Impact of Pumping Rate on Seawater Intrusion in Jefara Plain, Libya

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Abstract: Jefara Plain located at north western of Libya. Jefara Plain influenced by arid desert areas to the south and Mediterranean Sea to the north. Groundwater is the main source of water in the Plain where the scarcity of water is major issue. Current groundwater resources are not covering the rapid development in the plain. Numerical modeling is an effective tool for managing groundwater resources and predicting future responses, MODFLOW and MT3DMS used to simulate groundwater flow and solute transport in Jefara Plain. In this study, four suggested scenarios for years 1993 through 2040 have been explored by using the three dimensional finite difference flow model (MODFLOW 2000) to simulate the flow system, and the solute transport model (MT3DMS) to predict the transport of total dissolved solids. These scenarios include: first, model will run without abstraction from the aquifers; second, pumping of agriculture assumed constant in this scenario, and the pumping of municipal are varied depending on population demand; third, running of the model under 1993 situation where the pumping rate for agriculture and municipal remaining constant during the interval 1993-2040 without any management or climate change effects.; and finally, pumping of municipal and agriculture assumed varied depending on future predictions. Results indicate that the fourth scenario has biggest effect on the drawdown and seawater intrusion extent. Different parameters including TDS, recharge, model boundary and advection parameters were adjusted to run the model. The fourth scenario with highest pumping rate value caused a slight increase of TDS values over the values simulated by other scenarios.
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1. Introduction

95% of Libyan population resides in coastal area, where the population concentrated in Benghazi Plain and Jefara plain at North East, and North West of Libya respectively. 60% out of 6 million are living in Jefrar Plain. Groundwater is main source of water in Jefara Plain, The total pumping from the unconfined and confined aquifers were estimated to reach 767 Mm^3/yr in the year 1993 (NCB, MMD, 1993), which is far beyond the safe yield of the recharge (165Mm^3/yr.). Absence of full control on private wells and its pumping rates in addition to pumping from the water authority well fields resulted in verexploitation of water storage and deterioration of groundwater quality in some parts of the aquifer especially in Tripoli area. In Jefara plain, agriculture is completely dependent on groundwater. Extensive pumping leads to rapid groundwater levels lowering, and to its quality deterioration.

The unconfined and confined Jefara Plain aquifers are the main source of agriculture productions and drinking water. The area was subjected to a series of seawater intrusion studies, (Cederstrom &Bertiola, 1960; Ogilbee et al., 1962; GEFLI, 1972; Navarro, 1975; Pencol, 1978; Floegel, 1979; Krummenacher, 1982; NCB&MMD, 1993; Office of Researches and Engineering Consultants, 2002).

The previous studies indicated that the groundwater flow was from south to north till year of 1975, after that hundreds of wells were drilled and modern pumps were installed with high capacity resulting extraction of huge quantities of water which leaded to changing the hydraulic gradient direction causing seawater intrusion.

In Tripoli region seawater intrusion observed in the last fifties (1957) in east of Tripoli, and observed in many places after that due to excessive pumping.

The data used in present study collected from GWA, and NCB&MMD (1993).

2. Description of study area

Jefara Plain is nearly flat area bounded from north by Mediterranean Sea and from south by Jabel Nafusa and stretched from Tunisian board in west to Alkhums in east as shown in (Fig.1). Jefara plain is flat area and the elevations increasing gradually from north to south, it can be divided into three different parts: the coastal strip in the north, the central parts and the foot of Jebal Naffusah (mountain) in the south. Jifara Plain elevates gradually southwards and reaches about 400 m above mean sea level in the south and 700 m at some parts between the Mediterranean Sea and Jebal Naffusah.

The land use in the study area is dominated by agriculture. More details are clarified in (Fig.2).

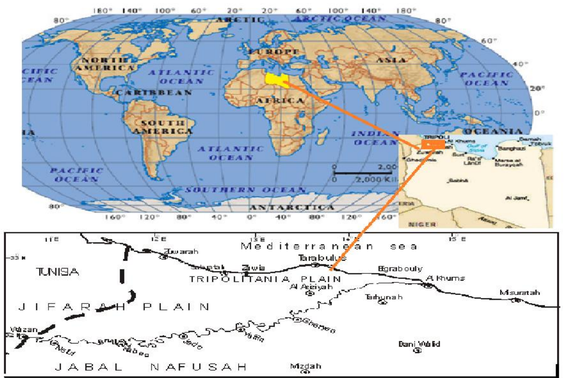

Fig.1: Location of Jefara Plain

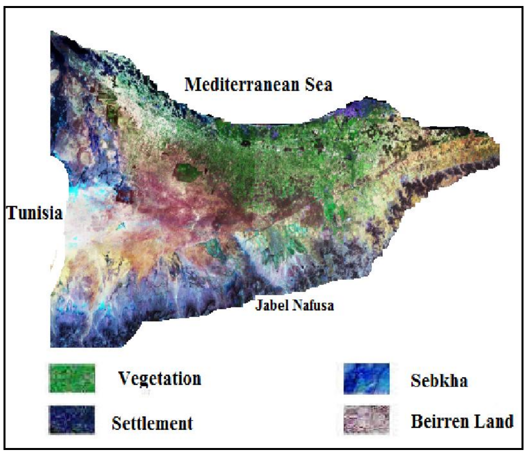

Fig.2: Landuse Patterns in Jefara Plain (Trriki, 2006)

2.1 Geology

Jefara Plain can be classified into three parts all of them covered by Quaternary deposits with occasional outcrops of limestone hills belonging to Al Aziziyah Formation (IRC, 1992). These parts are coastal strip, the central strip, and the foothill strip.

The coastal strip bonded by the sea cliffs, which are made of calcarenites, covered by coastal sand dunes and brown silt of Jefara Formation. This strip extends to the south for a distance ranges from 10 to 20 km and its low topographic area covered by sebkha sediments.

The central part extends from southern boundary of coastal strip up to 60-90 km, elevation in this part reach to 130m above sea level. Its harmony distributed by the outcrops of dolomitic limestone of the Al Aziziyah Formation which rises about 100 meters above sea level. The central part of Jefara Plain covered mainly by poorly consolidated eolian deposits mixed with the brownish silt of the Jefara Formation.

The foot hill strip mainly made of fluvial and proluvial coarser sediments of the Qasr Al Haj Formation, the elevations of this part ranging from 130 t0 200 meters above sea level.

The overall geological framework of Jefara Plain superficially very simple. Consisting of Tertiary to Quaternary strata resting on a faulted and tilted Mesozoic base, the plain stretches from the sea in the north to the edge of Jabel Nafusa in the south (Fig.3-6). However, this simplification hides some structural complexity of a number of faults, including one hydrogeologically important, the Al Aziziyah fault which runs through the town of the name. Significant thickness of the main Miocene-Quaternary unconfined aquifer is found to the north of this fault. The change in topography between the plain area and the Jabel Nafusa is probably marked by a fault (NCB & MMD, 1993).

The most important structural feature within the Plain is Al Aziziya west-east trending fault that divides thick Tertiary-Quaternary sequences to the north of it and only thin Quaternary deposits to the south. Parallel to Al Aziziya fault Coastal fault occurs more to the north. Possibly, also the boundary between the JabalNaffusah and the Plain, expressed as a conspicuous escarpment, has been pre-disposed by a fault. Several authors suggest that other faults occur in the Plain, mainly of NW-SE strike, but these do not seem to be hydrogeologically important (, Pallas, 1978, 198, IRC 1992).

The important geological formations in the study area are:

Gargaresh Formation: this formation makes steep cliffs along the shore stretched from Tajura in the east to Tunisian boarders in the west. The Gargaresh Formation is made of calcarenite including shell fragments and minor sandy grains intruded with occasional silty, Gargaresh formation extends from shoreline up 3 to 6 km in south.

Jefara Formation: this formation consists of fine materials (silt & sand) occasionally with gravel and caliche bands. It covers the extensive parts of Jefara Plain.

Abu Shaybah Formation: this Formation located below Miocene rocks in middle and east of Jefara Plain at depths ranging from 400-600 m under ground level, This formation widely distributed in Jefara Plain where it is easily recognized by its red color. Its age is Carnian. It's unconformable overlain by the Abu Ghaylan Formation.

Al Aziziyah Formation: the Al Aziziyah Formation is unconformable overlain by Abu Shaybah Formation where the contact marked by an undulating surface. Lithologically it's mainly consisting of limestone which is partly siliceous and partly dolomitic. Clays and chert bands are common occurrences.

Kurrush Formation: Lithologically the Kurrush Formation consists of a succession of yellow to green clays and pale red to brown micaceous sandstone with minor calcareous interbeds near the top.

2.2 Hydrogeology

The aquifers include significant amounts of water in Jefara Plain have been classified by Krummenacher (1982) as shown in table (1).

Many studies were carried out to determine the groundwater resources in Jefara Plain, these studies mentioned that groundwater in northern Jefara Plain is tabbed from the Quaternary as well as from the Miocene rocks. A Miocene deposit consists of several important aquifers; depth to water table ranges from 141-450 m. fig.3 represents the hydrogeological section of Tripoli.

Tab.1 Classification of aquifers in Jefara Plain(Krummenacher, 1982)

Group	Predomintal	Comment
Miocene-Quaternary	Sands, sanstone and sandy limestone	The main aquifer of Jefara Plain; unconfined
Oligo-Miocene	Calcareous sandstones	Significant confined aquifer in the north of Jefara Plain
Cretaceous	sandstone and limestone	the main aquifers of this group are the Sidi As Sid limestone which is unconfined aquifer
Jurassic	Detrital limestones and sandstones	Significant source of water at the foot of JabelNafusa
Triassic	Limestone and sandstones	The main aquifers of this group are the Aziziyah limestone and the Abu Shaybahsandstone and clay; important source of water in Central Jefara

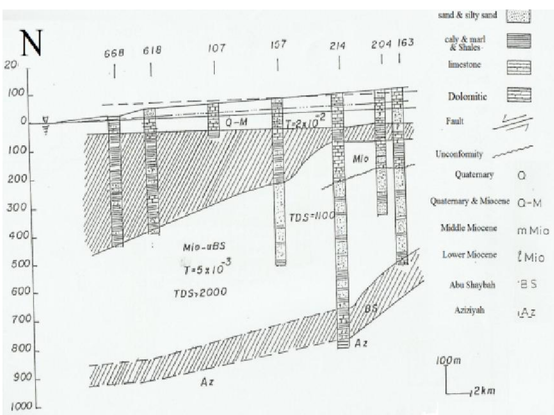

Fig.3: Tripoli hydrogeological section (Kruseman and Floegel, 1978)

The Miocene-Quaternary unconfined aquifer is the main and important source of groundwater in Jefara Plain which is located to the north of Al Aziziyah fault, thus constitute the main source of irrigation and domestic supplies in Jefara Plain, Miocene Aquifer located north of Al Aziziyah fault, this aquifer consists of limestone, sandy limestone, dolomitic limestone, and clay. Thickness of this aquifer varies from few tens of meters in the east (near Garabulli) to several hundred meters in the west (near Sabratah). Transmissivity varies from 7 to 337 m2/d (GEFLI, 1972). Clay layers separate this aquifer from the quaternary and lower Miocene aquifers, Abu ShaybahAquifer located at depth ranges between 300-700 m and consists of thick layer (125-450 m) of sandstone, which intruded with clay and shell. This aquifer has good yield (sometimes more than 100 m3/h). The depth to water table is not fixed and affected by extensive abstraction, and Al Aziziyah Aquifer is confined except in the south central part between the southern limits of the Miocene transgression and the foothills of the Jebal Neffusah and is rather deep seated; around 1000 m below ground in the Tripoli area and located under Abu Shaybah formation rocks. It is located to the north of Al Aziziyah fault and consists of dolomitic limestone, limestone, and dolomite with intruded by clay and marl.

A typical section taken from north to south by Krummenacher (1982) showing more details for the mentioned aquifers as shown in fig.4

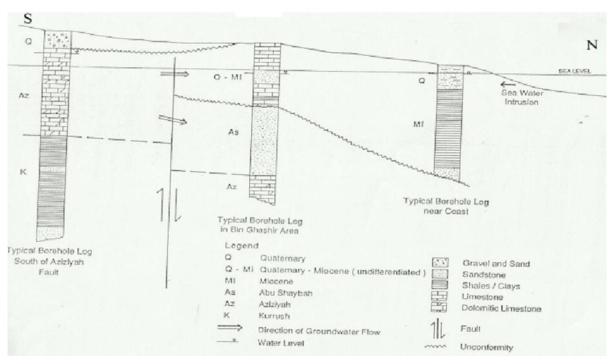

Fig.4 typical cross section from north to south of Al Aziziyah fault (Kruseman and Floegel, 1978)

2.3 Hydrochemistry

The historical hydrochemical data for the wells in Jefara Plain Basin collected from more than 198 wells scattered all over the basin (NCB & MMD1993) The values of TDS (mg/l) calculated by multiplying the values EC of (ds/m) by 640, fig.5 shows the distribution of these wells and TDS contours.

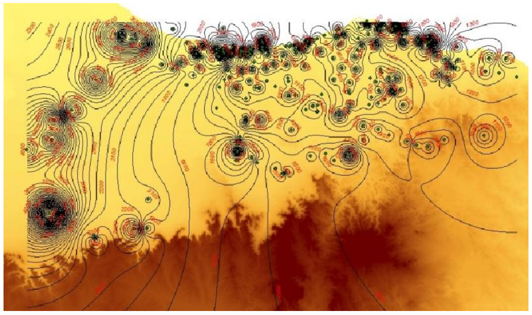

Fig.5 wells &TDS contours distribution over Jefara Plain

2.4 Recharge

Recharge to Jefara plain aquifer system comes from direct rainfall, according to Pencol (1978) and Krummenacher (1982) (the estimated recharge is between 5-15% of the rainfall), other sources of recharge are irrigation losses, water supply networks losses, and surface water recharge. GEFLI (1972) found that the total recharge from surface runoff in Jabel Nafusa and Jefara Plain equal to 71.3 Mm3/yr. Krummenacher (1982) estimated recharge value of Plain which is equal to 42.7 Mm3/yr. NCB & MMD (1993) estimated that the value of recharge to the plain equal to 9.7 Mm3/yr.

NCB & MMD (1993) estimated the total recharge to Jefara Plain aquifer system as clarified in table (2) per year.

Table.2 Estimated of the recharge value in Jefra Plain aquifer system by NCB & MMD (1993)

Recharge source	Volume Mm^3/yr.
Rainfall	83.9
Surface runoff infiltration	9.7
Irrigation and municipal losses	76.9
Total	165

2.5 Discharge

Many studies carried out to estimate groundwater abstraction from Jefara Plain. Table (3) is showing the estimation of Agriculture use and municipality use per year.

Table (3) (Elgzeli, 2010)

Date of estimation	Author	Agriculture use Mm^3	municipal useMm3	TotalMm3
1959-1962	USGS	195	15	210
1972	GEFLI	313	65	378
1975	GEFLI	475	92	567
1978	SDWR	461	94	555
1980	GEFLI	483	91	532
1993	FAO	802	200	574

Data from 1962 to 1993 have been interpolated as shown in figures (6) & (7) and the abstraction rate from whole Jefara Plain groundwater determined.

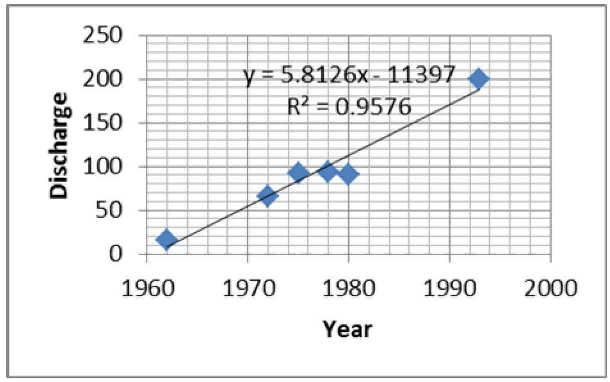

Figure (6): interpolation of abstraction rate from 1962 to 1993 (municipal).

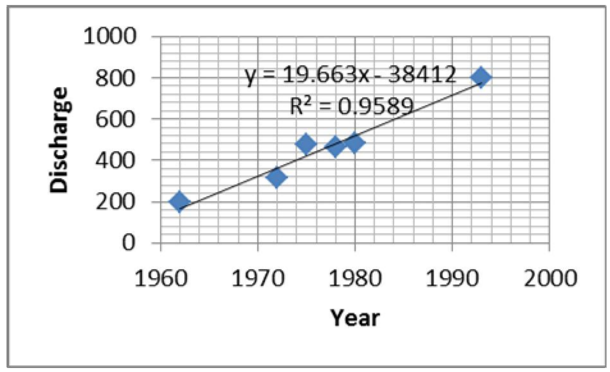

Figure (7): interpolation of abstraction from 1962 to 1993 (agriculture).

3. Model description, calibration and application

3.1 Model Description

The conceptual model for Jefara Plain Basin adapted by this study consists of three hydrogeological layers, two aquifers and a confining layer. The unconfined aquifer is taken as the first layer, followed by the confining layer as the second layer. The third is the confined aquifer. Interaction between the various aquifer systems is represented by leakage terms. These layers in addition to the surrounding boundaries are distinguished from each other by the hydraulic conductivity for each element in its field. First layer forming the unconfined aquifer, which consists of Quaternary, and Miocene deposits, hydraulic conductivity of this aquifer varying between 5-15 m/d, and specific yield varying between 4-10%. Third layer forming the Triassic deposits of the Abu Shaybah and Aziziyah aquifers.

The model domain consists of 111 rows, 195 columns and three layers, grids used in this study are the same for both the flow and transport model. Model covered an area of 21,462 km^2 for whole Jefara Plain.

Constant head boundary is only specified in cells representing the sea in all layers. Constant head boundary is in the north (sea), and south of the domain. The topographic elevation of Jabel Nafusa in the south defined the constant head where flow comes from this side. No flow boundary conditions are in the east, and west.

3.1.1 Governing Equations

The partial-differential equation of ground-water flow used in MODFLOW is (McDonald and Harbaugh, 1988)

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left[\left(k_z\frac{\partial h}{\partial z}\right)+W=s_s\frac{\partial h}{\partial t}\right.$$

Where

kx, ky, and kz are values of hydraulic conductivity along the x, y, and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (L/T), h is the potentiometric head (L), W is a volumetric flux per unit volume representing sources and/or sinks of water, with W<0.0 for flow out of the ground-water system, and W>0.0 for flow in (T^{-1}), Ss is the specific storage of the porous material (L^{-1}); and t is time (T).

In steady state calibration the first part of previous equation was used as following:

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left[\left(k_z\frac{\partial h}{\partial z}\right)+W=0\right.$$

In addition to the flow equation, a second partial differential equation is required to describe solute transport in the aquifer. Ground-water flow causes the redistribution of solute concentration, and the redistribution of solute concentration alters the density field, thus, affecting groundwater movement. Therefore, the movement of ground water and the transport of solutes in the aquifer are coupled processes, and the two equations must be solved jointly (Guo and Langevin, 2002).

$$\frac{\partial C}{\partial t}=\nabla.(D.\nabla C)-\nabla.(VC)-\frac{qs}{\theta}C_s+\sum_{K=1}^{N}(Rk)$$

The above partial differential equation describes the transport of solute mass in ground water

Where:

D: is the hydrodynamic dispersion coefficient [L^2 T^{-1}],

V: is the fluid velocity [L T^{-1}],

Cs: is the solute concentration of water entering from sources or sinks [ML^{-3}], and

Rk: (k=1, …, N) is the rate of solute production or decay in reaction k of N different reactions [ML^{-3} T^{-1}].

3.2 Steady State Calibration

Numerical modeling has emerged as an effective tool for managing groundwater resources and predicting future responses, especially when dealing with complex aquifers systems and heterogeneous formations. Among these models, MODFLOW and MT3D are the most commonly used simulators for groundwater flow and solute transport in subsurface systems, respectively (Abu-El-Sha'r & Hatamleh, 2007)

MODFLOW and MT3D models used herein as a management tool for the Jefara Plain basin, one of the most important groundwater resources for domestic and agricultural sectors in Libya.

3.2.1 Steady State Calibration using MODFLOW2000 of 1993 year

Steady state calibration for the flow model was achieved by comparing the hydraulic heads obtained from available groundwater levels of the upper and lower model layers and the calculated hydraulic heads of the MODFLOW, data for 1993 from GWA used to calibrate the head in observation wells. Simulation time for steady state was 365 days. During calibration, horizontal and vertical hydraulic conductivities values were adjusted in sequential model runs to match the simulated heads and measured head.Figure (8) compares the simulated results with the observed water level values. The modeled values show a correlation coefficient of 0.99 with the observed values.The calibration results for the groundwater heads for the steady state models are regarded as satisfactory with a RMS value of 2.37 m.

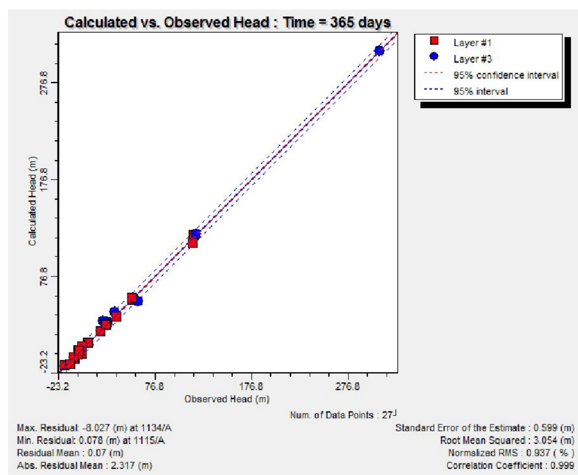

Figure (8): Steady state calibration results (head)

3.2.2 Solute Transport Mdel

Constant concentration cells were assigned along the sea line to the north as 35000 mg/l, and to the south varied from 2500-1500 mg/l depending on distribution of contour lines from data introduces to GIS.

Recharge concentration specified as 1750 mg/l where the area effected by irrigated & municipal recharge water, and specified as 640 mg/l in the area affected by rainfall & surface runoff recharge (NCB &MM 1993), , andSpecific concentrations assigned to each domestic well location to reflect the actual conditions.Figure (9) compares the simulated results with the observed concntration values. The modeled values show a correlation coefficient of 1.00 with the observed values. The calibration results for the groundwater concntration for the steady state model are regarded as satisfactory with a RMS value of 29.87 mg/l.

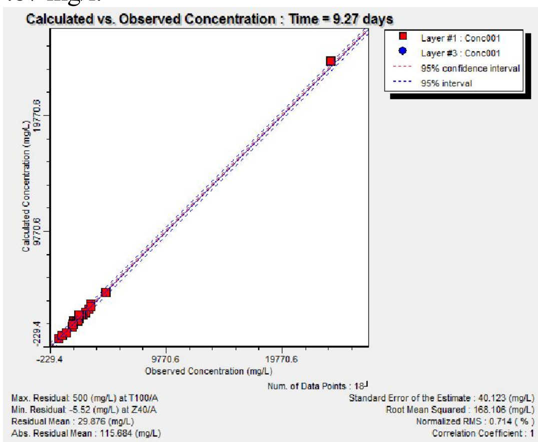

Fig.(9) Steady state calibration results (TDS)

3.3 Model Verification

The data observed by GWA in 2010 and 2002 for head and concentration respectivily compared to the data introduced by model as shown in tables 4&5.

Table 4.verification of head values 2010

Well No	GWA 2010	model 2010
1054	-3	-2.5
1006	-40	-41
1311	-10.67	-10
1057	-18	-11
1134	15	22
1115	119	122
1194	309	301
1020	7	6
1344	36.6	36.12
1054	-3	0

Table 5. Verification of TDS values 2002

well	x	y	Observed 2002	calculated 20(
T23	323100	3633200	947.2	751
T24	333700	3641000	3110.4	3040
T50	340300	3639350	2880	2500
T60	350200	3638950	3436.8	3281
T100	304200	3632000	34352	32372
T203	315350	3632350	691.2	539
T403	335850	3639050	2771.2	2607
Z20	258900	3632400	3993.6	3762
Z100	257500	3633600	2816	2607
T10	301040	3631000	2291.2	2376
Z40	275600	3629400	3417.6	3508
Z52	289300	3629600	2156.8	2444
Z302	273100	3629300	4288	4942
Z400	282900	3630200	5856	6130
Z501	294100	3630200	2368	2590

3.4 Model Predictions

Model predictions have been conducted in order to evaluate the response of the model for four future scenarios. These scenarios vary in terms of pumping rates for the different operating well groups in the basin as follows: the first scenario assumes that the model will run without abstraction from the aquifers, to check if the groundwater levels and quality can return to the situation prior to the excessive abstraction from the aquifer system.; the second scenario assumes pumping rate of agriculture requirements constant, and the pumping rate of municipality are varied depending on population demand. This scenario approximately represents the actual situation because the agriculture area did not increase due to increasing commercial activities against agriculture activities; in the third scenario, running of the model under 1993 situation where the pumping rate for agriculture and municipal remaining constant during the interval 1993-2040 without any management or climate change effects.; the fourth scenario assumes that the pumping rate will include of both agriculture and municipal uses as predicted in figures 6&7.

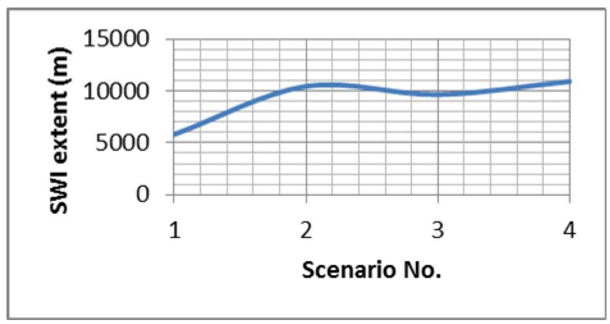

Figure (10): In-land Seawater Intrusion for all scenarios at Ain Zara section.

The maximum drops in GW levels for all the scenarios considered are given in Table (6).These indicate that the fourth scenario has the biggest effect on GW drops.

Table 6: Maximum simulated GW levels below surface for the four scenarios.

Scenario No.	Year	Max Draw Down(m)
Scenario No.2	2020	-117
	2040	-128
Scenario No.3	2020	-99
	2040	-125
Scenario No.4	2020	-118
	2040	-142

4. Results

Since Jefara Plain is coastal area so the main concern is seawater intrusion affecting the groundwater quality due to excessive pumping rate.

Four sections were distributed over the coastal area using DEM in GIS, three of them are applied to Tripoli in Gergaresh (west), Ain Zara (middle), and Tajoura (east) and the last one applied over the western part of Jefara Plain calles Sabrata section as mentioned in figure (11).

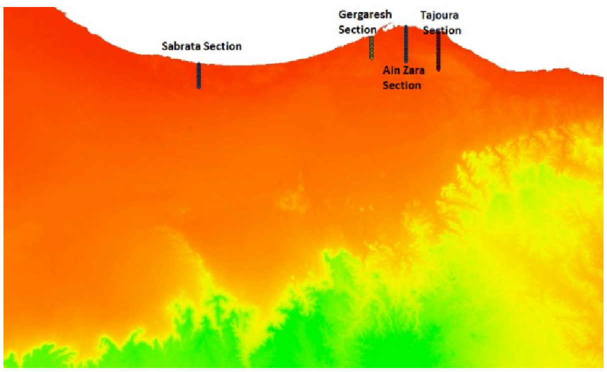

Figure (11): Distribution of sections over Jefara Plain.

The models used in this study, MODFLOW2000 andMT3D, provided an effective tool managing Jefara Plain aquifers by evaluating the effect of the different alternatives under consideration. Simulation results indicate that:

- Pumping rate has huge effect on both seawater intrusion and groundwater drawdown, where scenario No.4 has the bigger amount of pumping rate, so this scenario worst scenario in increasing in-land seawater intrusion rate and in drawdown.
- The most critical scenario for the extent of seawater intrusion is scenario No.4 since this scenario will cause an extent rate about 150 m/yr, while the extent rate of seawater intrusion in scenario 2 (reference scenario)was 140 m/yr.
- In Tripoli area the worst scenario for the unconfined and confined aquifers is scenario No.4 where the inland seawater intrusion reached 10914 m & 2600 m respectively.
- • The total dissolved solids due to seawater intrusion decrease by increasing the distance from sea shoreline with the involvement of two factors; the first is the location of the well from the sea shoreline, and the second is the depth of the well from the ground surface.

• Scenario 1 results (2040) showing that the water levels in upper aquifer increased up to more than levels observed in 1972 which mean that the upper aquifer fully recovered, however in Bin Ghashir area the water table did not reach the previous level in 1972.

• Decreasing pumping rates by 50% will decrease concentrations between 10% and 40% as compared to the reference scenario.

• Increasing pumping rates by 100% will cause increasing in the concentrations between 3% and 22%, depending on the well distance from sea shoreline.

• In all scenarios the area south of Tripoli in Bin Ghashir and Al Swani are dried up for an unconfined aquifer due to heavy agriculture requirements.

• Increasing pumping rate decreases the head in both aquifers, and vice versa.

• The maximum inland seawater intrusion in unconfined aquifer at Tripoli area happened at Ain Zara section, while the minimum inland seawater intrusion happened at Gergaresh section.

• The maximum inland seawater intrusion in confined aquifer at Tripoli area happened at Tajoura section.

• No seawater intrusion observed at confined aquifer in Gergaresh section (Tripoli area) and in Sabrata section (western of Jefara Plain) for all periods of model running.

• The maximum drops in GW levels values for all the scenarios considered indicated that the fourth scenario has biggest effect on GW lowering.

• For any management plan to be successful for Jefara Plain, pumping from both municipal wells and agricultural well must be addressed. This is due to the fact that they both have high impacts on water table elevation especially in Tripoli area that has negative heads.

• Seawater intrusion has taken place and will continue to move landwards if the water table position cannot be stabilized.

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