 10.2174/1874378101004010001

El Ramly, M. 1997 Hydrogeological and water quality characteristics of the saturated zone beneath the various land uses in the Nile Delta region, Egypt. In: *Freshwater Contamination (Proceedings of Rabat Symposium S4, April–May 1997)*, IAHS Publ., Wallingford, UK, No. 243, pp. 255–261.

International Panel of Experts (IPoE) on Grand Ethiopian Renaissance Dam Project (GERDP) 2013 *Final Report*, Addis Ababa, Ethiopia, May 31. Available: http://www.internationalrivers.org.

Kashef 1983 Salt-water intrusion in the Nile Delta, *Ground Water*, **21** (2), 160–167.

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. *Hydrology and Earth Systems Sciences Discussions*, **10**, 10873–10911.

Ministry of Water Resources and Irrigation (MWRI) 2013 *Proposed Climate Change Adaptation Strategy for the Ministry of Water Resources and Irrigation in Egypt*. Ministry of Water Resources and Irrigation.

Morsy, W. S. 2009 Environmental Management to Groundwater Resources for Nile Delta Region, PhD Thesis, Faculty of Engineering, Cairo University, Egypt.

Mulat, A. G. & Moges, S. A. 2014 Assessment of the impact of the Grand Ethiopian Renaissance Dam on the performance of the High Aswan Dam. *Journal of Water Resource and Protection* **6**, 583–598.

MWRI 1954 Irrigation and drainage network Nile Delta map, Scale 1:200,000. Prepared by Ministry of Water Resources and Irrigation.

NWRC 2003 Egyptian code of water resources and irrigation works, chapter 3: Horizontal expansion, Planning and designing of irrigation and drainage canals, pp. 1–7.

Ramadan, S. M., Negm, A. M., Smanny, M. & Helmy, A. 2015 Quantifying the impacts of impounding grand Ethiopian Renaissance dam reservoir on Nasser lake active reservoir. In: *Eighteenth International Water Technology Conference, IWTC18, Sharm ElSheikh*, 12–14 March.

RIGW 1992 Hydrogeological map of Nile Delta, Scale 1: 500,000, 1st edn, ND.

RIGW 2002 *Nile Delta Groundwater Modeling Report*, Research Inst. For Groundwater, Kanater El-Khairia, Egypt.

RIGW 2003 Monitoring of groundwater microbiological activities in the Nile Delta aquifer. A study completed for the National Water Quality and Availability Management project (NAWQAM), Kanater El-Khairia, Egypt.

RIGW 2015 General management of irrigation-Delta Barrages, Water level in main canals in the Nile Delta 2008.

Roest, J. 1999 Regional water distribution in the Nile Delta of Egypt. ILRI workshop: water and food security in (semi-) arid areas. In: *Proceedings of the Wageningen Water Workshop*, June, The Netherlands, pp. 61–82.

Said, R. 1962 *The Geology of Egypt*, Elsevier, Amsterdam, The Netherlands.

Shahin, M. 1985 *Hydrology of the Nile Basin Developments in Water Science*, 21, Elsevier, Amsterdam.

Shamrukh, M., Corapcioglu, Y. & Hassona, F. 2001 Modeling the effect of chemical fertilizers on ground water quality in the Nile Valley aquifer, Egypt. *Ground Water* **39**, 59.

Sherif, M. M. 2003 *Assessment, Modeling and Management of Seawater Intrusion in the Nile Delta Aquifer*, IGME, Madrid.

Sherif, M. 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. *Journal of Hydrology*, **464–465**, 186–198. DOI:org/10.1016/ j.jhydrol.2012.07.007

Wahaab, R. & Badawy, M. I. 2004 Water quality assessment of the River Nile system: an overview. *Biomedical and Environmental Sciences* **17**, 87–100.

Wilson, J., Townley, L. R. & Sa Da Costa, A. 1979 *Mathematical Development and Verification of a Finite Element Aquifer Flow Model AQUIFEM-1, Technology Adaptation Program, Report No. 79–2*, MIT, Cambridge, MA.

First received 30 October 2016; accepted in revised form 6 March 2017. Available online 31 March 2017