Application of mathematical modeling in the study of sea water intrusion in the coastal quaternary aquifer, Delta Wadi El Arish, Egypt

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Abstract

In recent years, the risk of Sea Water Intrusion (SWI) is continuously threatening coastal parts of the Quaternary Aquifer in Delta Wadi El-Arish (QADWA), where the agricultural activity entirely depends on rainfall and groundwater. Field research was carried out during October 2006 and October 2008. Twenty one water samples were collected for routine chemical analysis and water level monitoring were carried out and interpreted. These field measurements were compared with those collected from the previous studies to delineate SWI phenomenon. QADWA capacity was determined via carrying out three long duration pumping tests. The recharge rate from local rainfall was estimated through carrying out three infiltration tests and applying Infiltration-Rainfall method. Two numerical models were applied (MODFLOW and SINM codes). The two-dimensional finite difference simulation algorithm (MODFLOW) was formulated in order to perform a steady-state calibration for the physical parameters, and boundary conditions of the hydrodynamic system. In addition, the interface toe positions and its temporal migration under different testing scenarios had been accomplished by applying two-dimensional finite element simulation algorithm (SINM) depending on the calibrated outputs of the MODFLOW code. Simulation results indicated that the proposed scheme successfully simulated the intrusion mechanism. The results showed that the seawater/freshwater interface will migrate, after 15 years, 5.5 Km landward from its initial position if the present groundwater production policy (19 million m^3/yr) continued operating in the area. The predicted interface toe positions will migrate 13 Km from its initial position after 15 years in case of increasing the groundwater production by 4%. While the climatic change will cause its migration by 5.3 Km landward from its initial position assuming a rise of sea water level by 0.5m. To mitigate its migration, subsurface flow toward sea of 144443 m^3/day is needed. It is recommended to perform monthly or bi-monthly groundwater level and salinity measurements for better model calibration and verification. The policy opts for increasing groundwater pumping in the southern part of QADWA and to avoid any pumping in the north close to the Mediterranean Sea is highly recommended. Testing extraction barrier to identify the best operation strategy for SWI domesticity is also recommended.

Keywords: Hydrogeology, Coastal aquifers, Sea water intrusion, Numerical simulation, MODFLOW model, Delta Wadi El-Arish, Egypt.

1. Introduction

The increase in the use of fresh groundwater in coastal areas upsets the existing dynamic balance between fresh groundwater and saline sea water. Most studies on Sea Water Intrusion (SWI) are based on the Ghyben-Herzberg relationship (Bear, 1979), in which the freshwater and saline water are considered to be immiscible fluids. In fact, they are miscible, and the sharp interface is not realistic especially when the width of the dispersion zone is considerable. Henery (1960) was one of the first investigators who solved the coupled flow and mass transport equation for steady state by means of Fourier-Galerkin double series expansion. Henery (1964) developed the first analytical solution that included the effect of dispersion in confined coastal aquifer under steady state conditions.
Shamir and Harleman (1967) presented a finite difference method for solution of dispersion problems in steady three-dimensional potential flow field in porous media. Pinder and Cooper (1970) determined the movement of saltwater front in confined coastal aquifers including the effect of dispersion. Pinder and Frind (1972) used Galerkin's procedure in conjunction with the finite element technique to simulate this phenomenon. Lee and Cheng (1974) formulated a finite element model using stream function to obtain a steady state solution for the convective-dispersive transport equation. Segol and Pinder (1976) used the fluid pressure and concentration as dependent variables in

the finite element technique to solve the transport equation. Kawatani (1980) proposed the longitudinal dispersion coefficient as a constant to avoid the instability problems. Pandit and Anand (1984) made a parametric study of the Henry problem and concluded that the cyclic flow was existed when the characteristic velocity at the seaward boundary was bigger than longitudinal dispersivity. Voss (1984) employed a 2-D hybrid finite element method and integrated finite difference method to simulate the fluid density-dependent saturated or unsaturated groundwater flow and transport of solute in groundwater. Huyakorn *et al.* (1987) developed a 3-D finite element model for simulation of SWI in multilayer coastal aquifer with phreatic top aquifer using Picard sequential solution algorithm with special provisions to enhance convergence of the iterative solution. Sherif *et al.* (1988) used 2D-FED model in coastal aquifer and applied to the Nile Delta aquifer and concluded the cyclic flow at the sea boundary.

Risk *et al.* (1995) applied MOCDENSE program to simulate SWI in El-Arish area and concluded that it will move 100m after 25 years. ACSAD (1998) applied MODFLOW program to simulate groundwater flow in the Kurkar aquifer in El Sheikh Zuwayid-Rafah coastal area and predicted inland SWI to 3Km under pumping of 12 million m^3/year. The concentration of pumping wells which enhanced upward leakage of saline water from deeper formation and/or the coastal erosion created by natural and human factors may be the two main factors controlling SWI in QADWA (Kaiser and Geriesh, 2007).

Delta Wadi El-Arish is characterized by fan-shaped outline with district borders. It is located between longitudes 33° 45' 00", 33° 56' 30" E and latitudes 31° 00' 00", 31° 11' 00" N with an area of about 90 Km^2 (Figure 1). It is located in the semi arid belt of Egypt which is characterized by hot summer, cold, rainy winter, and high evaporation rate. The average daily temperature varies from 31°C in summer to 11°C in winter. The mean monthly relative humidity value over the area is 74%. The main annual rainfall ranges from 60 mm to 80 mm. The daily mean value of evaporation reaches 4 mm/day. The Delta of Wadi El Arish has a special hydrographic significance sustained heavy pumping for irrigation. It is intensively cultivated by olive, date palms and vegetables.

Geomorphologically, Wadi El Arish basin is one of the most outstanding water collectors in Sinai Peninsula (El Ghazawi, 1989). It covers about 23500 Km^2. The headwaters of this wadi originates from El Tih-El Igma plateau at about 1000 m height. It consists of numerous tributaries which have steep slope and well defined channels. At El Daiqa Gorge (60 Km south east El Arish city), these tributaries join to form the main trunk of Wadi El Arish. Along the course (250 Km length), it exhibits variable morphologic features reflecting the impact of the lithologic, tectonic and topographic features. Wadi El Arish main trunk extends in NNW-SSE direction from El Daiqa Gorge to the Mediterranean Sea (some 60 Km length). At Lehfein area, Wadi El Arish flood plain smoothly grades into a broad delta (maximum 7 Km width). Its top set beds are generally flat with slight slope towards the sea (1^o-5^o). The northern coastal belt area can be classified into coastal and continental sand dunes, the flood plains, the raised beaches and the modern beaches.

Geologically, north Sinai is occupied by sedimentary rocks ranging in age from Triassic to Quaternary (Shata, 1956, Taha, 1968 and Said, 1962). The Quaternary deposits form the main water-bearing formations in Delta Wadi El-Arish. They consist of sand dunes, old beach sand and the Kurkar. The thickness of these formations is about 80 to 100 m (JICA, 1992). Kurkar Formation consists of calcareous sandstone of shallow marine environment while the old beach sand consists mainly of fine to coarse sand intercalated with gravel and clayey layers. These deposits are conformably overlying the Kurkar in some places with a thickness ranging from 20 m to 60 m. On the other side, the sand dune deposits are extensively distributed along the coastal plain covering the old beach sand and locally intercalated with clay and gravel layers. The thickness of the sand dunes ranges between 20 m and 40 m.

Structurally, north Sinai is occupied by well known Syrian Arc System which is characterized by double plunging folds, thrusts and reverse faults. A typical fold can be observed at Gebel Maghara, Yelleq and Halal. These double plunging folds are in a NE-SW to ENE-WSW direction. Ragabet EI-Naam Fault extends from Naqb through Nakhl to the area in the south of Gebel Hamra through the front of the Syrian Arc zone. The characteristics of this geological structural unit are observed in the lineaments. The predominating directions of the lineaments (ENE-WSW and WNW-ESE) form a mesh-like network. The direction of lineaments governs the direction of Wadi channels and may have an influence on the directions of the groundwater recharge and flow in the QADWA (Figure 2).

Groundwater is mainly exploited from the QADWA. It is mainly identified in the coastal plain and along Delta Wadi El Arish flood plain. It is differentiated into three water-bearing formations as mentioned before. Water is extracted from pumping wells, galleries and hand dug wells. The underlying Pre-Quaternary rocks are mainly composed of shale and limestone rocks that develop at depth of 60 m below ground surface along the sea coast but in land, it generally decreases in depth forming an impervious boundary (Figure 3).

The sand dune aquifer lies at the top of the QADWA. It is composed mainly of loose quartzitic sand. It covers the coastal plain with a thickness ranging from 20 to 40 m but thinning inland direction. The groundwater exists under unconfined conditions. Precipitation is the main recharging source of this aquifer zone (4.2 million m^3/year, Saad 1981). The depth to groundwater varies from less than one meter to about five meter from the ground surface.

Groundwater in the lower aquifer zone is augmented with groundwater leakage from the Holocene sand dune deposits through the intervening sandy clay aquitard (Sewidan and El Ghazawi, 1992, El-Bihery and Lachmar, 1994 and El-Said, 1994).

In addition, the alluvial gravel aquifer zone extends 10 Km along the main course of Wadi El Arish. It consists of gravel and sand with clay lenses of maximum 50 m thick. The boundary between the alluvial gravel aquifer zone and the upper sand dune aquifer zone is hardly detected in many places reflecting a hydraulic connection between these two aquifer zones. The groundwater present under free water-table conditions.

The Kurkar aquifer zone is formed of calcareous sand deposits broadly distributed in the coastal plain and along Wadi El Arish alluvial plain by about 10 Km inland. It is overlain by gravel deposits. Its thickness ranges from 10 to about 40m. The Kurkar aquifer zone is generally semi-confined to unconfined but wherever a thick clay layer overlies it, a confined condition is formed. The groundwater levels have declined by an average of about 0.5 m since 1981 in response to an increase in pumping and consequently an increase in SWI has occurred in the northern part of the QADWA (El-Bihery and Lachmar, 1994). Table 1 shows the water budget of the QADWA for the year 2006.

The three mentioned groundwater-bearing layers form the QADWA which exhibits a freshwater porous medium are in contact with the saline water boundary located along the Mediterranean Sea in the north. Numerical model was introduced in this paper to investigate the problem of SWI into the QADWA.

2. Materials and methods

The materials used in this paper included both collecting groundwater intake database and water sampling for physical and chemical analyses. Groundwater database included collection of archival data (such as well drilling reports) and registration of discharge, distribution of wells, piezometeric heads, and recording potential sources for quality changes. A number of 21 water samples representing the present three water-bearing formations were sampled from domestic ground water intake in QADWA. Physical parameters including measuring EC, temperature and pH and the chemical analyses (Cl ions concentration) were carried out. Analyses were run according to the standard analytical methods in the central laboratory of

Table 1: Water budget of QADWA for the year 2006 (after Mekhemer and Abd Alla, 2007).

Water Balance Item	Inflow (m^3/day)	Outflow (m^3/day)
Storage	1058	0
Constant head	18936	2778
Wells	1350	52206
Recharge	33641	0
Total	54985	54985

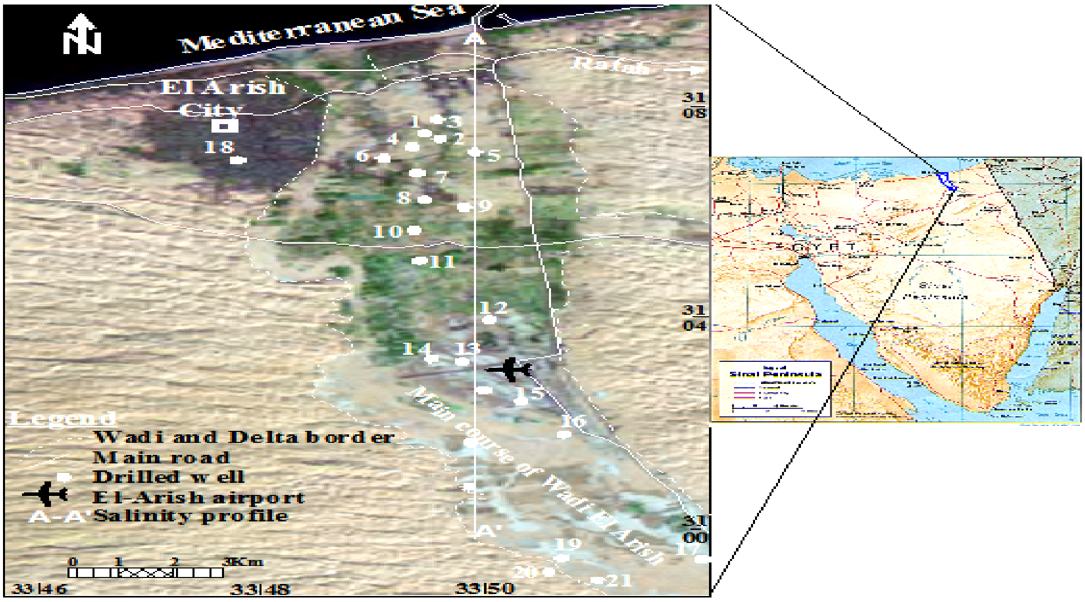

Figure 1: Location map of the QADWA showing the location of the tested wells.

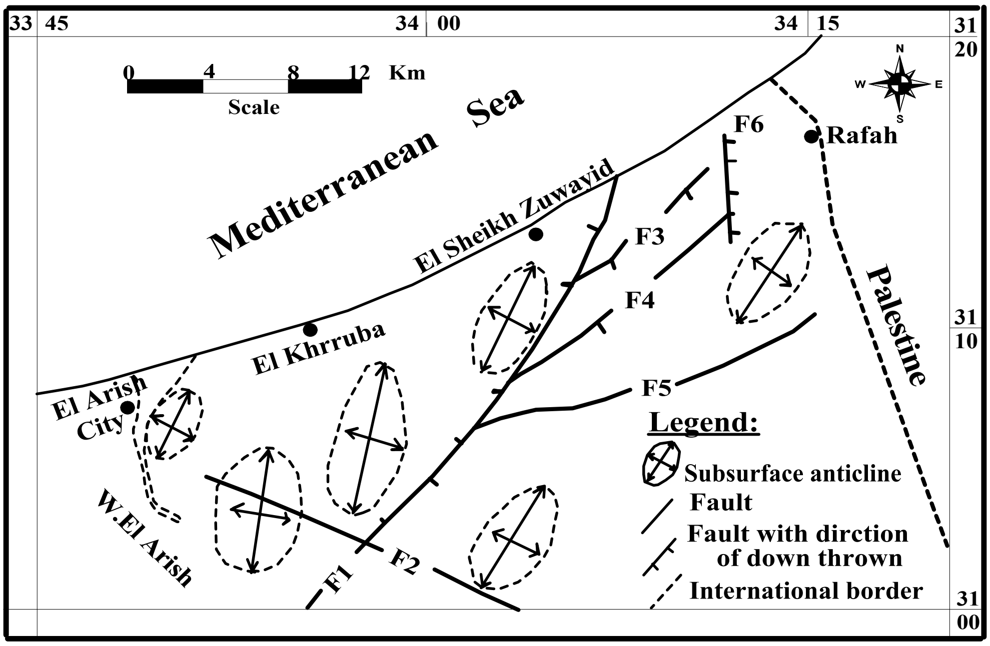

Figure 2: The structural map of the study area (compiled after RIWR, 1988).

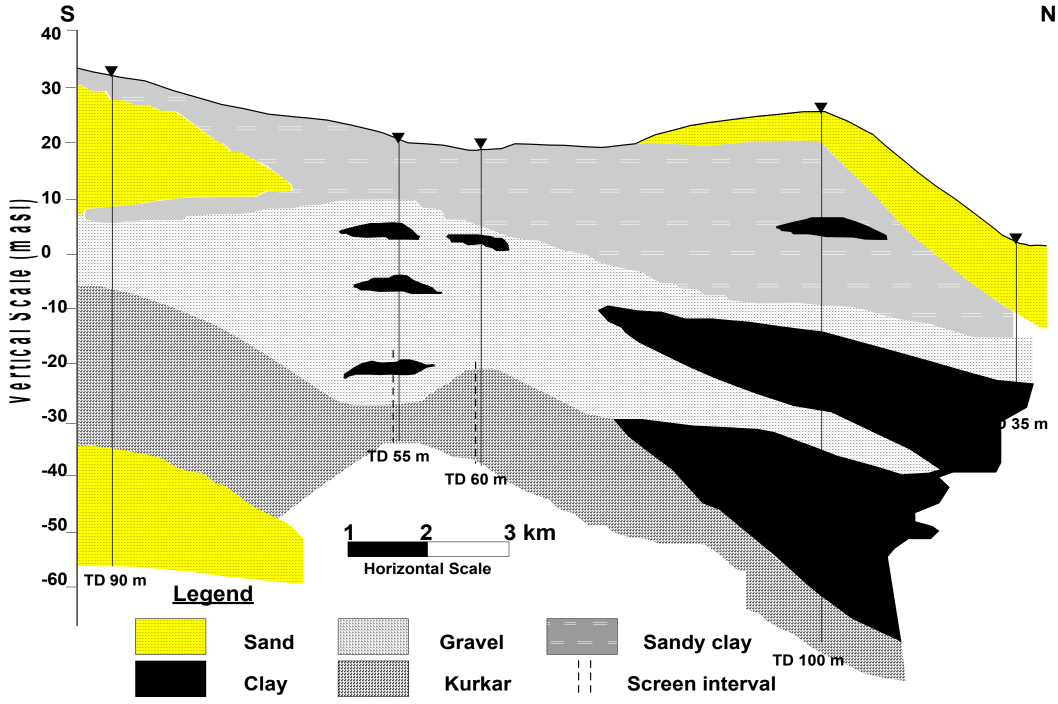

Figure 3: The cross-section along the QADWA monitoring well line in N-S direction showing different water-bearing zones (sand, gravel and Kurkar zones) (after Mekhemer and Abd Alla, 2007).

the Desert Research Center. The location of these wells was given in Figure 1 and the water level records of 18 wells during October 2006 (m asl) and both total dissolved solids (TDS in mg/l) and chloride concentration in mg/l at September 2006 and September 2008 were tabulated in Table 2.

The behavior of fresh-salt water contact in El-Arish area at Sep 1962 was traced according to Saad (1981) (Figure 4). The salinities of selected groundwater samples were compared with the historical data sited in Saad (1981) and Eweida (1993) via a transverse profile A-A' in N-S direction to determine the deterioration level in the groundwater of the QADWA and to form a background for further assessment studies (Figure 4).

The QADWA capacity was estimated through carrying out three pumping and recovery tests and the data were analyzed applying Cooper and Jacob (1946) straight line method. The results were given in Table 3.

In the past, rainfall was representing the only source of groundwater recharge in the QADWA. It was estimated that about 10% of the average annual rainfalls (140 mm/year) fed the QADWA (Zaghloul, 1995). Average recharge for QADWA (recharge areas 200-km^2) was estimated about 27,000m^3/d by Dames & Moore, 1985 and about 22,240 m^3/d by Helwa, 1993. Nowadays, sewage effluent constitutes an additional source of recharge along El-Arish city center, where about 50,000 m^3/d of the total sewage volume of the city (60,000m^3/d) drains to the groundwater via the poorly developed septic tanks and house gardens. This amount (50,000 m^3/d) is estimated as the difference between total water input to the city users (60,000 m^3/d) and output (10,000 m^3/d) through sewage collecting station (Ghodeif & Geriesh, 2006).

In this study, the recharge rate to the QADWA from rainfall was estimated from the calculated soil infiltration rate (Table 3) resulted from the data analysis of the three performed double ring infiltration tests as described by Black (1973). The field data were analyzed according to Philip (1957) equations:

$$D = S_p\, t^{0.5} + k\, t \quad (1)$$

$$I = 0.5\, S_p\, t^{-0.5} + k \quad (2)$$

Where, D is cumulative infiltration (L), t is elapsed time (T), S_p is the sorpitivity, k is the soil parameter related to hydraulic conductivity of saturated soil (LT^{-1}) and I is the soil infiltration rate (LT^{-1}).

The recharge from rainfall was estimated applying the following relation (Raghunath, 1997):

R = f * A* Normal rainfall in monsoon season (3)

Where, f is the rainfall infiltration factor (dimensionless), A is the area occupied by the formation (L^2), (the areas where the slope is more than 20% were excluded), R is the groundwater recharge from rainfall (L^{3}T^{-1}). The recharge from the subsurface flow through the southern boundary of the QADWA was estimated from Darcy's law.

Characteristics of the intrusion mechanism and its spatial and temporal variation, as well as its future behavior, were thoroughly investigated by means of two numerical codes (MODFLOW, McDonald and Harbaugh, 1988 and the modified SINM, El Ghandour, 2005). MODFLOW was applied to calibrate the physical parameters for definition of the flow mechanism, and the initial conditions for flow were evaluated accordingly. The model describes groundwater flow of constant density under non-equilibrium conditions in a heterogeneous and anisotropic medium according to the following equation (Bear, 1979):

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t}$$

………………(4)

Where K_{xx}, K_{yy}, K_{zz} are values of hydraulic conductivity along the x, y and z coordinate axes (LT^{-1}); h is the piezometric head (L); W is a volumetric flux per unit volume and represents source and/or sinks of water (T^{-1}); S_s is the specific storage of the porous material (L^{-1}) and t is time (T).

The simulation procedure was started by dividing the QADWA domain into a suitable grid pattern on which all the input items were performed via input menus. The computational grid was divided into 100 columns and 30 rows finite difference (Figure 5). The QADWA was considered as shallow and phreatic. Vertical homogeneity was assumed adequate to allow treatment as a single layer. The hydraulic properties of the QADWA were obtained from the field work and literature (Table 3). The base of the simulated freshwater zone was obtained from the cross-section along the QADWA monitoring well line. The boundary conditions used in this model were defined as timely variable constant head boundary for the southern boundary and a constant head along the Mediterranean Sea. The eastern and western boundaries were considered as no-flow boundaries.

In addition, the 2D SINM subroutine code (Abdel-Gawad, 2004) was utilized to incorporate the diffusion and hydrodynamic dispersion mechanisms into the simulation domain. This two-dimensional finite element model was based upon a velocity dependent dispersion coefficient (Abdel-Gawad, 2004). The equation describing the transport in the two-dimensional model, which includes advection, dispersion and adsorption, was written as (Bear, 1979):

$$\frac{\partial}{\partial x}[D_x\frac{\partial C}{\partial x}]+\frac{\partial}{\partial Z}[D_z\frac{\partial C}{\partial Z}]-\frac{\partial}{\partial x}(C v_x)-\frac{\partial}{\partial Z}(C v_z)$$

$$-\frac{C_o W}{nb}+\sum R_k=\frac{\partial C}{\partial t}(1+\frac{\rho_b}{n}K_d)$$

……..… (5)

Where‘ D_x, D_z are the dispersion coefficients in x, z directions (L^2 T^{-1}). C is the concentration of the solute (ML^{-3}).v_x ,v_z are the seepage velocity (LT^{-1}). C_o is the solute concentration in source or sink fluid (ML^{-3}). W is the source or sink term (LT^{-1}). n is the effective porosity. B is the aquifer thickness (L). R_k is the rate of addition or removal of solute (ML^{-3}T^{-1}). t is time (T). ρ_b is The bulk dry mass density (ML^{-3}). K_d is the distribution coefficient (L^{3}M^{-1}). In this model, the modified 6-node bi-linear triangular finite elements were used (El Ghandour, 2005) to solve numerically the governing equations using Gauss-Siedel iteration method. The study domain is 10 Km in length (El-Arish sea-coast along the Y-direction with zero values for X-coordinate) and 18 Km Delta Wadi El-Arish inland length (X-direction) with total surface area of 180 Km^2.

The computational grid for the domain of QADWA was divided into 90 rows and 50 columns of triangular finite elements (Figure 5). Vertical homogeneity was assumed adequate to allow treatment as a single layer with a mean hydraulic conductivity of 14 m/day. Longitudinal and lateral dispersivities were set equal to 10 m and 1 m, respectively. The effective porosity was set equal to 7% (average specific yield 7%, Table 3). The northern boundary is saline sea-water transport boundary (35 g/l) since the QADWA was in direct hydraulic contact with the Mediterranean Sea in which the water level is known (zero). In the southern boundary, the salinity is assumed to be fixed (≈ 5 g/l) and the groundwater level reached 8 m asl. The groundwater salinity ranged between 5 g/l and 2 g/l above datum on the eastern and the western sides, respectively. For the upper boundary, the water-table was considered higher than the Mediterranean Sea water level. The concentration was constant and equal to the groundwater concentration. The bottom boundary was impermeable, i.e.; the normal flux through the bed for both fluid and salts was equal to zero.

2.1. Model calibration and verification

To use the two numerical models in simulating SWI in the QADWA, the model should be calibrated and verified using the available historical records. The MODFLOW model was calibrated first for the assumed steady state conditions in 1960s to adjust the hydraulic conductivity and the aquifer recharge rate. Using the trial and error procedures, a good match between the observed head and the calculated head was achieved (Figure 6). The steady state model was used next to calibrate the specific yield values. Using the available head data in 1962 along with the given annual pumping rate of 11.3 million m^3, a 26-year transient calibration was carried out by adjusting both the specific yield and the net recharge values to match the observed head at 1988. During the transient simulation period, the southern boundary along the QADWA was assumed as regional head boundary.

As expected, it was found that the model was very sensitive to the boundary conditions along the QADWA. The calibrated model was verified next by simulating the aquifer system for 18 more years starting from 1988 until 2006. During this period the net recharge rate was adjusted according to the increase in the pumping rate. The annual pumping rates in the QADWA increased from 11.3 million m^3 in 1960s (Saad, 1981) to 19 million m^3 in 2006 (Mekhemer and Abd-Alla, 2007). The calibrated hydraulic conductivity and the aquifer recharge rate under steady state as well as the predicted heads were used as input data for SINM model to predict the interface toe positions under different testing scenarios.

2.2. Testing scenarios

In addition to the present annual pumping rate of 19 million cubic meters (MCM), three proposed pumping scenarios were simulated based on the potentiality of QADWA to examine the impact on the SWI. The first scenario considered an annual increase in the pumping rate by 0.25 MCM (1.3% of the present discharge) from the southern zone of QADWA as a result of new agricultural activities (Table 4). For the second scenario, beside the extra 0.25 MCM from the southern zone, an additional 1.3 % of the present discharge was pumped from the middle zone (airport locality) due to drought cycle. Accordingly, the total additional extraction reached 0.5 MCM from the model domain. The third scenario accounted for increasing the annual pumping rate from the middle zone by an additional 0.25 MCM for increasing population. With the third scenario, the total annual extraction rate from the QADWA reached 19.75 MCM. The fourth scenario examined the effect of climatic change on SWI assuming a rise of sea water level by 0.5 m. A summary of the proposed additional extraction for the three scenarios was shown in Table 4. For the coastal zone of QADWA, groundwater extraction did not change during the proposed scenarios.

To analyze the aquifer response to SWI under the three proposed scenarios, six observation points were selected as shown in Figure 6 to represent the overall aquifer zones. Observation points P1, P2 and P6 represented the northern part of the QADWA (the coastal area) where most of the pumping wells were concentrated and excess groundwater pumping was prohibited in this zone. Observation points P3 and P4 were located in El-Arish airport area, just close to the toe of the assumed sharp interface and drawdown was not allowed to keep the sharp interface at its current position. The last observation point P5 was located far from the deteriorated areas (the southern part of the QADWA) and sharp drawdown was not allowed to avoid the undesirable SWI.

3. Results and discussion

The results of the routine chemical analysis of the selected groundwater samples (TDS and Cl in mg/l, Table 2) showed a little increase during the period 2006-08. While the long-term records (1962-2006) exhibited sharp increase in groundwater salinity (Fig. 4) which reflected that the QADWA was over-pumped, particularly in the coastal and central parts during last decades. This had accelerated SWI and caused continuous landward migration. According to the records of 1962, the migration of SWI was at a distance of 2 Km inland (Figure 4). At 2006, the groundwater levels ranged from 8 m asl in the south to about -12 m asl in the extreme north with general flow direction from south to north (Figure 7A). Otherwise, Figure 7A showed three depression cones. The first was located east El Arish City where groundwater heads were sharply decreased (-12 m asl) reflecting intensive pumping and migration of SWI and/or salt water upconing from the underlying zones. The second was present south El Arish-Lahfen road where groundwater heads recorded -10 m asl. The third depression cone was formed south El Arish-Airport where groundwater heads recorded -8 m asl. These depression cones may be attributed to the unbalance between the pumping rate and the recharge rate to the QADWA. Both the Total Dissolved Solids (TDS) distribution map and chloride concentration map (Figure 7B and7C) assured these findings.

The results of the pumping tests showed that the QADWA had moderate groundwater potentiality (Transmissivity coefficient ranged from 208 to 468 m^2/day and mean specific yield of 0.07, Table 3). This reflected the need to use a proper pumping rate to domesticate SWI migration. In addition, the results of the infiltration tests showed that the soil cover of the QADWA had high infiltration rate (from 10.44 to 26 m/day) which exhibited a high recharge rate from local rainfall.

Table 2: Records of the groundwater levels (m asl) and results of chemical analysis of TDS and chloride concentration of the selected wells in the QADWA (September 2006 and September 2008).

S.No	Well name	Longitude	Latitude	Records of Sept. 2006 (m)			Records of Sept. 2006 (mg/l)		Records of Sept. 2008 (mg/l)	
				GE	DTW	WL	TDS	Cl	TDS	Cl
1	**Maghool**	33.84	31.06	40.1	42	-1.9	2722	1028	---	---
2	**Beer El-Magles**	33.86	31.15	56	62	-6	2925	1427	---	---
3	**Salm Eid Gomaa**	33.84	31.13	31.7	40	-8.3	3016	1454	---	---
4	**Abdel-Rahman Sallam**	33.86	31.03	55.2	65	-9.8	3185	1613	---	---
5	**Eng-Atef Solim**	33.85	31.07	55.7	50	5.7	3435	1507	3683	1775
6	**Batn El-GABAL**	33.84	31.02	48.2	40.8	7.4	3530	1702	---	---
7	**Magles**	33.84	31.12	38.6	32.5	6.1	3617	1773	---	---
8	**El-Rai 37**	33.85	31.04	44.8	50.82	-6.02	3627	1702	3906	1985
9	**Nassar Awwad Farm**	33.84	31.06	38.3	36.9	1.4	3799	1596	---	---
10	**Abdel-Rahman Sallam**	33.86	31.03	45.2	66	-20.8	3820	1972	---	---
11	**El-Rai 38**	33.85	31.04	43.7	50.82	-7.12	3903	1844	3985	1868
12	**Eng-Atef Solim**	33.85	31.07	55.7	50	5.7	3994	2172	4288	2585
13	**Maghool**	33.84	31.06	41.6	42	-0.4	4051	1844	5056	1925
14	**Magles well 34**	33.84	31.10	48.7	61	-12.3	4255	2039	---	---
15	**Nassar Awwad Farm**	33.84	31.06	35.5	36.9	-1.4	1515	650	---	---
16	**Taameer-8**	33.83	31.12	21.9	18.9	3	3700	2083	---	---
17	**Hag Abu Aiman Farm**	33.88	31.15	22.3	22	0.3	4879	2482	---	---
18	**Cousin of Ibrahim**	33.85	31.05	41.8	40	1.8	5181	2704	5117	2735
19	**-----**	33.84	31.11	---	---	---	5185	2527	---	---
20	**-----**	33.82	31.12	---	---	---	5246	2482	---	---
21	**-----**	33.82	31.11	---	---	---	5574	2748	---	---

Note: GE = Ground elevation (m asl), DTW = Depth to groundwater (m), WL = Absolute groundwater level (m asl), TDS = Total dissolved salts in mg/l and Cl = concentration of chloride in groundwater in mg/l.

Table 3: The hydraulic parameters and the soil infiltration rate of QADWA.

Well No	Location		Pumping T (m^2/day)	Recovery T (m^2/day)	Average T (m^2/day)	Specific yield	Diffusivity (m^2/day)	Infiltration rate (I) (m/day)
	Long.	Lat.						
7	33.84	31.12	489	391	440	0.068	6471	15.78
14	33.84	31.10	183	232	208	0.08	2600	26.06
17	33.88	31.15	429	507	468	-----	-----	10.44

Table 4: Scenario descriptions based on the additional extraction from the selected zone of QADWA.

Aquifer zone	Present extraction (million m^3/year)	Additional extraction (million m^3/year)		
		Scenario 1	Scenario 2	Scenario 3
Coastal area	3	0	0	0
Airport area	8	0.0	0.25	0.5
Southern area	8	0.25	0.25	0.25
Total	19	0.25	0.5	0.75

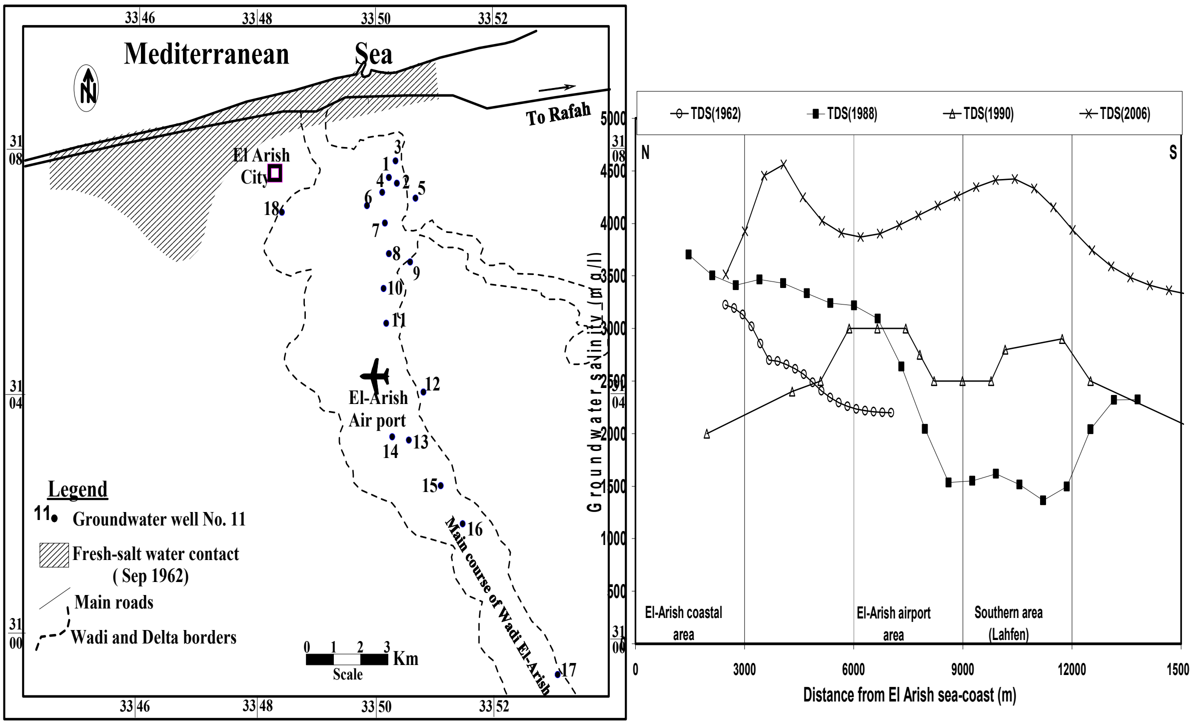

Figure 4: Approximate interpretation of the behavior of fresh-salt water contact in El-Arish area at Sept. 1962 (left map, modified after Saad, 1981) and profile A-A' in N-S direction showing the spatial and temporal changes in groundwater salinity in QADWA [right map, Sept. 1962 after Saad (1981), Sept. 1988 and Sept. 1990 after Eweida (1993) and Sept. 2006 (present work)].

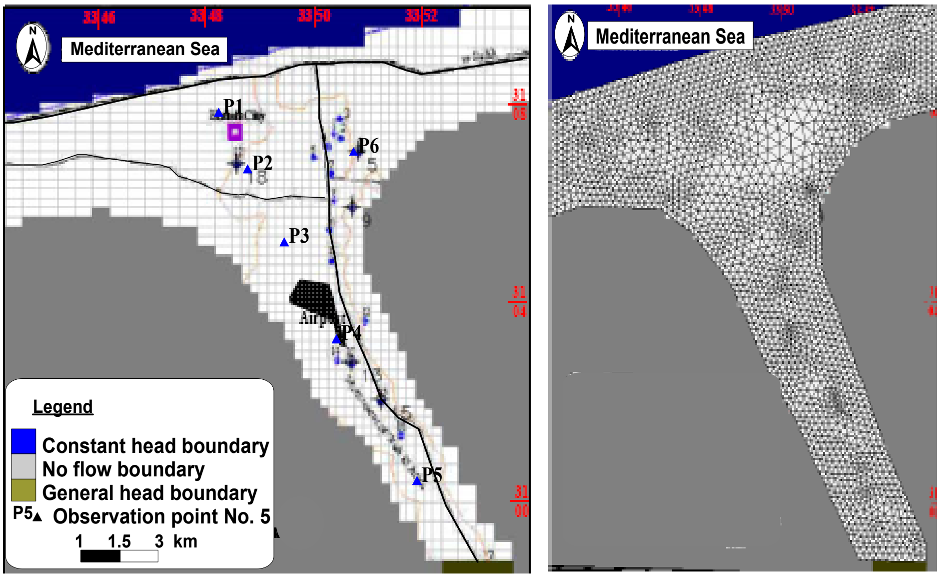

Figure 5: The finite difference grid for MODFLOW (left image) and finite element grid For SINM (right image) of the model domain in QADWA.

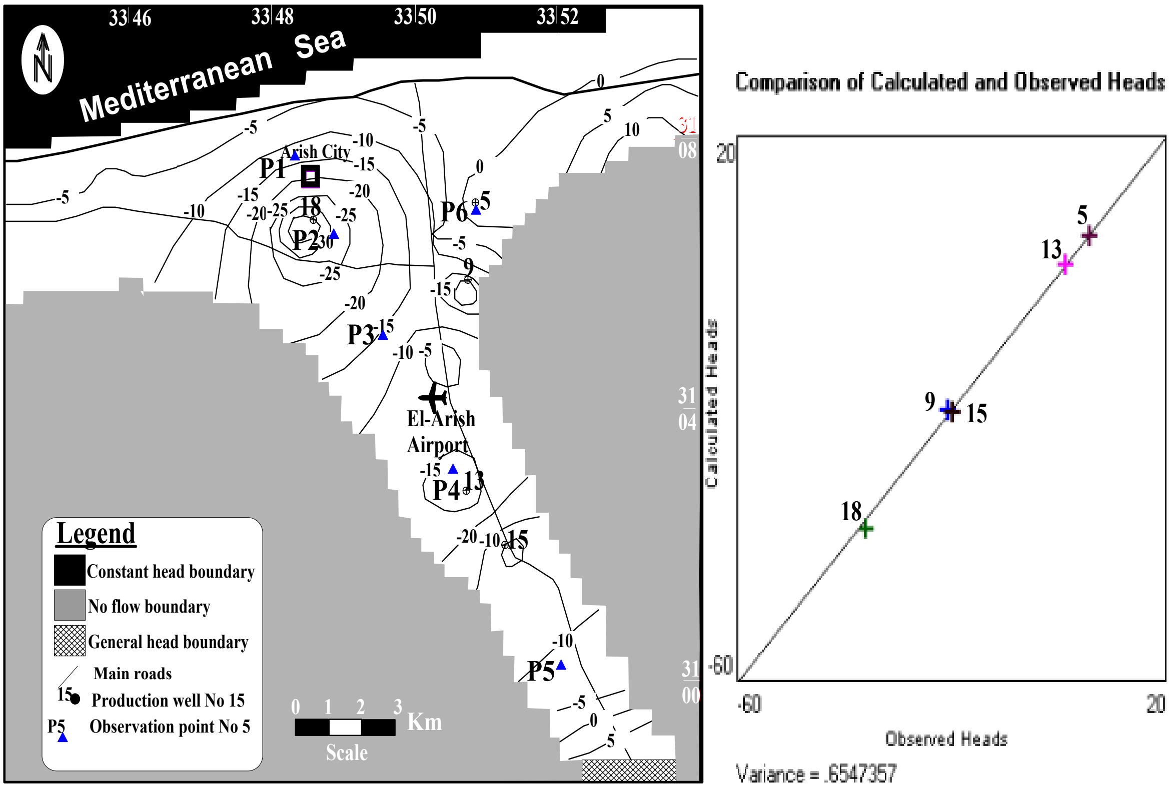

Figure 6: The observed and the estimated head in the model domain of QADWA (calibration state).

The estimated net recharge rate to the QADWA from rainfall and return flow after irrigation applying Time-lag method (Gad, 2009) was given in (Figure 7D) while the recharge from the southern boundary was evaluated by Darcy's law (2x10^6 m^3/year). Figure 7D showed that the net recharge from rainfall to the QADWA ranged from 0.0032 to 0.0054 mm/day. These values were used in calibrating the constructed models.

In addition, the long-term impact of the present pumping conditions (19 MCM) and the proposed pumping stresses, applying the MODFLOW model, showed a continuous decline in the groundwater level (Table 5 and Figure 8). This predicted decline will range from 1.6 to 3.75 m in the coastal zone, from 6.21 to 7.45 m in the airport zone and reached 3.17 m in the southern area of QADWA after 15 years. As expected, the third scenario has the most impact on the groundwater level due to the extensive proposed pumping during the period of simulation (15 years). The predicted groundwater level at observation point (P1) indicates that the drawdown in the coastal zone will very minimal and almost exceeded one meter. Similarly for the observation points P3 and P4, the predicted drawdown will occur for the third scenario as well, with a value of 24.37 and 29.19 m north and south of the airport zone respectively.

For the observation point located in the southern area of QADWA (P5), the predicted drawdown will reach 11.85 m. This high drawdown values (at P3, P4 and P5) will accelerate the inland movement of the sharp interface. Lastly, for the coastal zone of QADWA, the observation points (P1, P2 and P6) showed that the predicted drawdown will remain at the same value for all the proposed scenarios with a maximum value of 4 m as shown in Table 5. Again this drawdown will allow for more intrusion to the aquifer from the adjacent sea water.

For the proposed fourth scenario, the MODFLOW results indicated that the predicted groundwater level in the coastal area of QADWA will vary in the different observation points. The highest drawdown (4 m) will predict at observation point P6 which reflects the sharp SWI due to the climatic change scenario.

As mentioned before, the calibrated and predicted groundwater levels in the QADWA resulted from MODFLOW model was applied as inputs for SINM model in order to predict the future behavior of the intrusion. The prediction of the interface toe positions under different stresses from pumping applying SINM model was determined. A definition sketch of the studied domain including different data and the meaning of the parameters used in every case was related to these figures. SINM model outputs showed the advancing of SWI in case of both the current and the proposed pumping stresses from 18 pumping well fields located at distance more than 2 Km from the coast. The current pumping stresses (Q_w = 52206 m^3/day) will cause SWI to invade the QADWA for a distance of 1.2, 3.8 and 5.5 Km from its current position after 5, 10 and 15 years respectively (Figure 9).

In general, the advanced interface toe to the well field location goes to be undulated in all scenarios. This behavior may attribute to the increase in the local effect of every well field as the interface toe approaches to the well field location (El Ghandour, 2005). This undulation increases with increasing the spacing between wells (Mahesha, 1995, Saafan, 2000 and Zhou *et al.*, 2000). So, the average location from the coast for interface toe at each row of nodes perpendicular to the coast for biggest well spacing is smaller than that for small spacing. This finding may help in decrease the SWI of definite localities in the QADWA by choosing the proper well spacing.

To catch the maximum allowable pumping rate from the QADWA, the problem must be solved for different consecutive increasing rates of pumping with interval difference equal to 10 m^3/day till the well field system was polluted. In this analysis, the position of the interface toe under the proposed four scenarios reached 4.8 Km, 8 Km, 13 Km and 5.3 Km from its current position respectively after 15 years (Figure 10). To prevent more SWI, the groundwater flow to the sea (Q_s) will reach 534443, 394443, 144443 and 144443 m^3/day respectively after the same period of simulation (Fig. 10). The similarity between Q_s due to 3rd and 4th scenarios reflects the negative impact of the climatic change on the groundwater resources management of the QADWA. In the other side, the shallow wells less than 30 m at distances of 11Km from the coast will polluted and the deeper wells will pump more saline water because of the rising of the sea water level. It is quite clear that present water production policies need to be modified otherwise the aquifer will be severely contaminated by progressive seawater intrusion.

4. Conclusion

Numerical research was introduced in this paper to investigate the problem of SWI into the QADWA along the Mediterranean coast of Egypt. The hydrogeological investigation of the QADWA revealed that the aquifer system was continuously replenished by the rainfall (10%), and subsurface flow (2 MCM). The historical data showed that there is a continuous increase in SWI. The transmissivity of the QADWA ranges from 208 to 468 m^2/day and 0.06 to 0.08 for specific yield. Characteristics of the intrusion mechanism and its spatial and temporal variation, as well as its future behavior, were thoroughly investigated by means of two numerical models. The first model (MODFLOW) was applied to calibrate the physical parameters for definition of the flow mechanism and the initial conditions for flow and to simulate the QADWA under different operational scenarios. The second model (SINM), depending on the MODFLOW outputs, was applied for predicting the interface toe positions under the proposed scenarios. This was accomplished utilizing the coupled behavior of the fresh water flow and the salt transport mechanisms that occur in coastal aquifers. Steady-state calibrations with data reported for 1960s and the history matching period 1988-2006 were found to be adequate. Transient simulation runs have shown that too much groundwater has been extracted from QADWA. Inevitably, this has accelerated SWI and caused landward migration of the intrusion (5-Km from the coast). Future predictions clarify that the landward migration will reach a distance of 1.2, 3.8 and 5.5 Km from its current position after 5, 10, and 15 years respectively. Three proposed pumping scenarios were assumed based on the potentiality of QADWA to examine the impact on the SWI. The first scenario considered an annual increase in the pumping rate by 0.25 MCM from the southern zone of QADWA as a result of new agricultural activities, the second scenario, assumed an additional annual increase in the pumping rate by 0.25 MCM from the middle zone, due to expected drought cycle, the third scenario accounted for increasing the annual pumping rate from the middle zone by an additional 0.25 MCM for increasing population and the fourth scenario examined the effect of climatic change on SWI assuming a rise of sea water level by 0.5 m. The position of the interface toe under these proposed four scenarios reached 4.8 Km, 8 Km, 13 Km and 5.3 Km from its current position respectively after 15 years. To domesticate SWI, the groundwater flow to the sea may be greater than 144443 m3/day and the discharge from the QADWA should be properly managed. Migration rate of SWI could be reduced by thorough investigation and planning new management policies for optimal use the freshwater in the QADWA. It is recommended to perform monthly or bi-monthly groundwater level and salinity measurements for better model calibration and verification. Testing different discharge-recharge cycles or extraction barrier to identify the best operation strategy is also needed.

Table 5: The computed head drawdown at the six observation points applying the three additional extraction scenarios in QADWA and sea water rise due to climate change scenario.

Aquifer zone	**Observation**	**Present conditions**		**Additional extraction**						**Scenario 4**	
				Scenario 1 ($0.25x10^6 m^3$)		Scenario 2 ($0.5x10^6$ m^3)		Scenario 3 ($0.75x10^6$ m^3)		Sea water rise by 0.5 m	
		After 10 years	After 15 years	After 10 years	After 15 years	After 10 years	After 15 years	After 10 years	After 15 years	After 10 years	After 15 years
Coastal zone	P1	1.05	1.60	1.05	1.60	1.05	1.60	1.05	1.60	1.21	1.83
	P2	2.48	3.7	2.48	3.7	2.48	3.7	2.48	3.7	2.39	3.55
	P6	2.51	3.75	2.51	3.75	2.51	3.75	2.51	3.75	2.67	4
Airport zone	P3	4.14	6.21	4.14	6.21	10.27	15.4	16.24	24.37	4.14	6.21
	P4	4.97	7.45	4.97	7.45	12.31	18.45	19.48	29.19	4.97	7.45
Southern zone	P5	2.12	3.17	7.91	11.85	7.91	11.85	7.91	11.85	2.12	3.16

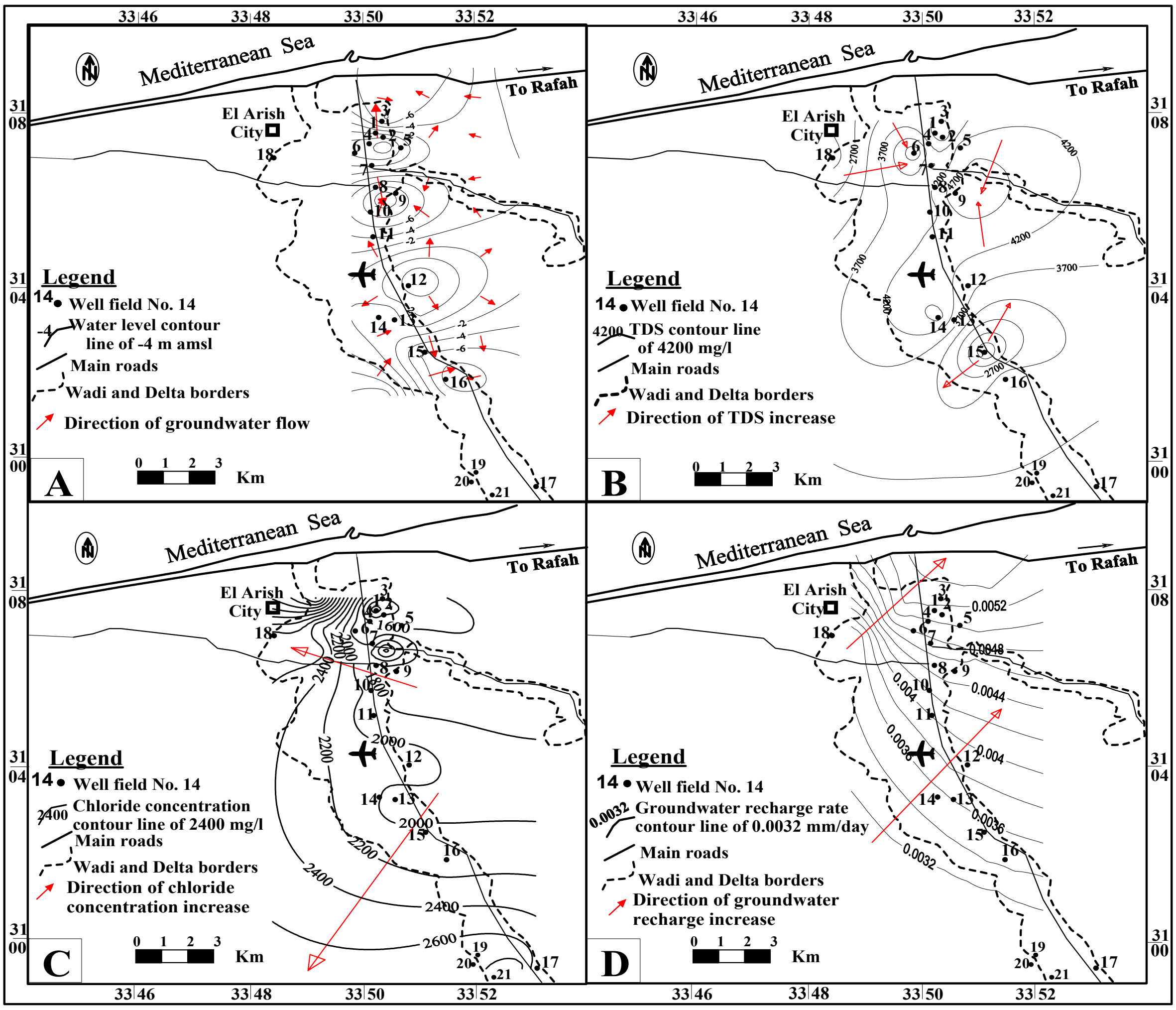

Figure 7: (A) Water-table contour map in m asl, (B) TDS distribution map in mg/l, (C) Chloride concentration contour map in mg/l, and (D) groundwater net recharge contour map from local rainfall of QADWA (Sept. 2006) in mm/day.

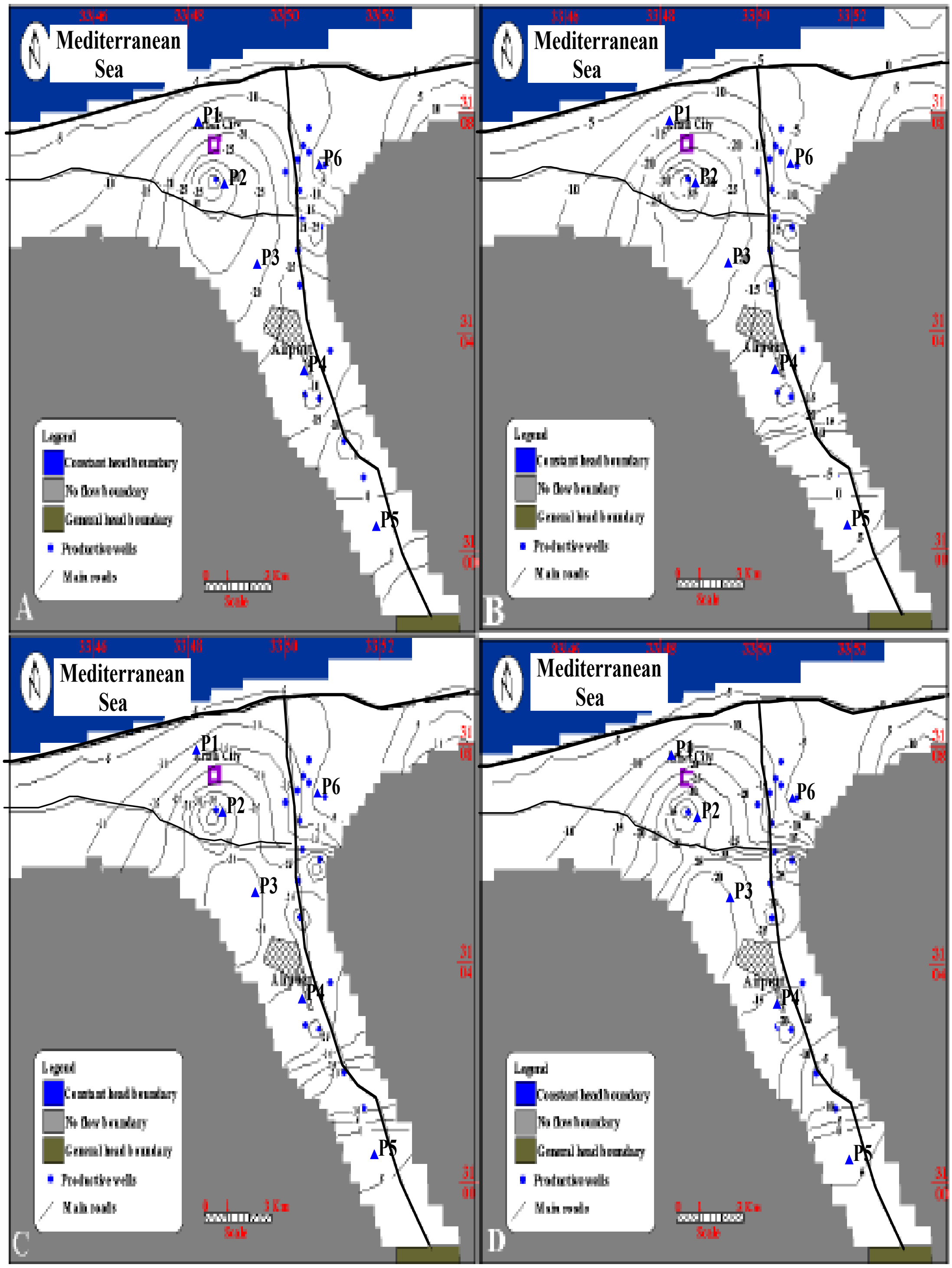

Figure 8: The predicted heads after 15 years in the QADWA applying: A) 1st scenario, B) 2nd scenario, C) 3rd scenario and D) 4th scenario.

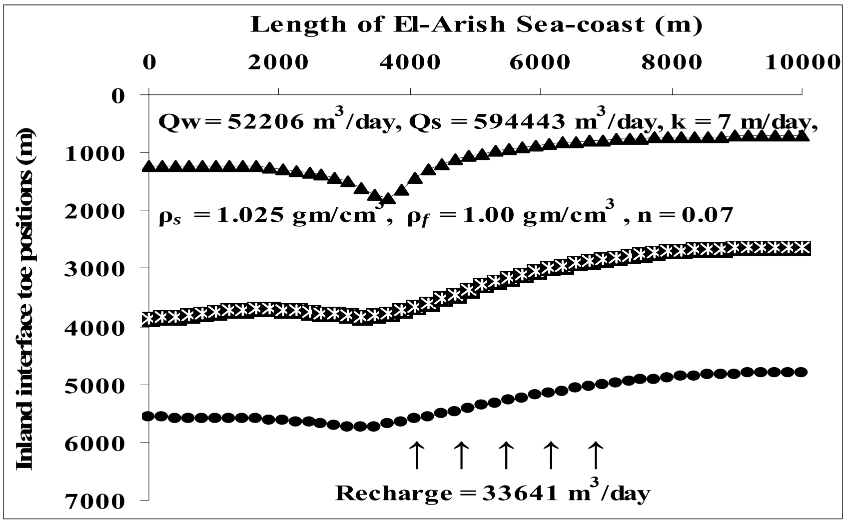

Figure 9: The predicted inland interface toe positions from its initial position after 5 years (line with triangles), 10 years (line with squares) and 15 years (line with circles) under the current state of pumping (19 MCM/yr) in the QADWA.

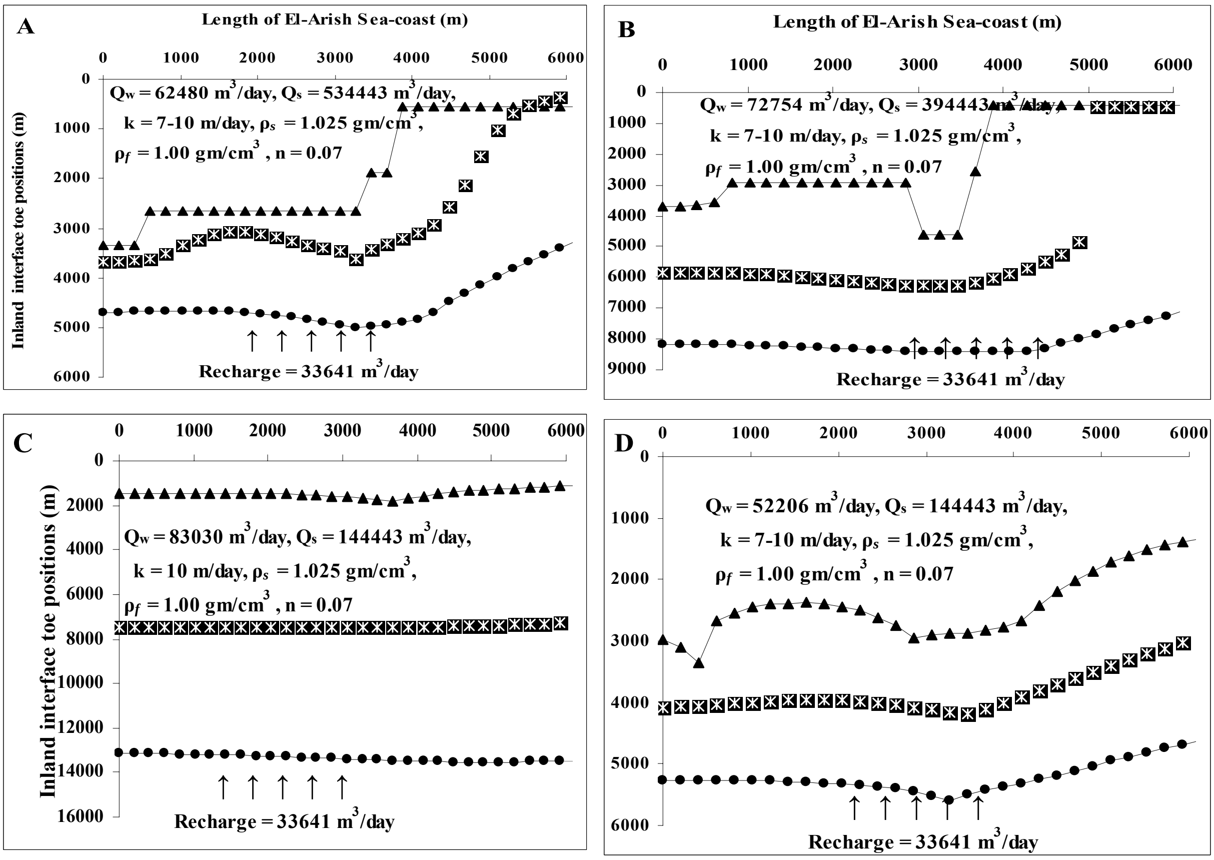

Figure 10: The predicted inland interface toe positions from its initial position after 5 years (line with triangles), 10 years (line with squares) and 15 years (line with circles) in the QADWA under: A) 1st scenario, B) 2nd scenario, C) 3rd scenario and D) 4th scenario.

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"الإمكانيات والاحتياجات المائية لتنمية منطقة العريش- رفح شمال سيناء- مصر"

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تطبيق النمذجة الرياضية في دراسة تداخل ماء البحر في الخزان الجوفي الرباعي الساحلي - دلتا وادي العريش - مصر

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في هذا البحث تم استخدام نموذجين رياضيين (SINM و MODFLOW) لمحاكاة مشكلة تداخل ماء البحر بالخزانات الساحلية بالساحل الشمالي الشرقي لمصر كالخزان الرباعي بدلتا وادي العريش بسيناء. حيث تم محاكاة الخزان باستخدام نموذج المودفلو (MODFLOW) وطبقت على المنطقة المدروسة شبكة من 3000 خلية، وأدخلت جميع البيانات المطلوبة إليها. فتم أولاً بناء الشكل الهندسي للنموذج بإدخال الظروف الحدية والسطح العلوي والسفلي لطبقة الخزان والتي تم الحصول عليها من القياسات الحقلية. ثم بناء النظام المائي للخزان بإدخال المعاملات الهيدروليكية المختلفة مثل التوصيل الهيدروليكي (K) والناقلية (T) والتي تم الحصول عليها من تحليل تجارب الضخ الثلاث التي تم إجراؤها، وكذلك بيانات مناسيب المياه الابتدائية المقاسة بعدد 18 بئراً. وتم تشغيل النموذج ومعايرته فى حالة الإتزان بمناسيب المياه المقاسة ومعدلات تغذية الخزان الجوفي من الأمطار الساقطة والتي حسبت من نتائج تجارب الرشح الثلاث التي تم إجراؤها. وقد طبقت على النموذج أربعة سيناريوهات مستقبلية للتنبؤ بمناسيب المياه الجوفية بعد مرور15 سنة كنتيجة لازدياد معدلات الضخ، وكذلك تأثير فترات الجفاف المتوقعة والتغيرات المناخية والتي يترتب عليه زحف ماء البحر داخل الخزان. وقد استخدمت هذه المناسيب المتوقعة بعد مرور 15 سنة في تغذية نموذج سينم (SINM) ثنائي الأبعاد للتنبؤ بالتوزيع المكاني للحد الفاصل بين ماء البحر المالح المتداخل مع ماء الخزان الجوفي العذب كنتيجة لتغير مناسيب المياه الجوفية لكل سيناريو وكانت نتائج المحاكاة كالآتي :

- بافتراض بقاء معدل الضخ الحالي ثابتاً (19 مليون متر مكعب/السنة) فإن مناسيب المياه الجوفية بالخزان ستنخفض بعد مرور 15 سنة حوالي 4 متر بالمنطقة الساحلية، 7 متراً بمنطقة مطار العريش و 3 متراً بالمنطقة الجنوبية للخزان. وترتب على ذلك زحف ماء البحر مسافة 5.5 كم من موضعه الحالي (1 كم جنوب مدينة العريش). وأوضح النموذج أن كمية المياه المنصرفة من الخزان جهة البحر يجب ألا تقل عن 594443 م^3/اليوم للحفاظ على التوازن الطبيعي بين المياه المالحة والعذبة ومنع تقدمها.
- على افتراض زيادة الضخ بمعدل 0.25 مليون متر مكعب/السنة بالمنطقة الجنوبية من الخزان كنتيجة ازدياد النشاط الزراعي بها (السيناريو الأول)، بينما السيناريو الثاني يفترض زيادة الضخ بنفس المعدل بمنطقة مطار العريش لزيادة الطلب على الماء للزيادة السكانية خلال فترة المحاكاة (15سنة) وافتراض زيادة أخرى للضخ بمعدل 0.25 مليون متر مكعب/السنة بمنطقة مطار العريش لتغطية احتياجات الزراعة المطرية بالمنطقة الساحلية في حالة حدوث فترة جفاف وندرة للأمطار الساقطة (السيناريو الثالث). وقد لوحظ أن مناسيب المياه الجوفية تنخفض بصورة كبيرة خلال فترة المحاكاة، حيث بلغ انخفاض مناسيب المياه الجوفية بالمنطقة الجنوبية من الخزان حوالي 12 متراً للسيناريوهات الثلاث، بينما انخفضت مناسيب المياه الجوفية بمقدار 7.5 و 18 و 29 متراً للسيناريوهات الثلاث على الترتيب بالمنطقة الوسطى للخزان (منطقة المطار). بينما لم تتأثر المنطقة الساحلية بهذه السيناريوهات. وترتب على ذلك زحف ماء البحر مسافة 4.6 و 8 و 13 كم من موضعه الحالي للسيناريوهات الثلاث على الترتيب. وبلغ السريان الجوفي جهة البحر 534443 و 394443 و 144443 م^3/اليوم بالنسبة للسيناريوهات الثلاث على الترتيب وذلك للحفاظ على التوازن الطبيعي بين المياه المالحة والعذبة ومنع تقدمها.
- السيناريو الرابع والذي يفترض ارتفاع منسوب سطح البحر لمسافة 0.5 متراً كنتيجة للتغيرات المناخية أو تآكل الشواطئ بالعوامل الطبيعية والإنسانية أظهر زحف ماء البحر مسافة 5.2 كم من موضعه الحالي. وللحفاظ على التوازن الطبيعي بين المياه المالحة والعذبة ومنع تقدمها يلزم صرف 144443 م^3/اليوم من المياه الجوفية جهة البحر.

وبناءً على هذه السيناريوهات المُقتَرَحةِ الأربعة يَجِبُ أنْ يُدار الخزان بشكل صحيح. كما أن معدل هجرةِ المياه المالحة يُمْكِنُ أنْ يخفّضَ بالتخطيط الشاملِ لسياساتَ الاستخدام المثالي للماء العذب في الخزان وتقليل الضخ. كما يُوصي بإجراء قياسات شهريةِ أو نصف شهريةِ لمستوى المياه الجوفيّةِ وملوحتها للتحقّقِ من نتائج النموذج. كذلك اختبار طريقة مانعُ الانتزاع لتحديد أفضل إستراتيجيةِ عمليةِ للحد من ظاهرة التداخل تَحتَاجُ أيضاً.