Management of saltwater intrusion in coastal aquifers using different wells systems considering climate change: Case study of the Nile delta

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ABSTRACT:

Saltwater intrusion (SWI) is a special type of pollution that adversely affects the quality of groundwater in coastal aquifers. The Nile Delta Aquifer (NDA) contains a large amount of fresh water. Increasing abstraction from the aquifer and sea level rise have led to increased SWI which reached to 100 km. Therefore, practical measures are required to prevent further SWI. This study aims to identify an optimal well system to manage the intrusion of saline water in NDA using a number of management systems including pumping of brackish water, recharge of aquifer and abstraction of fresh water. The SEAWAT code is used to simulate SWI in the aquifer considering different scenarios of pumping and sea level rise. Four scenarios are used to control SWI including; decreasing pumping from the aquifer, increasing recharge using treated waste water, increasing abstraction of brackish water for desalination and combination of these systems. The results show that increasing recharge could lead to greater retardation of SWI (19.50%) than decreasing pumping (6.20%) and abstraction of brackish water (5.90%). However, a combined well system of pumping, recharge and abstraction is shown to be a more effective tool to control SWI in coastal aquifers with retardation percentage of 21.30%.

Keywords: saltwater intrusion, control, pumping, recharge, abstraction, Nile Delta aquifer.

1. Introduction

The high rate of population growth over the past 100 years has increased the water demand in different areas of the world. The increasing water demand has increased pumping from groundwater aquifers which has in turn caused saltwater intrusion (SWI) in coastal aquifers. In normal circumstances, the freshwater flows in the coast direction but over-pumping may lead to reversal of the flow inland causing SWI (Bear et al., 1999). Also, climate change has been increasing at alarming rates in the last few decades which has led to rise in sea levels. The rise in mean sea level may occur due to thermal expansion of seas or melting of glaciers and ice caps. According to the Intergovernmental Panel on Climate Change (IPCC, 1996), over the 20th century, sea levels have risen about 1-2 cm/yr. The expected rise in sea level by the end of the 21st century is between 2-8.8 cm/yr. (IPCC, 2001).

The main causes of saltwater intrusion include over-abstraction, changes in groundwater flow, tidal effects, seismic waves, dispersion and sea level rise. One of the main impacts of the sea level rise on coastal regions is increasing SWI. It also has a direct impact on groundwater resources, soil salinity, and agricultural productivity in coastal zones. Saltwater intrusion into coastal aquifers should be controlled in order to protect groundwater resources from deterioration. The control of saltwater intrusion requires keeping an appropriate balance between water abstracted from and recharged to the aquifer (Bear et al., 1999). Different measures to control SWI were presented by Todd (1974) including: decreasing pumping rate, relocation of wells, use of subsurface barriers, natural and artificial recharge, and abstraction of saline water and disposal to the sea.

A number of numerical models have been used to improve understanding of the relevant processes that cause SWI and find appropriate control methods. A number of studies have investigated saltwater intrusion. However, a relatively small amount of research has been carried out to study the control of saltwater intrusion (Abd-Elhamid and Javadi, 2008). In this study, a number of effective methods to control SWI are examined and compared including; reducing pumping rates, artificial recharge, abstraction of saline water and combination of these methods. A comprehensive review of the developed models to study and control SWI is presented below.

Reducing abstraction rates aims to obtain a sustainable yield while using other sources of water to meet the demand for water. The control of SWI has been studied using number of models by managing the abstraction (e.g. Scholze et al. (2002), Zhou et al. (2003) and Bhattacharjya and Datta (2005)). Qahman and Larabi (2004) used the SEAWAT code to study the problem of extensive SWI in the Gaza aquifer, in Palestine. Saltwater intrusion was investigated under different scenarios of abstraction over the time. The study showed that the aquifer is very sensitive to pumping which should be managed to protect the aquifer from SWI. Narayan et al. (2006) used various pumping and recharge schemes to determine the current and possible future extent of saltwater intrusion in the Burdekin aquifer in Australia using the SUTRA code.

Artificial recharge helps to raise groundwater levels in aquifers. Surface spread of water from rivers or canals, treated wastewater, and desalinated water are possible sources of water for recharging unconfined aquifers, while recharge wells can be used for confined aquifers. The management of SWI in coastal aquifers using artificial recharge was studied by a number of researchers such as Narayan et al. (2006), Papadopoulou et al. (2005) and Kashef (1976).

Mahesha (1996a) simulated the effect of recharge wells on SWI in confined aquifers. Several conditions were studied by changing well spacing and recharge duration. The study showed that spacing of the wells and rate and duration of recharge can decrease SWI by repulsion of the saline wedge.

The abstraction saline water and its disposal to the sea helps to decrease the mass of saline water in coastal aquifers. This method was applied to control saltwater intrusion in coastal aquifers by a number of researchers such as Maimone and Fitzgerald (2001) and Kacimov et al. (2009). Sherif and Hamza (2001) studied the balance between saltwater and freshwater using abstraction of brackish water from the transition zone using a 2-D finite element model. Sherif and Kacimov (2008) examined different pumping scenarios and suggested that pumping brackish water can reduce the intrusion of saline water. The main problem in abstraction of brackish water is that the disposal of the saline water to the sea could affect the marine life, fishing and tourism in these areas (Abd-Elhamid and Javadi, 2008). Johnson and Spery (2001) studied a number of methods to control SWI in different states of the United States of America. In California, the saline water was abstracted and desalinated using Reverse Osmosis. The treated water was mixed with groundwater to produce an appropriate water quality for domestic use. In Los Angeles, treated waste water was used to recharge the aquifer using a system of wells to protect coastal aquifers from SWI.

Combination of two or more of the above methods could give a better control of SWI. Different combined methodologies to control SWI in coastal zones were used by a number of researchers (e.g. Zhou et al. (2003); Hong et al. (2004); Narayan et al. (2006), Paniconi et al. (2001); and Barrocu et al. (2004)). Mahesha (1996c) used a series of wells for abstracting saline water in combination with freshwater recharge wells. The study indicated that the combination of abstraction and recharge gives better results compared with the abstraction or recharge method, leading to larger spaces between wells and smaller recharge rates. Abd-Elhamid and Javadi (2011) introduced the ADR (Abstraction, Desalination and Recharge) method to control SWI. The ADR method includes abstraction of saline water, desalination and recharge to the aquifer. A finite element model was developed and used to simulate SWI. The results indicated that the ADR method is more effective than the abstraction or recharge method. A simulation-optimization model was developed by Javadi et al., (2012) to control SWI using the combination of the abstraction and recharge techniques. The developed model was applied to a confined coastal aquifer. The results showed that using the combined recharge and abstraction system is significantly more effective in controlling SWI than using abstraction or recharge wells separately. The combination of abstraction and recharge wells gave lower cost and lower salt concentration in the aquifer.

Javadi et al., (2013) used the SUTRA code integrated with a Genetic Algorithm optimization tool to identify the efficacy of different scenarios of controlling SWI in an unconfined costal aquifer. The method was based on a combination of abstraction of saline water and recharge of aquifer using surface ponds. The results confirmed that the combined system is more effective in controlling SWI than using separate methods. Javadi et al., (2015) presented a methodology based on the combination of abstraction of saline water and desalination for domestic use, and recharge of the aquifer using treated wastewater. The results showed that this method is effective to controlling SWI and it results in lower salinity and cost.

The Nile Delta Aquifer (NDA) in Egypt is subject to severe SWI from the Mediterranean Sea. The NDA is one of the largest aquifers in the world (Sherif et al., 1999). Water resources in NDA are threatened by the increasing population, over-pumping, subsidence, coastal erosion, contamination and salinization. These have led to high risks on water resources in the Nile Delta region and management of water resources has become crucial. Various studies on the NDA have indicated that SWI has been extended to 100 km inland. This aquifer is covered by the Delta and has a huge volume of fresh water. However, the quality of the abstracted water is adversely affected by SWI, upconing and contamination. A number of studies have been directed to identify SWI in the NDA using different numerical models (e.g., Farid (1980 and 1985), Amer and Farid (1981), Sherif et al. (1990), Darwish (1994), Amer and Sherif (1999), Sherif and Singh (1997) and Saifelnaser and Sherif (2012)). Abd-Elaty et al., (2014) studied the effect of sea level rise and climatic change on SWI in the NDA using SEAWAT. The study indicated that SLR, reduction in surface water recharge and increasing abstraction rate have strong impact on groundwater level but a combination of these scenarios would have larger impact on the aquifer.

The current research presents a numerical study to control SWI in the NDA using different well systems to those studied before. Different scenarios are considered in this study including, decreasing pumping rates, recharging the aquifer using treated wastewater, abstraction of brackish water a and combination of these three methods.

2. Numerical model

In this study, the SEAWAT-V4 code was used to simulate SWI and assess different scenarios for controlling SWI in the Nile delta aquifer. SEAWAT simulates variable-density, transient groundwater flow using MODFLOW and MT3DMS programs. The latest version (SEAWAT-V4) was designed to calculate fluid density, viscosity and heat (Langevin et al., 2007).

3. Study area

The NDA is one of the largest aquifers in the world (Sherif et al, 2012). This study focuses on the Middle part of the Nile Delta aquifer (MND) which is considered the highest part affected by SWI from the Mediterranean Sea (Figure 1a). The abstraction rate from this area is very high which has resulted in more SWI in the middle part. The MND is located between Latitudes 30˚ 20` and 31˚ 50`N, and longitudes 30˚ 10`and 31˚ 35`E. It is bounded by the Mediterranean Sea in the North, River Nile in the South and the East and the two branches of Nile in the West. It has an area of 9,000 km^2. The stratigraphy of the study area is divided to Pliocene sediments, an upper fluviatile sequence (late Pliocene), and Quaternary (Pleistocene and Holocene) sediments lying over the Pliocene sediments. The sediments constitute variable proportions of sand, clay and gravel with lateral variation and variable thicknesses (Sallouma, 1983). The thickness of the Quaternary aquifer varies from 200m in the South to 1000m in the North (RIGW, 1992). The main aquifer in the study area is the Quaternary aquifer. The aquifer is composed of loose sand with gravel related to the old litho-facies (Hefny (1980), Sallouma (1983) and Serag El Din (1989)) as shown Figure 1b (Sakr, 2005).

3.1 Aquifer geometry

The SEAWAT code is used to simulate heads and solute transport in the aquifer. The domain (9,000 km^2) is divided to 157 rows and 141 columns with square cells of dimensions 1 km^2 (Figure 2a). The depth was divided into 11 layers with varying depth from 200 m in Cairo to 1000 m at the sea. The top layer represents clay cap with depth varying from 20m in the South to 50m in the North. The other layers representing the Quaternary aquifer are divided into equal thickness. The aquifer is semi-confined due to the top clay layer. Two vertical sections are taken in X and Y directions as shown in Figures 2b and 2c.

3.2 Boundary conditions

The flow and concentration boundary conditions were allocated to the model with zero constant hydraulic head along the shoreline in the North and a specified head of 16.96 m in the South. The East and West boundaries were assigned according to the water levels in the Damietta and Rosita branches of the River Nile. Burrules Lake was assigned as a water body with zero specified head. A concentration of 40000 mg/l was applied along the coastal line, and 35000 mg/l in Burrules Lake which receives water from some drainages in the Nile Delta. The initial groundwater concentration was set to zero. The initial values of hydraulic parameters of the aquifer, obtained from previous studies, were used as input to the model.

3.3 Hydraulic parameters

The hydraulic parameters of the study area for each layer, including specific storage (S_s), specific yield (S_y), hydraulic conductivity (K) and porosity were taken from previous studies (e.g., RIGW, 1980). The conductivity in the vertical and horizontal directions (K_{cv} and K_{ch}) for the top layer was taken 2.50 and 25-55 mm/day respectively (RIGW, 1980). The average horizontal hydraulic conductivity (K_h) of the Quaternary aquifer sediments was taken 75 m/day (RIGW/IWACO, 1999). The specific storage and the storativity (S) were 0.20 and 2.5×10^{-3} respectively (RIGW 1980). The longitudinal and lateral dispersivities were taken as 100m and 10m respectively, and the diffusion coefficient (D*) as 10^{-4} m^2/day (Sherif et al. (1988)). The aquifer recharge ranges from 0.25 to 0.80 mm/day (RIGW, 1980).

Figure 3 presents the annual abstraction rates for the Nile Delta aquifer from 1990 to 2016. The abstraction reached 1.60 and 2.60 BCM in 1980 and 1991 (RIGW, 1992) and 3.02 and 4.90 BCM in 1999 and 2003 (Morsy, 2008). Also, the annual abstraction reached 3.50 BCM in 2003 (RIGW, 2003) and 7.00 BCM in 2016 (Molle et al., 2016). Mabrouk (2013) indicated that the abstraction rate of the aquifer increases by 0.10 BCM per year while the rate increased to 0.20 BCM per year from 2003 to 2010. The total number of pumping wells in the study area (MDA) is 946 (Figure 4). The total pumping from the MND aquifer was taken as $2.22*10^6$ m^3/day ($810*10^6$ m^3/year) (Morsy, 2008).

4. Model Calibration

The model was calibrated using field data collected by RIGW (2008). The solute transport model was calibrated in two steps. The first step was done for the hydraulic head using constant density option (visual MODFLOW) through several trials by changing the hydraulic parameters including hydraulic conductivity which ranges from 0.05 to 0.20 m/day for the clay cap and from 25 to 150 m/day for the Quaternary aquifer. The recharge rate ranged from 36 to 400 mm/year. Readings from 22 observation wells in the study area were used for calibration. The field data on hydraulic heads were collected by RIGW in 2008. From the model results the mean and absolute residual mean reached -0.07 and 0.144 m respectively while the root mean square was 0.153 m and normalized RMS was 1.341 %. The calibration target of the model was 10% of the difference between maximum and minimum groundwater heads which is about 1.40 m as shown in Figure 5.

The second stage was carried out using the variable density option (SEAWAT-V4) for concentration parameters of total dissolved solid (TDS) based on the data collected from field survey for groundwater quality monitoring wells and the measured salinity values based on RIGW (2008). The initial time was applied as 0.001 day using time step of 200 days while the model reached the steady state condition after 1825000 days. As the head convergence criterion, the tolerance of 1×10^{-7} m was assigned using the Preconditioned Conjugate Gradient (PCG) solver, while the the Generalized Conjugate Gradient Solver (GCG) was used for the transport equation with a Courant number of 0.75 to limit the time step size with maximum step size of 365 days using the simulation period of 1825000 days.

Figure 6a shows the distribution of TDS in the MND with average depth ranging from 675 m in the North to 150 m in the South. The Middle Nile Delta aquifer is subject to severe SWI from the Mediterranean Sea (100 km inland intrusion) as shown in Figure 6b. Form the current model results (base case), the 17,500 mg/l equi-concentration line reached to 82.75 km from shoreline and transition zone was 38 km as shown in Figure 6c. These results are consistent with field data of SWI in the Nile delta aquifer presented by Shrief et al (2012) and Nofal et al (2015). Moreover the salt mass balance of the aquifer that reached $4.4572*10^{13}$ kg.

5. Results and discussion

Different scenarios were studied to investigate SWI in the MND aquifer and to control SWI as will be discussed in the following sections.

5.1 Investigation of SWI in the MND

The SEAWAT code was applied to investigate the intrusion of saline water in the MND aquifer. Different scenarios and their impacts on SWI in the MND are studied including; 0.5 m SLR, 50% increase in the abstraction rate in pumping wells (946 wells) and combination of these cases.

Scenario 1: Sea level rise

In this scenario the effect of sea level rise is studied, where 0.5 m rise in the sea level is considered. The results show that SLR of 0.5 m would increase saltwater intrusion as shown in Figure 7b and the intrusion of the equi-concentration line 17500 mg/l would reach to 84.25 km from the shoreline.

Scenario 2: Increasing pumping rates

Population growth leads to increase the abstraction from groundwater aquifers. In this scenario, the model was used to assess the impact of increasing pumping rates by 50%. Figure 7b shows that increasing pumping rate by 50% would lead to increase in SWI with the equi-concentration line 17500mg/l reaching to 88 km from the shoreline.

Scenario 3: Combination of SLR and increasing abstraction rates

In this scenario, the combination of scenarios 1 and 2 (0.5 m SLR and 50% increase in pumping rates) is simulated. The results show that in this case saltwater intrusion increases as shown in Figure 7b. The intrusion of the equi-concentration line 17500 mg/l reached 89.50 km from the shoreline. Figure 7a shows that this scenario could result in higher SWI in the MND aquifer than the previous two scenarios.

5.2 Control of saltwater intrusion

The numerical model was used to study the control of SWI in the MND using different scenarios including; decreasing pumping rate from the aquifer, increasing recharge to the aquifer, increasing brackish water abstraction from the aquifer and combination of these scenarios. A number of wells were assigned to the model to represent recharge and abstraction from the aquifer. The distribution of 111 recharge wells, 159 abstraction wells and combination are shown in Figure 8a, b and c. The distribution of 946 pumping wells is shown in Figure 4. The results of the four scenarios are presented below and compared with the new position of SWI in the aquifer presented in scenario 3.

Scenario 4: Decreasing pumping

It was shown that increasing the pumping rates would increase the intrusion length (scenario 2). To prevent such increase in SWI, the pumping rate from 946 wells in the MND is reduced by 25% and 50% of the total pumping rate ($2.22x10^6$ m^3/day). The results show that the equi-concentration line 17500mg/l would reach to 86.50 and 84 km from the shoreline due to reduction of 25% and 50% respectively (Figures 9a and 9b). The relation between intrusion length (X_T) and reduction of pumping rates from wells can be seen in Figure 9c. The results reveal that decreasing pumping rate would lead to decrease in seawater intrusion. The relation can be used to determine the intrusion length (X_T) knowing the pumping rate.

Scenario 5: Increasing recharge

Another scenario is considered to control SWI by recharging treated wastewater to the aquifer using wells. 111 wells (150 m deep) in three rows are considered with spacing of 2 km and 5 km distance between rows. This water has TDS of 200 mg/l. It is assumed to be taken from treated wastewater treatment. The recharge rate is taken as 125% and 150% of the pumping rate. The results show that intrusion would reach 79 and 72 km from shoreline for the equi-concentration 17500mg/l for 125% and 150% increase in recharge respectively (Figures 10a and10b). Figure 10c shows the relation between (X_T) and increasing recharge rate. The results indicate that increasing recharge rate leads to decrease in seawater intrusion. The relation can be used to calculate intrusion length (X_T) knowing the recharge rate.

Scenario 6: Abstraction of brackish water and disposal to the sea

This scenario is used to study controlling SWI using 159 abstraction wells (350 m deep) installed in three rows in the north of the region with 2 km spacing and 10 km distance between the rows. The abstraction rate is taken as 125% and 150% of the pumping rate. Figures 11a and b show that SWI would reach 87 and 84.25 km from the shoreline for equi-concentration line 17500 for 125% and 150% of abstraction rates respectively. A relation between the intrusion length (X_T) and abstraction rate is shown in Figure 11c. The relation can be used to calculate the intrusion length (X_T) as a function of the abstraction rate. The results indicate that increasing abstraction of brackish water leads to decrease in seawater intrusion.

Scenario 7: Combination of scenarios 4, 5 and 6

In this scenario, a combination of the above three scenarios including reducing abstraction rate (scenarios 4), increasing recharge using treated wastewater (scenarios 5) and abstracting brackish water (scenarios 6) is applied to control SWI. The results show that the intrusion could reach to 78 and 70.50 km from shoreline for equi-concentration line 17500mg/l for the cases of 125% and 150% change as shown in Figure 12a and 12b. A relation between intrusion length (X_T) and combined scenario is shown in Figure 12c. The results show that decreasing abstraction of freshwater, increasing recharge and increasing the abstraction of brackish water lead to higher retardation of seawater intrusion. The relation can be used to determine the intrusion length (X_T) as a function of the recharge and abstraction rates.

The intrusion length in the MND aquifer due to different scenarios is summarized in Table 1 which shows a comparison between the different scenarios. The intrusion length reached 82.75 km under the current conditions (base case) which increased to 89.50 km (scenario 3) when 150% increase in pumping rate and sea level rise of 50 cm were considered. Different scenarios were considered to manage saltwater intrusion in scenario 3. The first three single well systems used in scenarios 4, 5 and 6 to control SWI are capable of reducing the intrusion and moving the transition zone towards the sea. Decreasing pumping rate by 50% (scenario 4) could move the equi-concentration line 175000mg/l back 5.50 km (6.20%) towards the sea. Increasing recharge by 150% (scenario 5) could move the equi-concentration line 175000mg/l back 17.75 km (19.5%) towards the sea. Increasing abstraction of brackish water from the aquifer by 150% (scenario 6) would move the equi-concentration line 175000mg/l back 5.25 km (5.90%) toward the sea. However, combination of these three systems (decreasing pumping, increasing recharge and increasing abstraction of brackish water by 150%) which was presented in scenario 7, could move the equi-concentration line 175000mg/l back 19 km (21.30%) towards. Scenario 7 is considered the best scenario as it gives the highest retardation to SWI. In addition to providing higher retardation for SWI, scenario 7 also has some other advantages including: (i) recharging the aquifer using treated wastewater can help in sustainable management of water resources; and (ii) abstracting brackish water that can be desalinated using e.g., solar-powered desalination plants, can provide additional source of freshwater to meet part of water demand that in turn can help to reduce abstraction of groundwater. This method can control SWI and protect the MND aquifer from deterioration.

6. Conclusion

Saltwater intrusion (SWI) threatens many coastal aquifers in the world. Increasing rates of abstraction of groundwater, climate change and sea level rise have increased SWI. Saltwater intrusion control is crucial for protection of groundwater storage in coastal areas. The Nile Delta aquifer contains a large quantity of freshwater (400BCM) but it is subject to severe SWI from the Mediterranean Sea. This paper presented a numerical study to simulate SWI in the middle Nile Delta (MND) aquifer. The impact of increasing pumping from the aquifer, sea level rise and combination of the two on SWI was studied, which resulted in increased intrusion by 1.50, 5.25 and 6.75 km respectively. Different scenarios were considered to control saltwater intrusion including; decreasing rate of abstraction from the aquifer, increasing recharge using treated waste water, abstraction of brackish water for desalination and combination of these scenarios. The results indicated that decreasing pumping, increasing recharge and increasing brackish water abstraction (scenarios 4, 5 and 6) can retard saltwater intrusion 6.20%, 19.50% and 5.90% respectively. However, combination of scenarios 4, 5 and 6 (scenario 7) can lead to further retardation of saltwater intrusion (21.30%).

Data Availability

All data, models, and code generated or used during the study appear in the submitted article

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Table 1: Intrusion Characteristic in the MND aquifer for different scenarios

Case	**Scenario No.**	**Scenario description**	**Intrusion for Iso-concentration line 35**		
			Length (Km)	**Difference from base case (km)**	**Percentage (%)**
Base case	-	Current situation	82.75	-	-
Different scenarios of SWI investigation	I-1	0.5 Sea level rise	84.25	-1.5	-1.81
	I-2	50% Increasing pumping	88	- 5.25	- 6.34
	I-3	Combination of 1 and 2	89.50	- 6.75	- 8.16
Different scenarios SWI management	M-4	-25% wells pumping rates	86.50	- 3.75	- 4.53
		-50% wells pumping rates	84	- 1.25	- 1.51
	M-5	+25% wells recharge	79	+ 3.75	+ 4.53
		+50% wells recharge	72	+ 10.75	+ 12.99
	M-6	+25% wells abstraction	87	- 4.25	- 5.14
		+50% wells abstraction	84.25	- 1.5	- 1.81
	M-7	-25 and +25% combination of 4, 5 and 6	78	+ 4.75	+ 5.74
		-50 and +50% combination of 4, 5 and 6	70.50	+ 12.25	+ 14.80

Figures

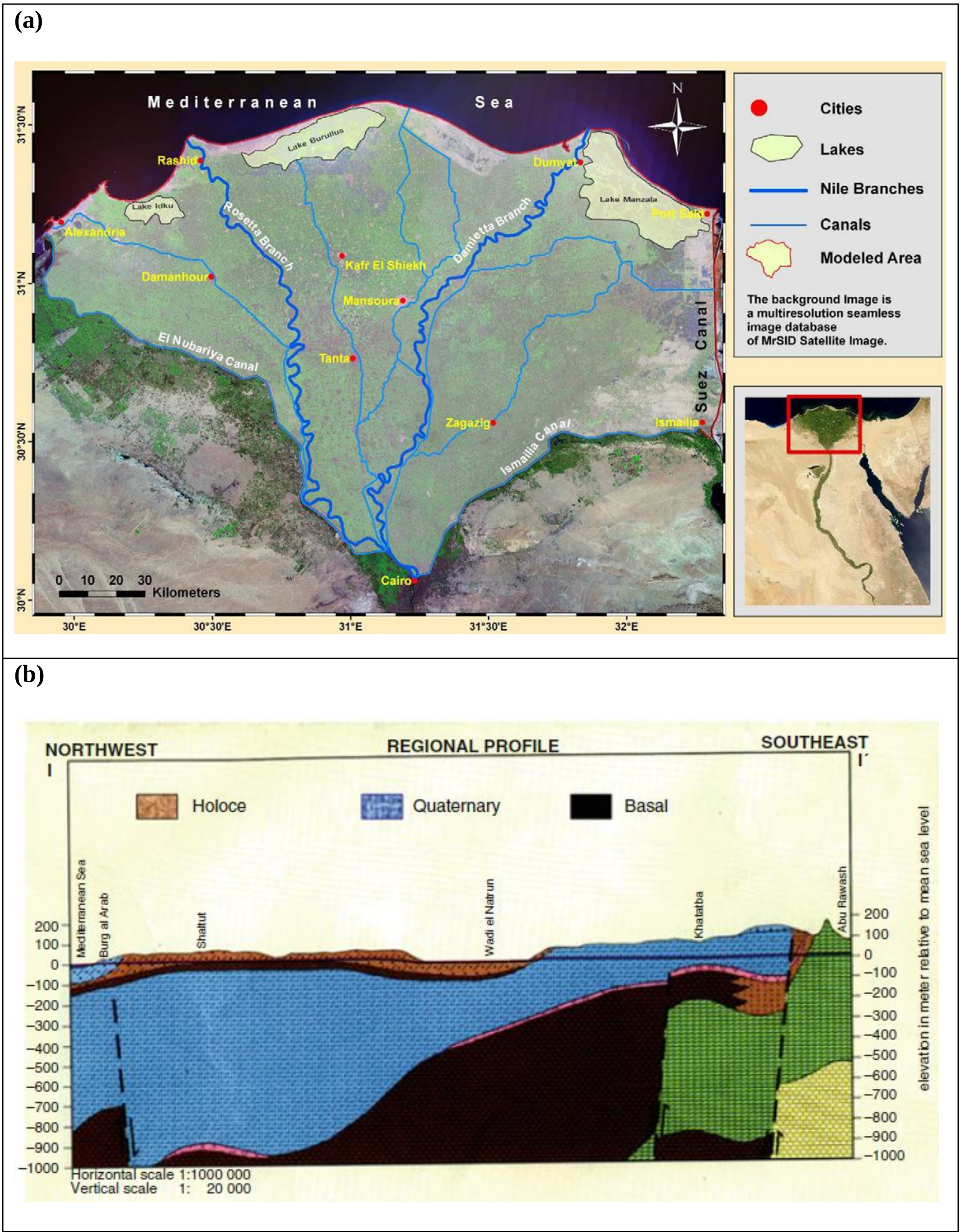


Figure 1. The Nile Delta aquifer (a) Location map (Sherif et al, 2012) and (b) Hydrogeological cross section (Sakr, 2005)

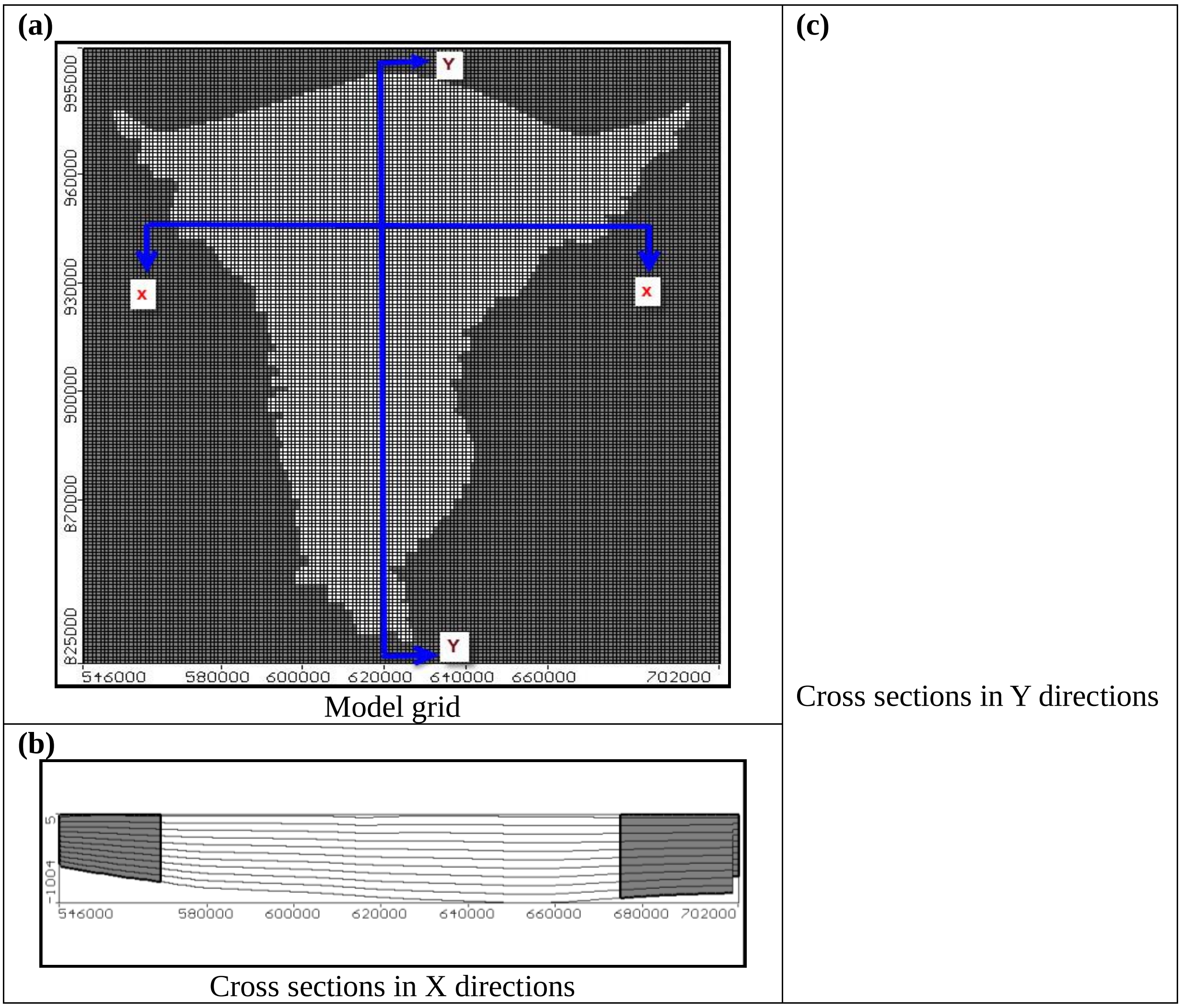


Figure 2: Model grid and cross sections in X and Y directions in the MND aquifer

Figure 3: Annual abstraction rates of Nile delta aquifer

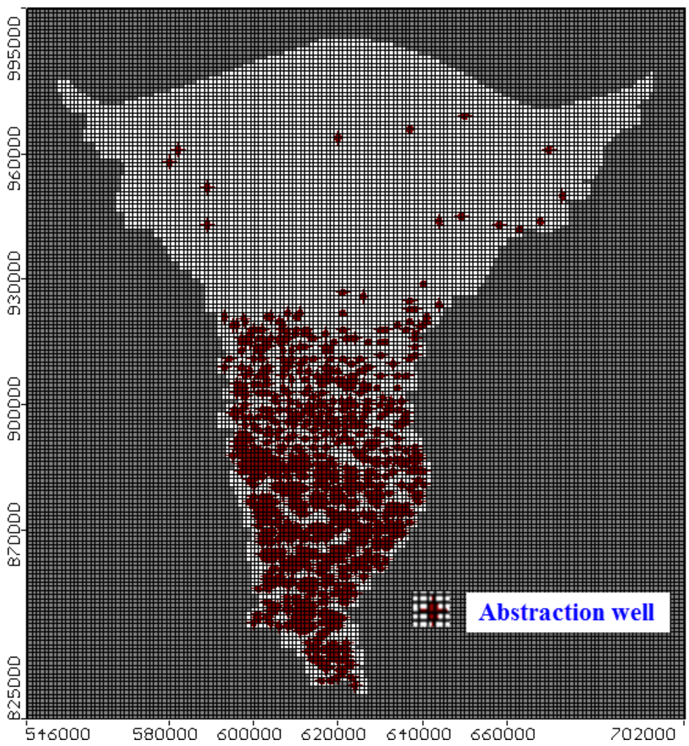


Figure 4: Distribution of abstraction wells in the MND aquifer in year 2008

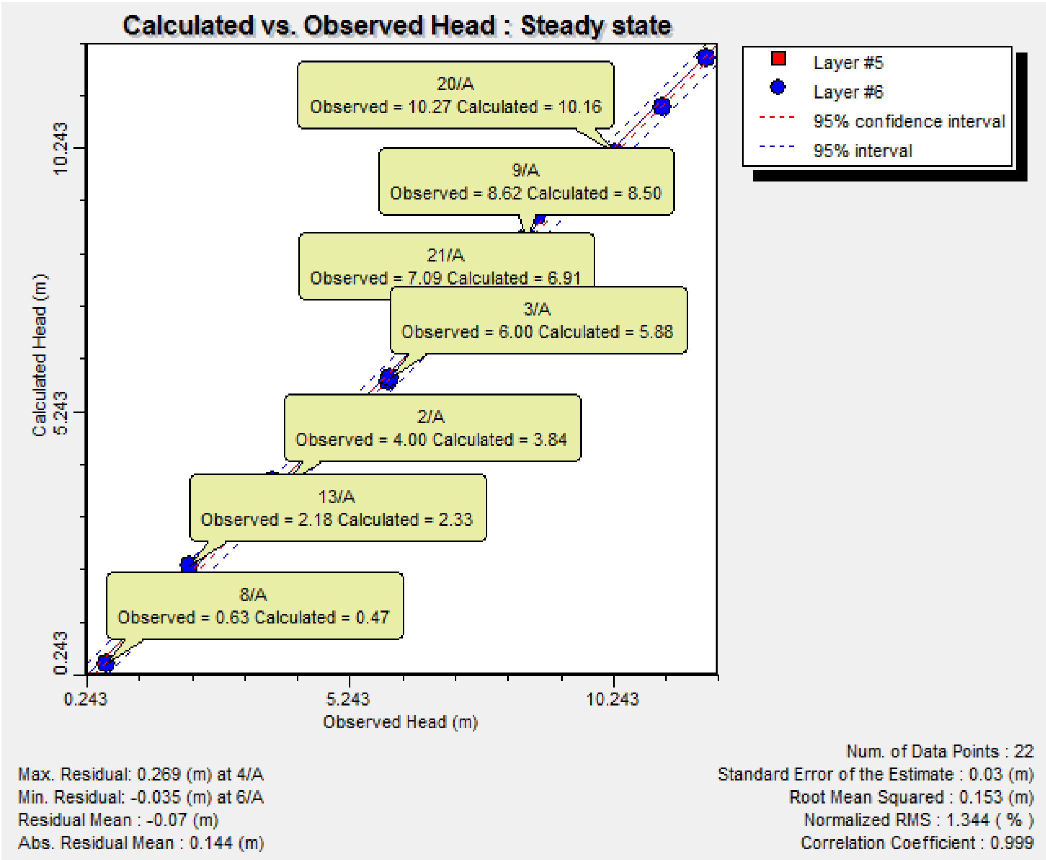
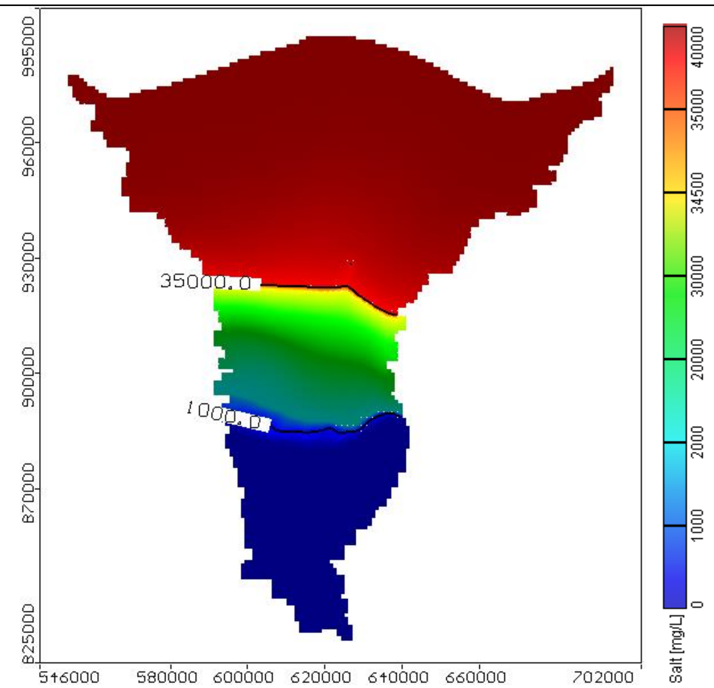
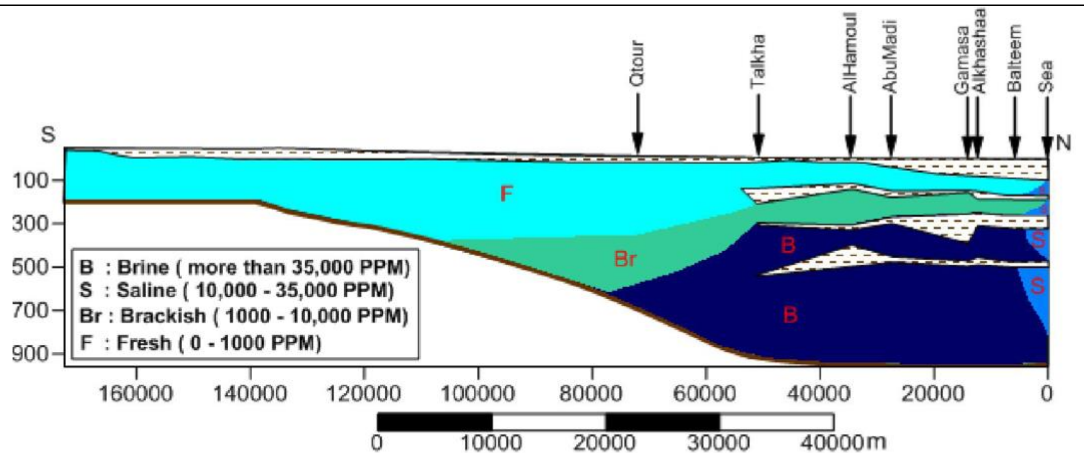


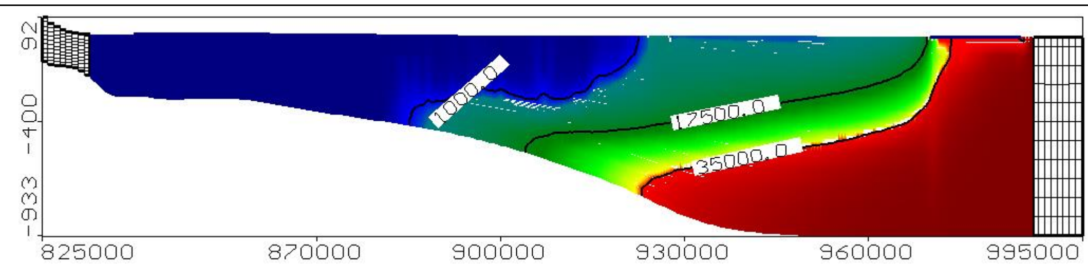
Figure 5: Calculated and observed groundwater heads for the MND aquifer



(a) A real view (output by SEAWAT)

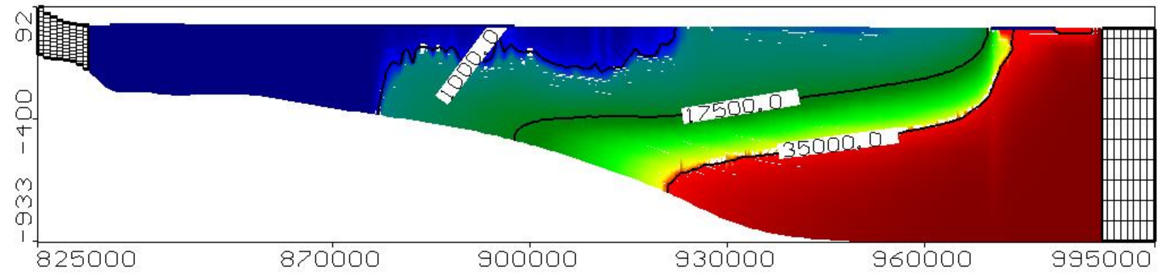


(b) Vertical distribution of TDS by Nofal et al (2015)



(c) Vertical distribution of TDS by current model (output by SEAWAT) from North to south

Figure 6: TDS investigation results in the MNDA for base case in year 2008



(a) Vertical distribution of TDS

(c) Relationship between proposed scenarios and intrusion length (XT)

Figure 7: TDS investigation results for combination of 50 cm SLR and 50% over- pumping in the MND (Scenario.1, 2 and 3)

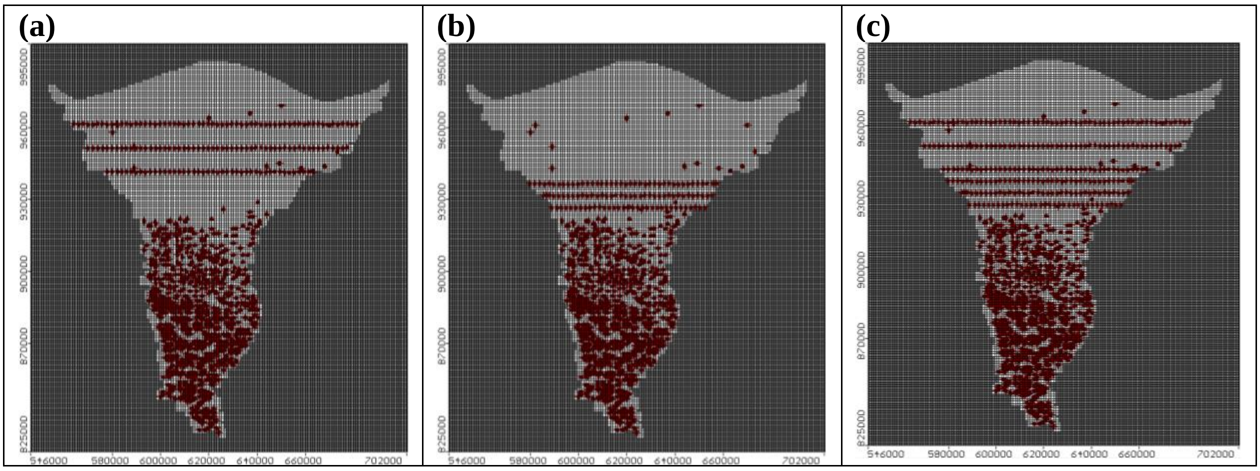
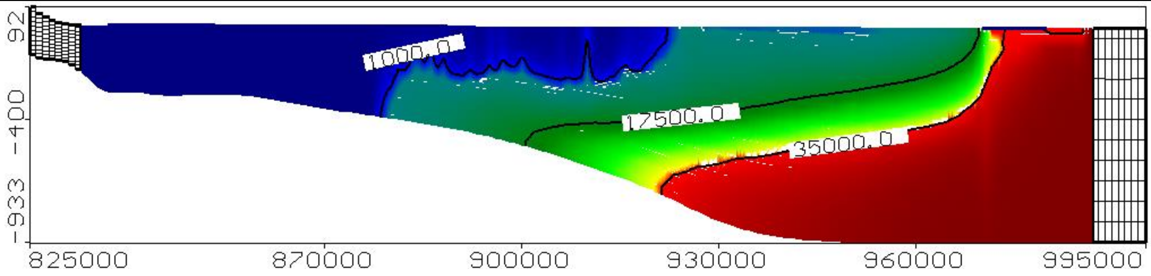
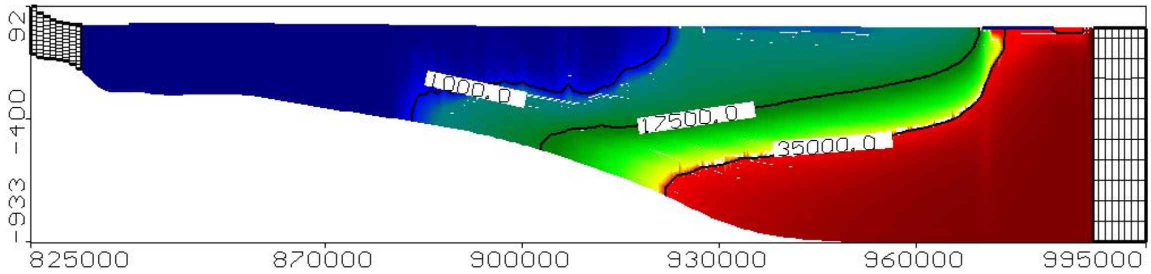


Figure 8: Areal distribution of (a) abstraction wells, (b) recharge wells, and (c) combination of abstraction and recharge wells in the MND aquifer



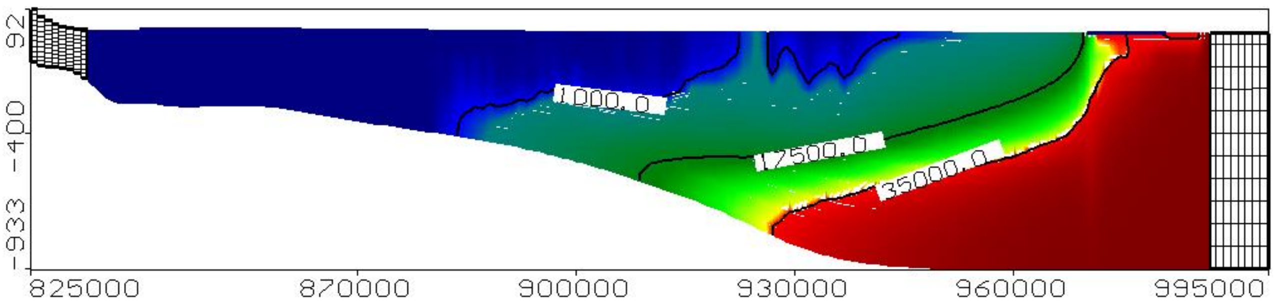
(a) Vertical distribution of TDS at -25% in well abstraction



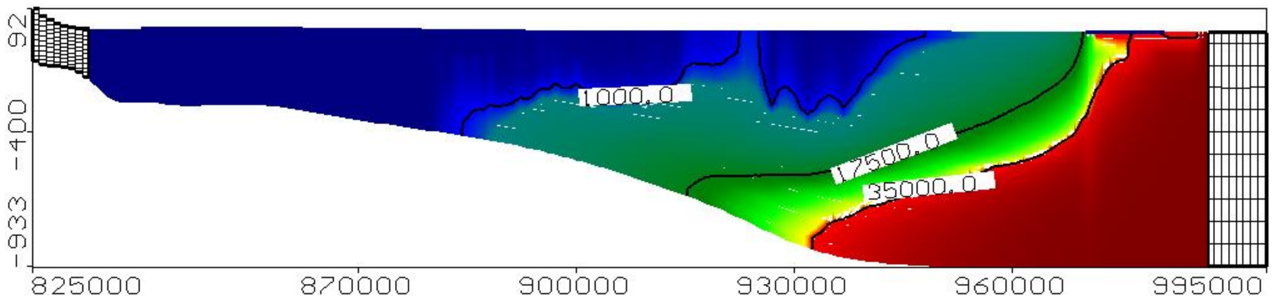
(b) Vertical distribution of TDS at -50% in well abstraction

(c) Relationship between reduction of pumping rates and intrusion length (XT)

Figure 9: TDS management results for reducing pumping rates in the MND (Scenario.4)



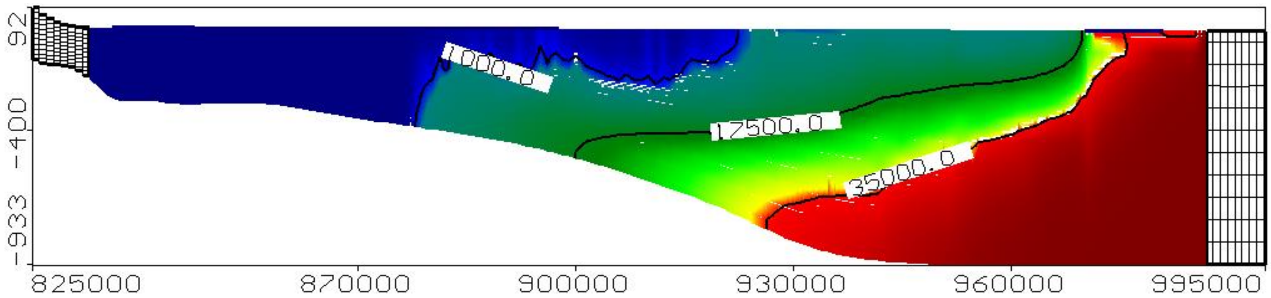
(a) Vertical distribution of TDS at +25% in aquifer recharge



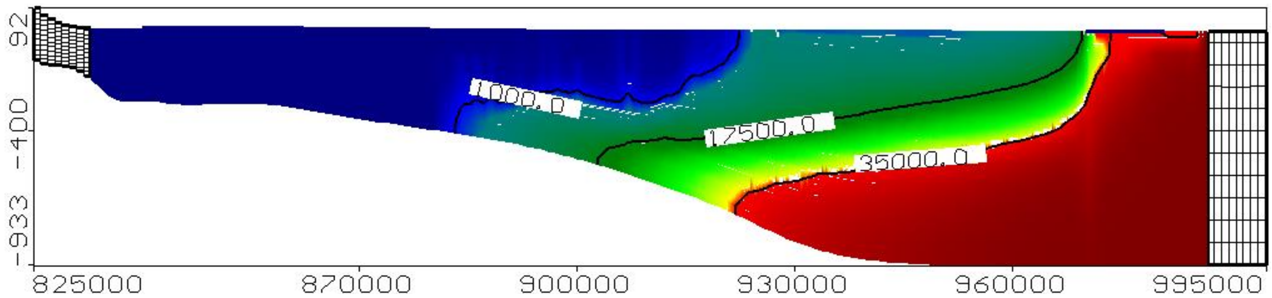
(b) Vertical distribution of TDS at +50% in aquifer recharge

(c) Relationship between increasing of aquifer recharge and intrusion length (XT)

Figure 10: TDS management results for increasing aquifer recharge in the MND (Scenario.5)



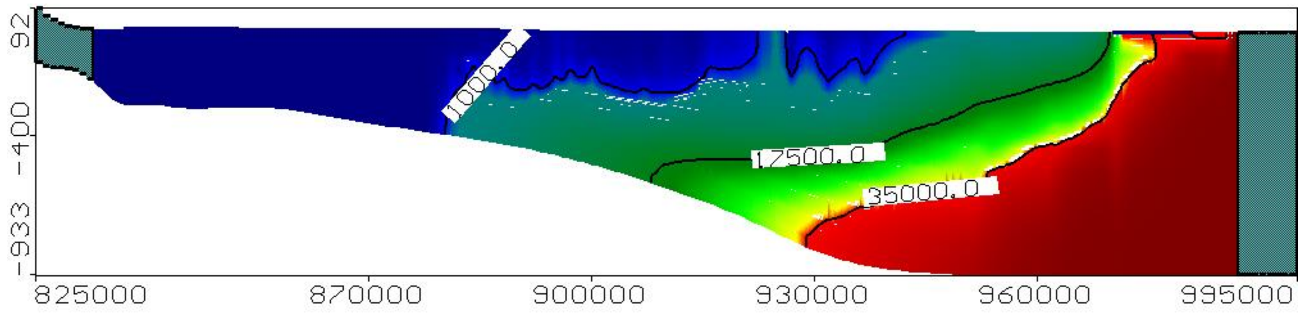
(a) Vertical distribution of TDS at -25% in abstraction of brackish water



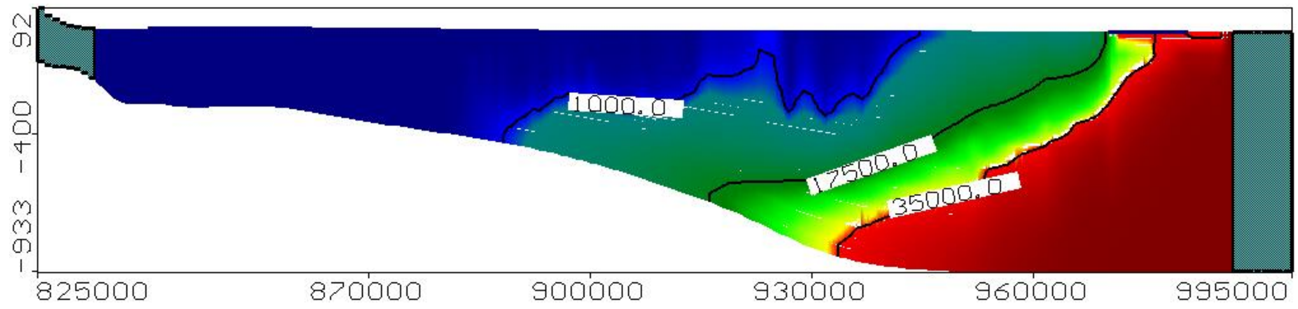
(b) Vertical distribution of TDS at -50% in abstraction of brackish water

(c) Relationship between abstraction of brackish water and intrusion length (XT)

Figure 11: TDS management results for increasing abstraction of brackish water in the MND (Scenario.6)



Vertical distribution of TDS at -25% in abstraction of brackish water



Vertical distribution of TDS at -50% in abstraction of brackish water

(c) Relationship between abstraction of brackish water and intrusion length (XT)

Figure 12: TDS management results for the combination of scenarios 4, 5 and 6 at changes in the MND (Scenario.7)