Studying the Vulnerability of Coastal Aquifers, Case Study Rafah-El-Arish area, Northern Sinai, Egypt

Marwa M. Aly

Abstract— Recently, groundwater has been the backbone in sustaining the development of many regions in Egypt, especially in Sinai. Growing of population, increasing in water demands and uncertain impacts of climate changes are major challenges for groundwater management in Rafah, Zowayeid, Kharouba and El-Arish areas. In order to assess the effect of previous factors; a mathematical model (Modflow) is used to simulate the groundwater system in the study area. The model is calibrated and consequently three scenarios are proposed to test and predict the response of the aquifer during simulation period. The main objective of the study is to examine the vulnerability of the aquifer to groundwater extraction, Sea water rise as a result of climate changes and the occurrence possibility of sea water intrusion. The results indicated that there is no significant effect of the Sea water rise on the aquifer but it is high vulnerable for both pumping rates and Sea water Intrusion. The most affected area through the three scenarios is Rafah area.

Index Terms — Coastal aquifers, Groundwater management, Modflow, North Sinai, Vulnerability.

1 Introduction

Coastal aquifer is vulnerable to over pumping and groundwater overexploitation, and as a result of being hydraulically connected to the sea, the probability of occurrence of sea water intrusion phenomena increased. Also, a sea level rise due to climate change results may affect the extent of seawater intrusion.

The aim of the present work is the assessment of the vulnerability of the coastal aquifer in North Sinai through current groundwater resources exploitation, Sea level rise and sea water intrusion.

Estimating groundwater potential in Sinai required the distinction between shallow groundwater in the Quaternary aquifer and deep groundwater in the fissured carbonate and Lower Cretaceous (Nubian sandstone) aquifer. A large portion of the water is pumped from the Quaternary aquifer in the northern part of Sinai (El Arish, Rafah, Bir el Abd). Fresh groundwater is mainly confined to the sand dunes which are recharged from direct rainfall. The Kurkar aquifer is one of the main productive aquifers in the Quaternary deposits in the study area; therefore, this study will aim to modeling this important coastal aquifer to be able to examine its vulnerability to groundwater extraction and sea-level rise.

2 Literature Review

Sherif and Singh (1999) investigated the effect of climate change on sea water intrusion in coastal aquifers. They considered two coastal aquifers, one in Egypt and the other in India, this study investigated the effect of likely climate change on sea water intrusion. Under conditions of climate change, the sea water levels will rise for several reasons, including variations in atmospheric pressures, expansion of warmer occasions and seas and melting of ice sheets and glaciers. The rise in sea water levels will impose additional saline water heads at the sea side and therefore more sea water intrusion is anticipated. Three realistic scenarios representing climate change were considered. Under these scenarios, the Nile Delta aquifer is found to be more vulnerable to climate change and sea level rise. A 50 cm rise in the Mediterranean Sea level will cause additional intrusion of 9.0 km in the Nile Delta aquifer. The same rise in water level in the Bay of Bengal will cause an additional intrusion of 0.4 km. Additional pumping will cause serious environmental effects in the case of the Nile Delta aquifer.

Hsu et al. (2007) adopted a numerical modeling approach to investigate the response of the groundwater system to climate variability to effectively manage the groundwater resources of the Pingtung Plain. The modeling result shows that the lowering water level in the proximal fan raises an alarm regarding the decrease of available groundwater in the stress of climate change, and the enlargement of the low-groundwater-level area on the coast signals the deterioration of water quantity and quality in the future.

Jong Ahn Chun et al. (2018) assess the climate change impacts on sea-level rise (SLR) and freshwater recharge rates and to investigate these SLR and freshwater recharge rates on seawater intrusion in coastal groundwater systems through the Saturated-Unsaturated Transport (SUTRA) model. They concluded that the study may provide a better understanding of the climate change

Marwa Mohamed Aly, E-mail: Marwaaly3@gmail.com, PH- 00201283464443
- *Assistant professor at Civil Engineering Department, Faculty of Engineering at Mataria, Helwan University11718, Cairo, Egypt,*
- *Assistant professor at Civil Engineering Department, High Institute of Engineering and Technology- Al-Obour*

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impacts on seawater intrusion by considering both SLR and freshwater recharge rates.

3 Study Area

The study area lies in Sinai peninsula which is considered the Eastern door for Egypt, it is expands between longitudes 33° 45'E & 34° 15'E and latitudes 31° 08'N & 31°15'N. (Fig. 1)

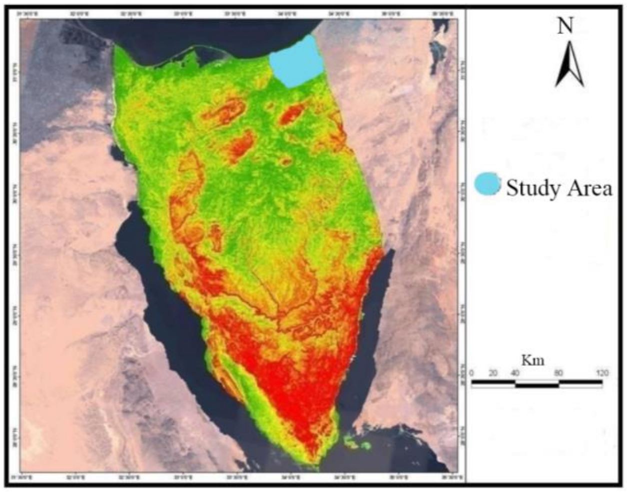


Fig. 1. Study area relative to Sinai Peninsula.

3.1 Meteorology

During the last decades, the Water Resources Research Institute (WRRI) constructed many meteorological stations, rain gauges and some isolated rainfall recorders. Generally, the recent recorded measurements by WRRI at different stations within the study area were as follows:

The climate of the study area is known as the Mediterranean type, where the daily thermal range is very wide: the temperature attains 42.2°C during the day at El-Themed in August and drop to below -0.8°C during night at El-Kuntilla in March.

The evaporation intensity ranges from 1401 to 1582 mm/year at El Arish and Rafah respectively while reaches about 4000 mm/year at El Maghara and Nekhel, 3000 mm/year at Quseima. The evaporation intensity increases from west to east.

The highest mean relative humidity is 83.4 % in October at El Rawafaa Station and the lowest value is 18.5% in November at El Gudeirat station. In summer, the midnight highly relative humidity of 80% may persist till early morning and drop to about 55 % at Noon.

The North-West and North can be considered as the prevailing wind direction with an annual average wind speed around 14 km/hr.

The Sinai Peninsula in general is characterized by low rainfall excluding the coastal area along the Mediterranean Sea from West at Port Said to East at Rafah. The average annual rainfall is 40 mm/year except the North east corner where the rainfall increases to reach about 83.36 mm/year at El Arish and 303.8 mm/year at Rafah.

3.2 Geomorphological Setting

Landform classification was carried out using the aerial photographs and Landsat image, as shown in fig. 2, the area was classified into the following items:-

1. The Sand Dunes, Wadis and Coastal &Gravel Plains where huge movable sand dunes are the dominant characteristics of the most of the Northern part of the study area especially the North western part.
2. Table Lands (Terraces, fans and pediments) where the terraces are surrounding the mountains and the major tributaries of upstream of wadi El Arish. The fans formations are due to the sedimentation of rivers of mountainous areas. The sediments of fans are mainly sand and gravels. The pediments formations are due to erosion, they are consist of a moderate mountain slope. They are distributed around the mountains and highlands.
3. Highlands, Mountains and Plateaus where the limestone and chalk of Tertiary are the main component of the mountains and highlands. The distribution of mountains has been dominated entirely by geological structures. The Southern part of the study area is mainly a part of Egma and El-Tih plateaus, wide and flat surface surrounded by steep ridges of the previous mentioned mountains.

Fig.2. Landform map of Sinai Penensula.

3.3 Geological Setting

From previous studies and publications on the geology of the study area, it was found that it is occupied mainly by sedimentary rocks belonging to the Late Tertiary which is differentiated into Oligocene (804 m), Miocene (738 m) and Pliocene (82m) to Quaternary (130). The sedimentary succession comprises several water bearing formations which are particularly influenced by the structural features.

The geological structure of North Sinai is divided into three major units (i) Central Sinai Stable Foreland (ii) North Sinai Strongly Folded Belt, and (iii) North Sinai

Foreshore Area. However, North Sinai forms a distinct geomorphological and structural unit which is characterized by a large number of NE trending elliptical anticlines and synclines. (Fig. 3)

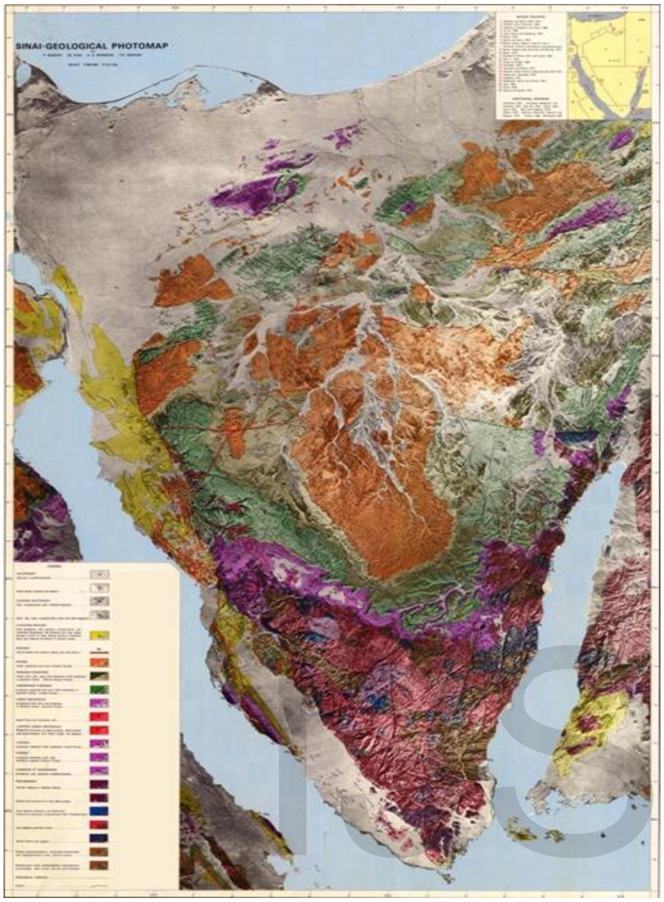


Fig.3. Geology of Sinai penensula

3.4 Hydrogeology of the Study Area.

The Quaternary Aquifers are hydraulically connected, hence they are considered one aquifer, and this aquifer extends along the coastal area of the Mediterranean Sea from east to west with (20-30) km width. The lithologic description from top to bottom is sand dunes with thickness about (20-30) meter, the uppermost 5 meters are recent movable dunes especially toward West at Bir EL Abd followed by the stabilized type; this layer is the most suitable for fresh water supply at Bir EL Abd and Rafah areas. The second layer of the Quaternary aquifer is the gravel or wadi deposits layer, the thickness of this layer is about (20-30) meter and observed especially in the river bed of wadi EL Arish and is considered to be the main source of fresh water, also the third layer is the calcareous sandstone (Kurkar) with (20-40) meter thickness, this layer extends from Rafah to EL Arish town and outcrops at Awlad Ali toward South of El-Arish area with decreasing of its thickness. El-Ramly (1975), Asad (1981), Darwish (1982), Seguin and Bakr (1992) ACSAD (1998), Seleem (2009), and Hawash (2012) concluded that the extension of the Kurkar aquifer and its potential are limited, the aquifer is depending in its water recharge on the direct rainfall . Based on JICA 1992 the Kurkar is extended from the eastern border of Egypt until it cross Wadi El-Arish with about 10 km.

The Pre-Quaternary Aquifer as main aquifer is consist of four sub-aquifer namely (a) Miocene aquifer which is distributed only in the coastal plain and extends south to Rafah and Sheikh Zowayeid, (b) Eocene aquifer which is distributed in the eastern side of the study area at Kuntilla, Quseima

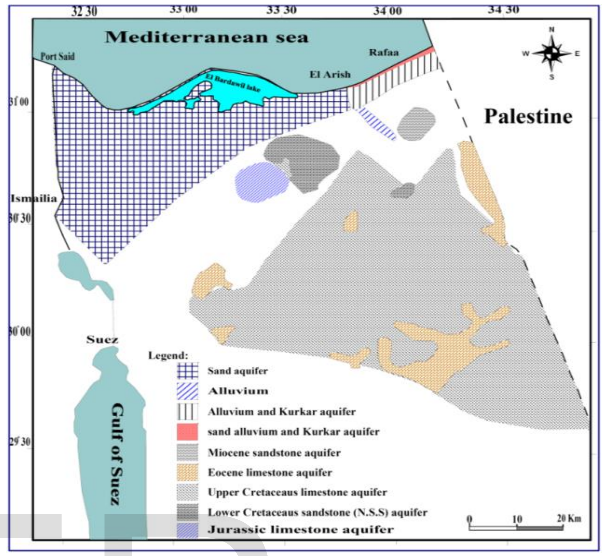


Fig.4. Aquifers distribution map of North Sinai (After El Sayed, 1994).

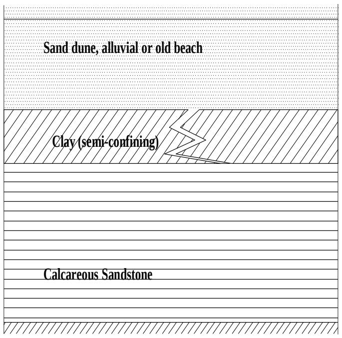
and around Arif El-Naga and Nekhel areas with an estimated thickness ranges from 200-300 meters, (c) upper cretaceous aquifers which are distributed in a large area of the Study area such as El- Hassana, Mountain Yelleg, Gifgafa and Nekhel. These aquifers are developed in fractured limestone (d) lower cretaceous Aquifers can be considered as the main aquifer and the target of all studies and drilling in Sinai Peninsula, many authors studied this aquifer from many points either the lithology, salinity, age dating of groundwater or hydraulic parameters etc.(Fig.4)

4 METHODOLOGY

In this research the visual MODFLOW 2011.1 was used to simulate the study area which will extend from Rafah to Wadi El-Arish in the East West direction with total length of about 60 km with depth of about 40 km in the North South direction from the shoreline. The modeled area is about 2400 km2.

4.1 Conceptual Model

Conceptual model is the key component in groundwater modeling because it is a descriptive representation of hydrogeological understanding of how water flows into, through and out of a groundwater system. It is grouped into three main units, namely, sand/gravel, clay and Kurkar



(calcareous sandstone). (Fig. 5).

Fig.5.conceptual model of the study area

4.2 Groundwater Model

The basis for building MODFLOW model is the hydrogeological conceptual model. Since there are no direct field measurements that support flow in the vertical direction, it is common to adopt a 2-D modeling approach. The model has been constructed with a rectangular grid system of 500 × 500 m. It covers an area of 60000 m length along the shore line and 40000 m perpendicular to it. The grid size has been selected compromising resolution and computational time. The origin of the model is (570000 m, 3430000 m) in x& y-directions respectively (UTM, WGS 1984, zone 36N). In x-direction a total of 120 cells and in y-direction a total of 80 cells were formed by the grid. (Fig.6)

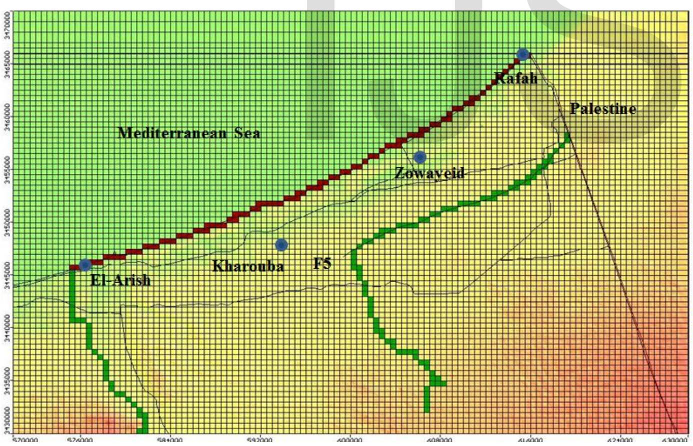


Fig.6. Model domain and grid system in plan view

4.3 Boundary conditions and Hydraulic Parameters

The boundary conditions of the modeled area consist of constant head boundary represents the Mediterranean Sea in the north (red cells) and general head boundaries (green cells) as shown in fig.6. Regarding the potentiometric map in the study area it is found that the water movement is from east towards west as it can be revealed from fig.7, so the boundaries are considered permeable and can transfer water to the model domain, meanwhile, one of the boundaries follows one of the major faults (F5) it is directed almost toward south west.

From previous studies and pumping test results the initial hydraulic parameters for the model we staked as shown in (Table 1). While based on the data available according to Abdel-Aal (1998), ACSAD (1998). The initial water level data collected at 2005 was used to calibrate the model as shown in fig.8.

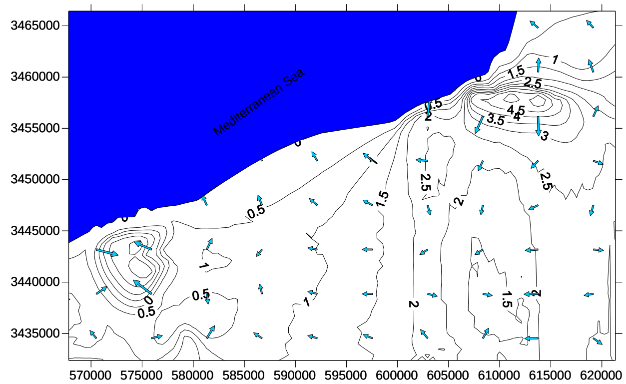


Fig.7. Groundwater flow movement in the modeld area.

TABLE 1
Hydraulic Parameters of the Aquifer

Hydraulic Conductivity	15 (m/day)
Specific Storage (Ss)	0.001 (1/m).
Specific Yield (Sy)	0.02
Recharge	13.28 mm/year
Recharge at El Arish Area.	15000m^3/day

4.4 Model calibration

The model hydraulic input parameters are never completely defined and they are always associated with various uncertainties, the model has been successfully calibrated for steady state conditions the observed water levels in the potentiometric map and the calculated water levels are shown in figs. 8, 9 respectively. Based on the calibration model, the estimated hydraulic conductivity values are ranging from 1 to 50 m/day.

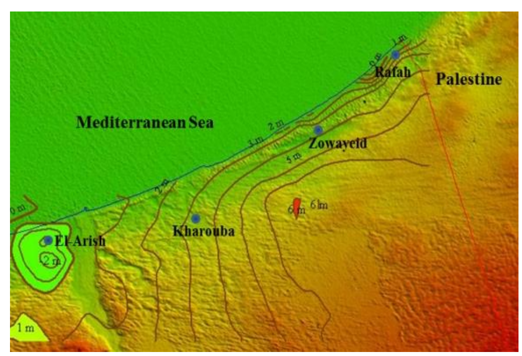


Fig. 8 Initial Water Levels (2005)

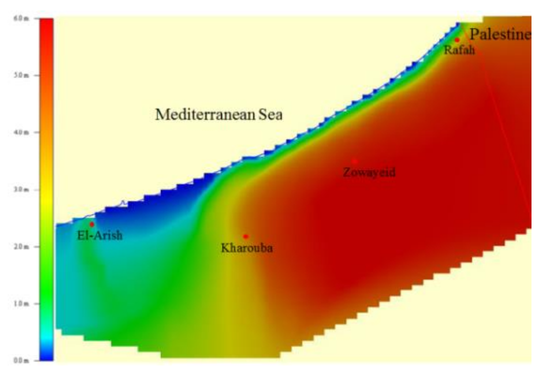


Fig. 9 Calculated Water Level (2005)

4.5 Transient Calibration

To achieve transient calibration, the model is allowed to run from the period of 2005 to 2018, it is worthily to mention that according to the current events in Sinai and for safety reasons, it was not possible to obtain the actual pumping rates from the study area and the potentiometric map has been created from available static water levels at 2018. Fig. 11 shows the 2018 measured groundwater levels.

The data of water level at year (2005) was measured from more than 1000 wells along the modeled area; the density of these wells along the modeled area is rather high; several wells can be located in the same cell of the mesh grid showing different values. To avoid the bad effect of mismanagement of well distribution the number of 1000 wells is reduced to 210 wells with the same extraction rate of discharge divided into 180 wells in Rafah, Zowayeid, and El-Arish and 30 wells in Kharouba as shown in fig. 10.

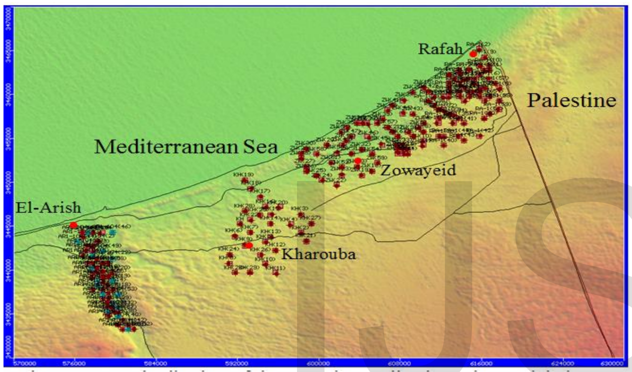


Fig. 10 Distribution of the pumping wells along the modeled area

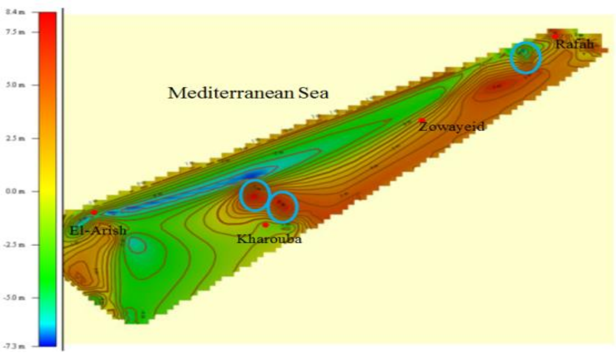


Fig. 11 Groundwater levels measured at 2015.

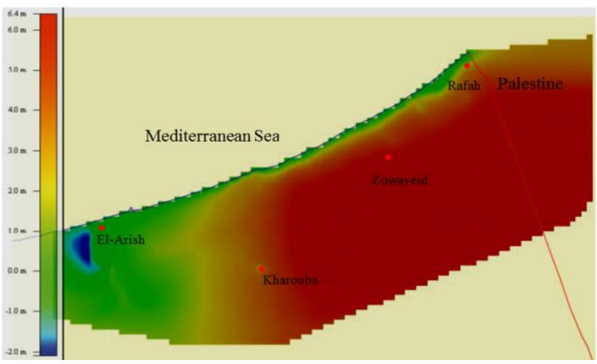


Fig. 12 Calculated Water Level 2015.

The discharge rate from the pumping wells is estimated to be 1500 m^3/day/well. Each well reaches the estimated discharge rate gradually along the thirteen years of the transient calibration period as shown in table 2

TABLE 2
Gradually distribution of the pumping rate along the transient calibration period (2005-2018)

Start (day)	End (day)	Rate (m^3/day/well)
0	365	-200
365	730	-300
730	1095	-450
1095	1460	-600
1460	1825	-800
1825	2190	-1000
2190	2555	-1150
2555	2920	-1300
2920	3285	-1450
3285	4745	-1500

4.6 proposed scenarios

Three scenarios were assumed to assess the response of the Quaternary aquifer in the modeled area representing the water head value during the simulation process from (2018-2065) through 4 x-sections in Rafah, Zowayeid, Kharouba and El-Arish areas and through 1 longitudinal section as shown in fig.13, then it was analyzed by making some comparison between the different years.

Base Case Scenario
Represents the existing policy of groundwater exploitation in the study area at 2018 and predicts the response of the aquifer during the simulation period.

Climate Change Scenario
This scenario studies the effect of sea water rise with values of 0.5m &1.0m based on the previous studies as a result of climate change impacts.

Sea Water Intrusion Evaluation
In order to assess the effect of the sea water intrusion, the third scenario was applied to the modeled area by changing the boundary condition at the northern boundary considering it no flow boundary. The results of this scenario will be compared with the result of the base case scenario in order to evaluate the interference of the sea water in the modeled aquifer as a whole. This assumption is due to the shortage of data.

5 Results and Analysis

The results of these scenarios were monitored in the period from (2018-2065) periodically each decade. Then it was analyzed by making some comparison between the different years of each scenario. It is worth to mention that special comparison took place between the first scenario and the third scenarios to check the sea water intrusion. Table 3 presents the minimum water head along the modeled area during the simulation period, showing the main area of deficit also fig. 13 shows these water head values compared to each other

TABLE 3
Minimum water head along the simulation period for the different Scenarios

Scenario	Area of Deficit	Year					
		2018	2025	2035	2045	2055	2065
Base case	Rafah	-22	-29	-34	-40	-35	-38
Climate Change (+0.5m)	Rafah	-22	-28	-34	-39	-36	-37
Climate Change (+1.0m)	Rafah	-21	-28	-32	-36	-35	-35.5
Sea Water Intrusion	Rafah	-30	-33	-36	-34	-36	-36

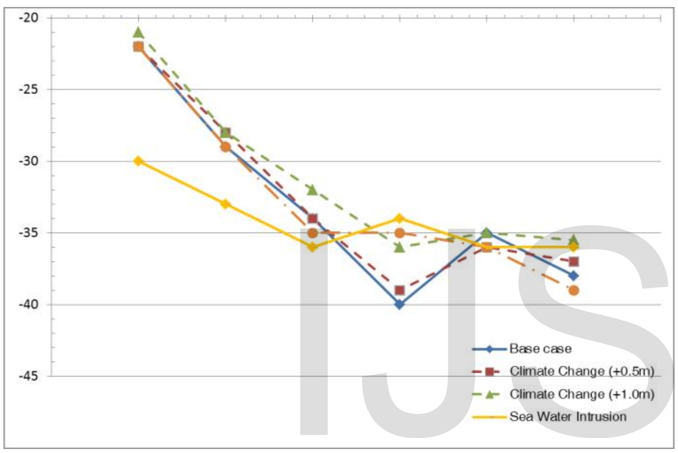


Fig. 13 Comparison between water heads in the modeled area for the different scenarios.

From the above results it is clear that the Kukar Aquifer under the Scenarios 1, 2, 3 have the same trend or behavior along the period of simulation where the minimum water head is allocated in Rafah area, this water head is decreasing until it reaches a value around -35m than it begin to increase for almost 10 years than it decrease another time. By comparing scenario 2 (Climate change scenarios) with Scenario 1 (base case scenario), it can be noticed that the sea water sea rise rather by 0.5or 1.0 m will affect the minimum water head by reducing the rate of decrease which can be an evidence for the sea water intrusion in the aquifer.

Scenario 3, which represents the effect of the sea water intrusion in the aquifer, shows strong evidence for the sea water intrusion, based on that the minimum water head decreased compared to the base case scenario. It is worth mentioning that under this scenario the minimum head is allocated also in Rafah area.

A longitudinal section is extracted from the modeled area as shown in fig. 14 in order to monitor the Water head as a response to the applied scenarios.

Four X-Sections through Rafah, Zowayeid, Kharouba and El-Arish areas are as follow;.

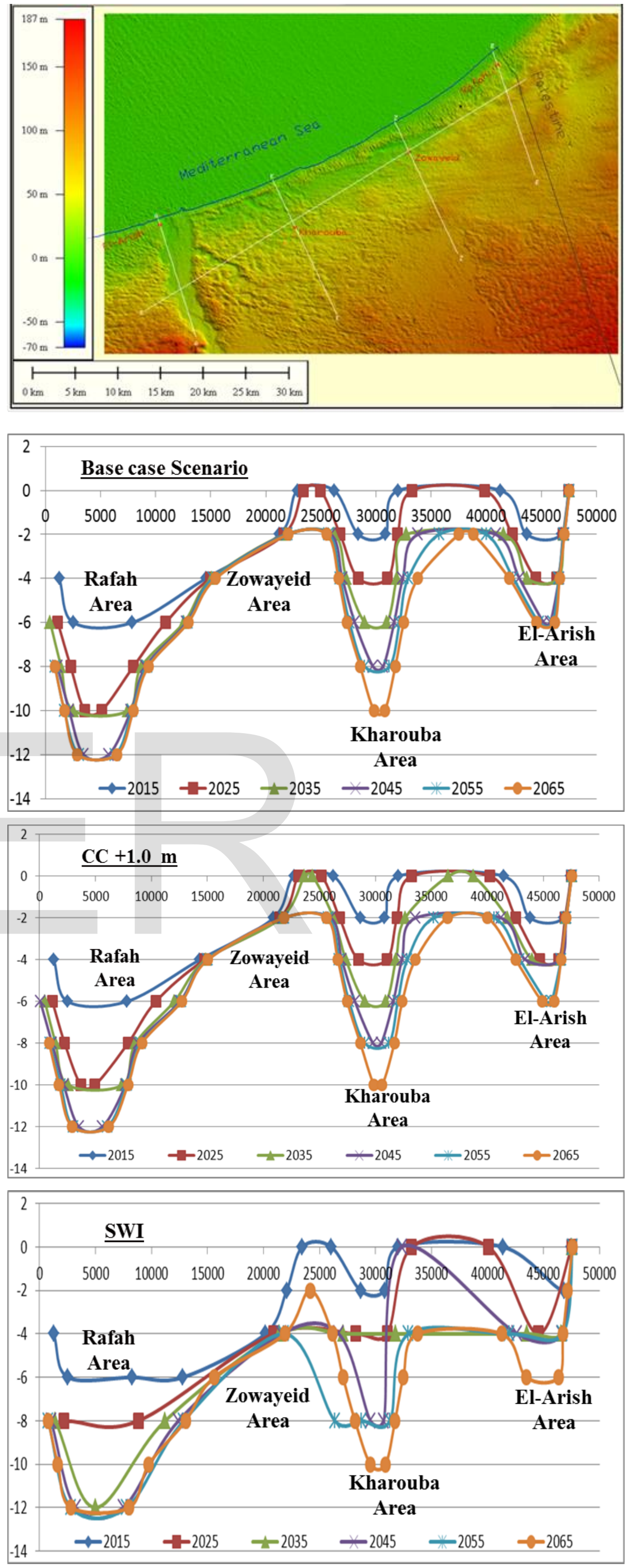


Fig. 14 Longitudinal sections through the modeled area due to the applied scenarios respectivly.

X-Section along Rafah Area

From fig. 15 which represents the X-section in Rafah area (R-R), it is well noted that during the simulation period the maximum water head reduction occurred 3km away from the shoreline with an average value (11m) for both first and second scenario while for the third scenario the water head value reached average value (12m).

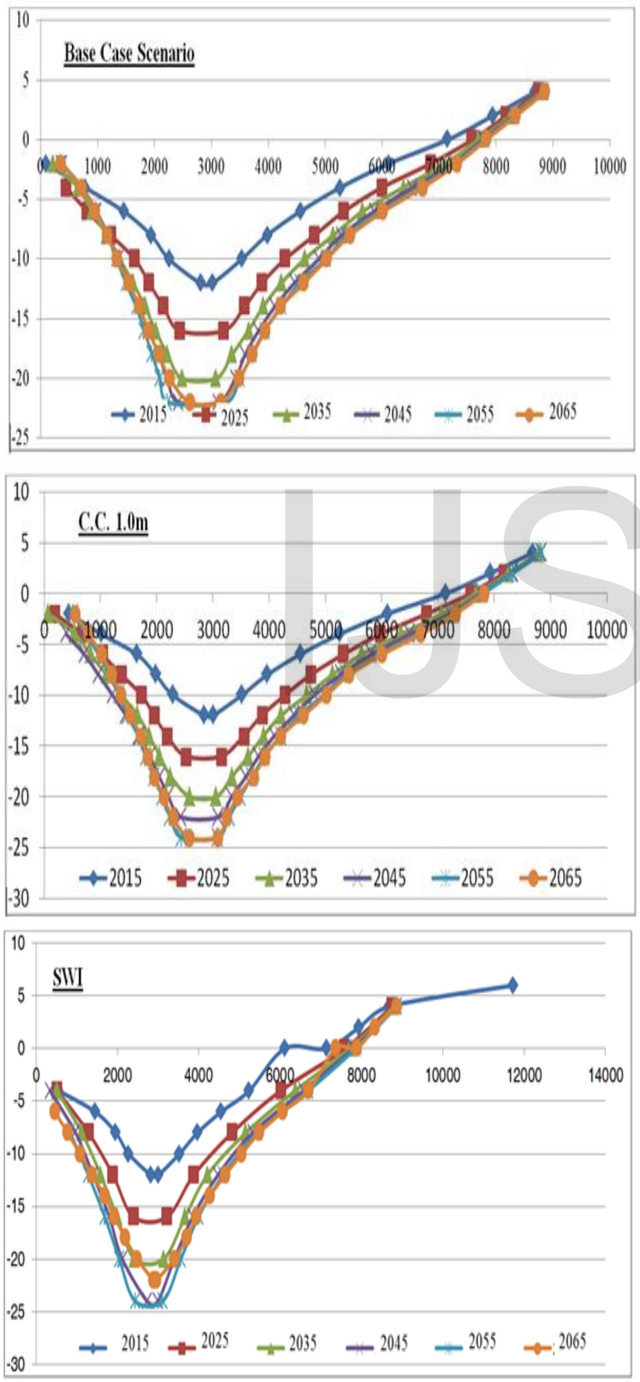


Fig. 15 X- Sections Along Rafah Area under three scenarios Respectively.

X-Section along Kharouba Area

As shown in fig.16 which represents the X-section in Kharouba area (K-K), the maximum water head reduction occurred 7km away from the shoreline with an average value (8m) for the three scenarios.

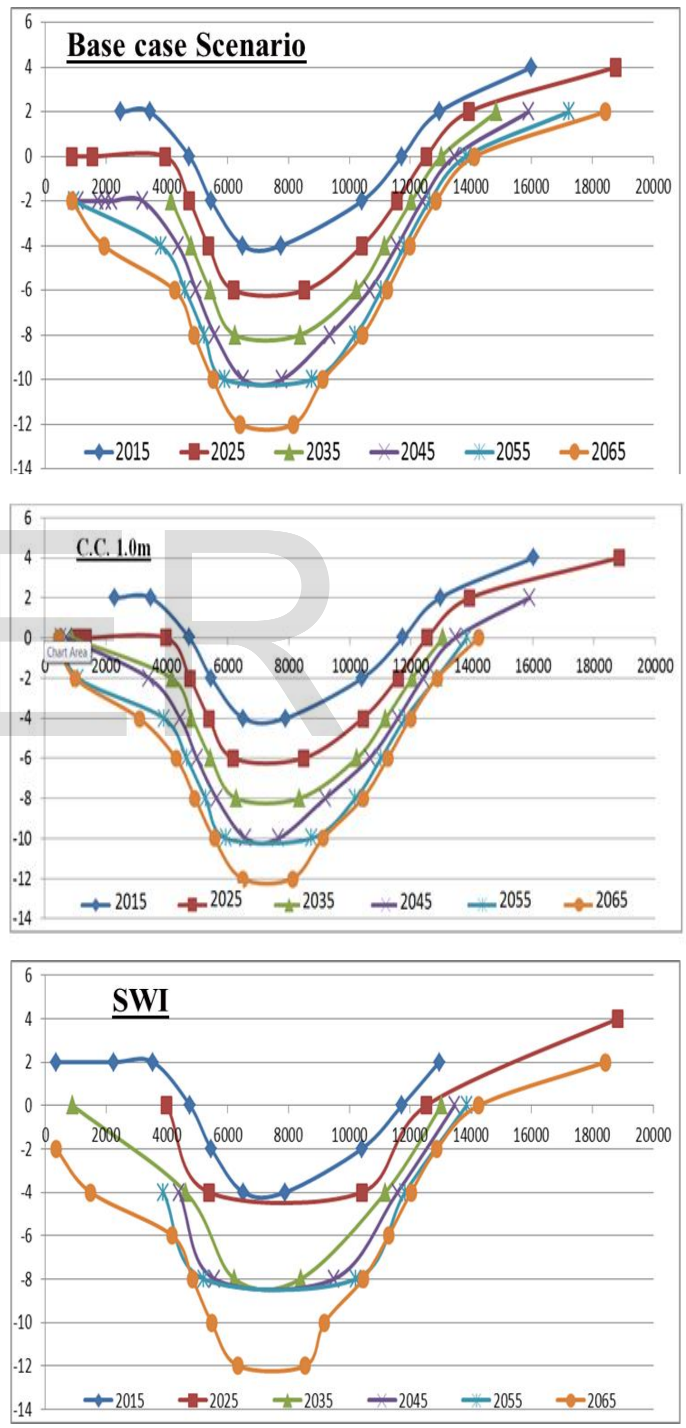


Fig. 16 X- Sections Along Kharouba Area under three scenarios Respectively.

X-Section along El-Arish Area

Finally the maximum water head reduction occurred 6km away from the shoreline with an average value (2m).as shown in fig. 17 which represents the X-section in El-Arish area (A-A).

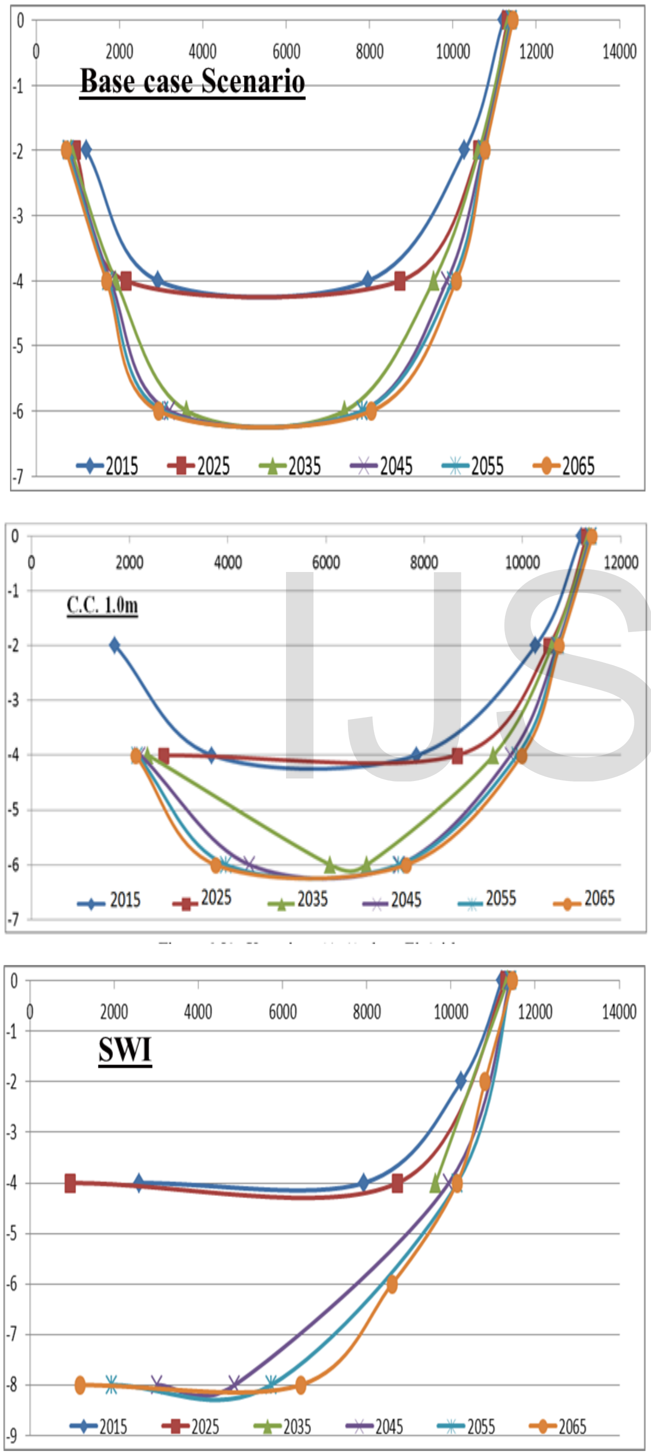


Fig. 17 X- Sections Along Arish Area under three scenarios Respectively.

X-Section along Zowayeid Area

From fig.18 which represents the X-section in Zowayeid area (Z-Z), there is almost no water head reduction along the simulation period under the first and second scenario. While in the third scenario the maximum water head reduction occurred 1km away from the shoreline with an average value (4m).

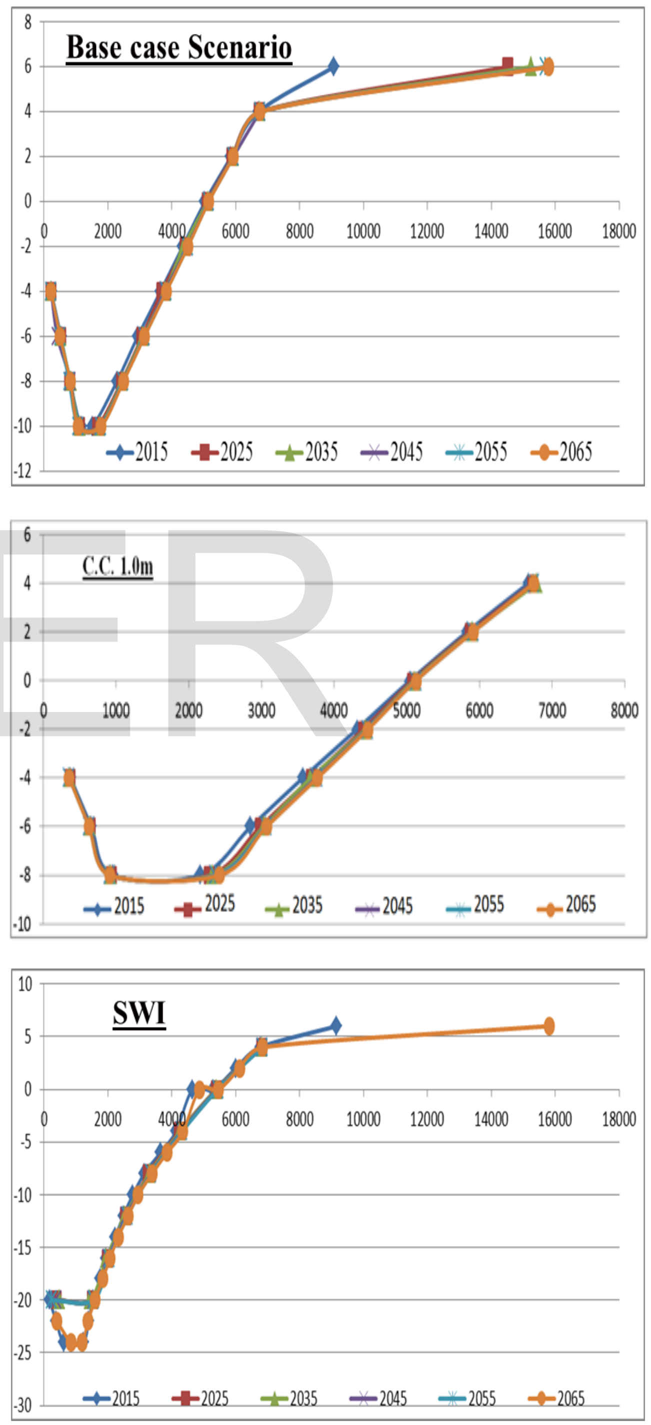


Fig. 18 X- Sections Along Zowayeid Area under three scenarios Respectively.

A summary of all the above results along the different X-sections is given in table 4.

Table 4

Summary of the Water Head depletion along the different X-Sections for the different Scenarios

X-Sections	Scenarios							
	Base case		Climate Change (+0.5m)		Climate Change (+1.0m)		Sea Water Intrusion	
	Dist. (km)	W.H. dep. (m)	Dist. (km)	W.H. dep. (m)	Dist. (km)	W.H. dep. (m)	Dist. (km)	W.H. dep. (m)
R-R	3	11	3	11	3	11	3	12
Z-Z	---	---	---	---	---	---	1	4
K-K	7	8	7	8	7	8	7	8
A-A	6	2	6	2	6	2	5	4

It can be concluded that the Kurkar Aquifer in the modeled area is not vulnerable for the Sea water rise due to expected climate Change effects on the other hand the aquifer is very sensitive for the increasing of the water pumping rate, Finally it is worthily to mentions that, the aquifer is vulnerable for the Sea water Intrusion specially in Zowayeid Area.

6 Conclusion

- ✓ The current extraction rate from the Quaternary aquifer in the modeled area leads to progressive decline in groundwater level under the current extraction policy about 0.15m/year, which means that at the end of the simulation period the saturated thickness will decrease by (25–30)%
- ✓ To conserve the storage of the Quaternary aquifer for sustainable development from the ground water resources in the modeled area, it is recommended that any decision of drilling new wells should satisfy the sustainability of the groundwater resources plan in the modeled area within some restricted rules to avoid the depletion of this important source of water and the priority should be given to the area located between Kharouba --- El-Arish and Kharouba--- Zowayeid Areas after studding groundwater quality before the start of any development.
- ✓ More individual studies should be implemented on El Arish Area, as it has special surface hydrology, in order to assess effectively the impact of the recharge and the Sea Water Intrusion.
- ✓ It is highly recommended that accurate studies should be done to analyze the impact of sea water intrusion and to estimate the effect of climate changes on groundwater recharge from precipitation on wadi El-Arish in order to help decision makers to sustain the water resources in this strategic area.

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